Final report

Nordic Energy Perspectives

Technology options for a low CO_2 energy system

Nordic case studies

March, 2009

Nordic Energy Perspectives

1 Preface

Nordic Energy Perspectives (NEP) is an interdisciplinary Nordic energy research project with the overall goal of demonstrating means for stronger and sustainable growth and development in the Nordic countries.

NEP analyses the national and international political goals, directives, and policy instruments within the energy area, as well as their influence on the Nordic energy markets and energy systems and the infrastructures and institutional structures. NEP aims at clarifying to decision-makers the consequences of political and strategic decisions for politicians, energy actors and the public. The project is to promote a constructive dialogue among researchers, politicians, authorities and actors on the energy markets. For further information about the project, please visit: *www.nordicenergyperspectives.org*. This series of reports are the second reporting from the second phase of the project. The following intermediate and final reports are now presented:

Synthesis report, March 2009:

- Second NEP2 synthesis report *(Responsible: Peter Fritz, Håkan Sköldberg, Bo Rydén)*

Final reports, March 2009:

- Widened view of energy efficiency and the resource management *(Responsible: Bo Rydén)*
- Technology options for a low CO_2 energy system *(Responsible: Tiina Koljonen)*
- Wood markets and the situation of the forest industry in the Nordic countries *(Responsible: Per Erik Springfeldt)*

Intermediate reports, March 2009:

- Reference and policy scenarios *(Responsible: The NEP model group)*
- Global scenarios *(Responsible: Janne Niemi)*
- Biomass market and potentials *(Responsible: Tiina Koljonen)*
- Nordic perspectives on the EU goals relating to CO_2, renewable energy and energy efficiency *(Responsible: Thomas Unger, Bo Rydén)*
- Prominent strategies for environmental sustainability in the stationary energy sector *(Responsible: Anders Sandoff)*
- The future of the Nordic district heating *(Responsible: Monica Havskjold, Håkan Sköldberg)*
- Trade within the RES directive and related power interconnection issues *(Responsible: Berit Tennbakk)*
- Natural gas in the Nordic countries *(Responsible: Peter Fritz)*

Our intention in NEP is to present all reports in English. Due to lack of time, some of the texts in some of the reports are at this stage still in Scandinavian languages. We apologize for this. These texts will as soon as possible be translated into English. The translated texts/reports will be available on the project's web site, *www.nordicenergyperspectives.org*, soon after the Oslo conference.

Oslo, March 2009
The NEP Research Group

Content

1 Introduction

The EU has agreed to adopt the necessary domestic measures and take the lead internationally to ensure that global average temperature increases do not exceed pre-industrial levels by more than 2°C. Secondly, Europe has agreed a political agenda to achieve its core energy objectives of sustainability, competitiveness and security of supply. This agenda means substantial change in Europe's energy system over the next years. In December 2008 the European Commission accepted a wide-ranging energy package, called 20-20-20 climate and energy package, which will stimulate Member States' investments in more efficient, low-carbon energy system. The document lays out a strategy by which Member States will be able to slash their collective greenhouse gas emissions by at least 20% and boost the share of renewable energy to 20% of total consumption by 2020 and a saving of 20% in future energy demand by 2020. A reduction in greenhouse gases (GHG) by 2020 rises to 30% if there is an international agreement committing other developed countries. The above emission reduction targets are necessary to ensure that the world stays within the 2 °C limit. The energy and climate package also includes a target to increase the use of renewables in transportation to 10% by 2020. All except the energy efficiency target are legally binding targets to justify the investment needed to transform Europe into a low carbon economy.

The above targets are challenging for the Nordic countries as renewable energy sources and nuclear comprise already now a large share of total energy supply in the Nordic area (see figure 1). The share of renewables in total energy supply is close to 30% and about 50% in electricity production in the Nordic area. Taking into account nuclear power production in Finland and Sweden, the share of carbon free fuel supply in electricity production is almost 70%[1].

In stationary energy production CO_2 emissions could be further reduced by increasing the use of renewable energy sources and by investing in new nuclear. Also, use of natural gas instead of coal would be possible in those areas that have natural gas pipelines nearby. In the Nordic area especially investments in wind power and biomass fired energy production have good possibilities to be increased in the future (see the report "Nordic perspectives on the EU goals relating to CO_2, renewable energy and energy efficiency"). On the other hand, investments in hydro power and nuclear installations are limited by national legislation. In the longer term, carbon capture and storage (CCS) could be an option to reduce greenhouse gas (GHG) emissions in fossil fuel fired energy production. However, this would require international legislation and rules to overcome the barriers to long term carbon storage. The EU has already taken the first steps to promote CCS by launching a new directive, which aims at making CCS possible for all the Member States, and later even compulsory at large scale energy production. Large scale CCS demonstration plants are also needed to prove that the technology is mature and safe, and to bring costs down and make the technology commercially viable. The EU has also target to build ten large scale demonstration plants before 2020.

In addition to low carbon technologies in stationary energy production, there are also major challenges to reduce CO_2 emissions in transport, residential, and industrial sectors. The EU has set a directive to increase renewable energy in transportation to 10% by 2020. The target

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[1] This percentage is calculated by assuming the efficiency of nuclear power as 1 (in statistics the assumption is usually 0,33)

can be set by replacing oil with liquid biofuels or renewable electricity. In the residential sector, CO_2 emissions in heating can be reduced by increased use of heat pumps, biomass or biofuels (i.e. pellets or liquid biofuels), or by moving to low energy, or even passive energy buildings.

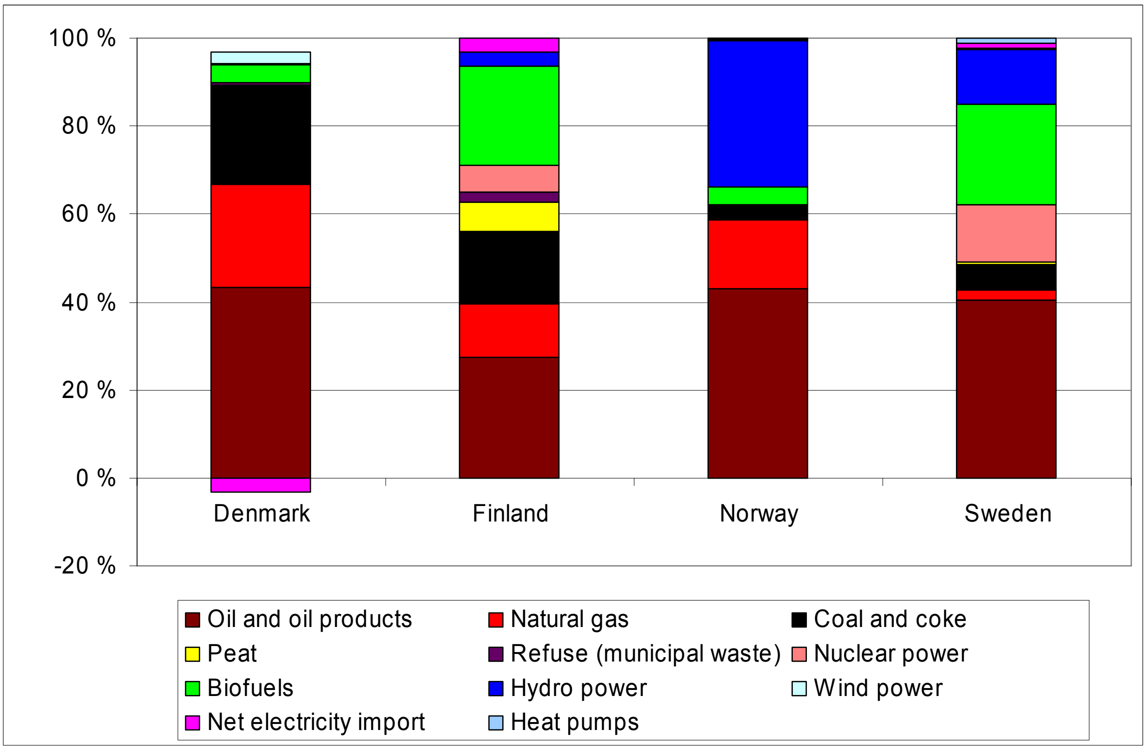

Figure 1. Primary energy supply in Nordic countries in 2006. Source: Country statistics 2006.

Figure 2 shows the share of renewable sources in final consumption of energy in the base year 2005 and the target share of renewables in 2020 set by the Commission for Denmark, Finland, and Sweden. Norwegian goals for energy efficiency and renewable energy are not separately quantified. However, Enova has signed a contract with their owner (The Norwegian Ministry of Petroleum and Energy) committing themselves to achieve at least 12 TWh in 2012, and 30 TWh in 2016. The target is to be reached through a combination of energy savings (through energy efficiency measures), renewable electricity and renewable heat.

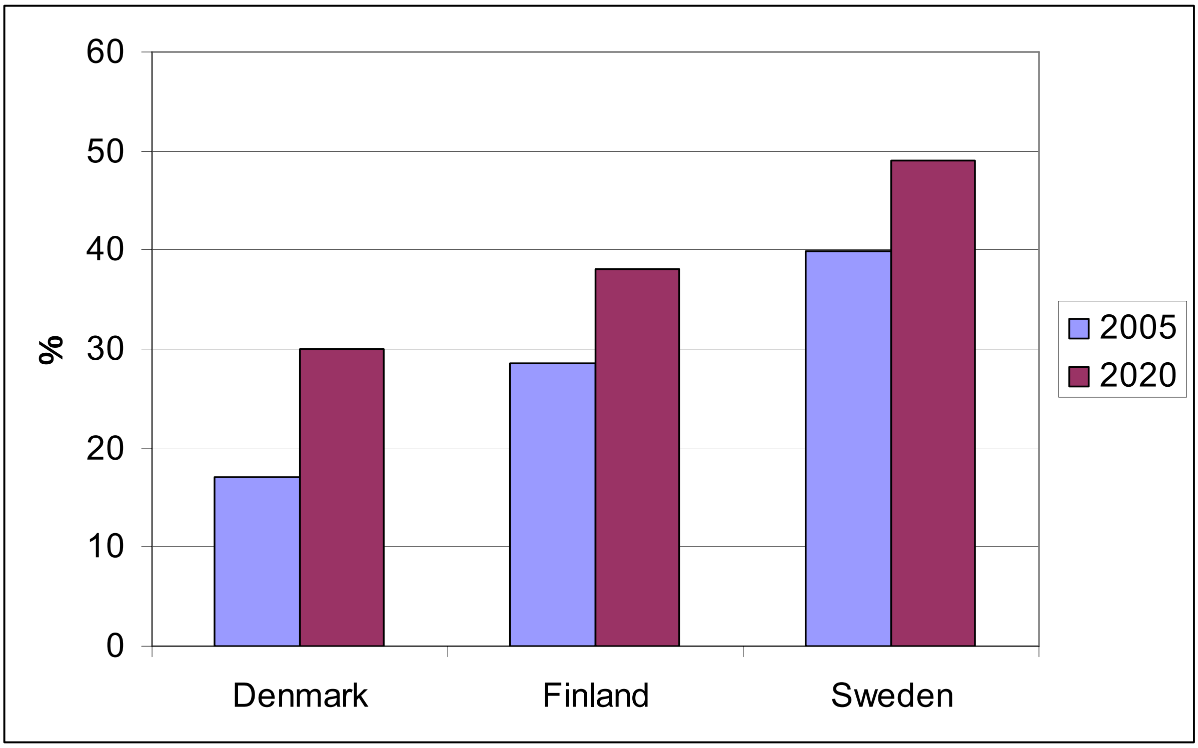

Figure 2. National overall targets defined by the Commission for the share of energy from renewable sources in final consumption of energy in 2020. Source: EU 2008b.

The above targets imply an increase in renewables in the energy sector by more than 100 TWh in the Nordic area (see e.g report "Nordic perspectives on the EU goals relating to CO_2, renewable energy and energy efficiency"). It is evident that fulfilling the targets would mean major changes to the Nordic energy system.

In this report of the Nordic Energy Perspectives project an overview of the major technology options for a low CO_2 emission system is given. This report gives an overview of the possible pathways to transform Nordic area a low carbon, high efficient economy. Firstly, we give an overview of the renewable energy potentials in the Nordic area. Biomass potentials and markets are reported in more detailed in a separate report "Biomass markets and potentials". Secondly, some examples of technology options for a low CO_2 energy system have been evaluated and verified in the Nordic context. The report is written by Tiina Koljonen, Göran Koreneff, Martti Flyktman and Satu Helynen from VTT. The global scenarios have been compiled by Antti Lehtilä from VTT.

2 Impacts of the EU's 2 C target on the Western European energy systems

The Global TIAM model has been used to simulate the impacts of the EU's energy and climate policies on regional energy systems. Below are shown the long term energy and emission scenarios for Western Europe (i.e. EU-15, Iceland, Malta, Norway and Switzerland) to give a widened view of the impacts of EU's policies on future energy systems. Two scenarios have been studied: Baseline scenario and climate policy scenario with deep emission reductions. The regional and global scenarios for GDP development were obtained from studies made under the IEA / ETSAP collaboration, and were further calibrated with the global dynamic GTAP model developed by VATT. The Baseline assumptions are described in more detailed in the NEP report "Global scenarios". In the policy scenario the impact of the EU's 2 °C target on greenhouse gas emissions have been simulated assuming global emissions trading and global consensus to tackle climate change. The so called 2 °C Market simulation case represents global minimum in costs (or global maximum in consumer welfare) to tackle climate change. Figure 3 shows the greenhouse gas (GHG) emissions for Baseline and 2 °C Market scenario indicating that Western Europe should reduce their GHG emissions by about 50% by 2050 from the current level and by the end of this century the whole energy system should be practically emission free. The base year for the simulations was 2005.

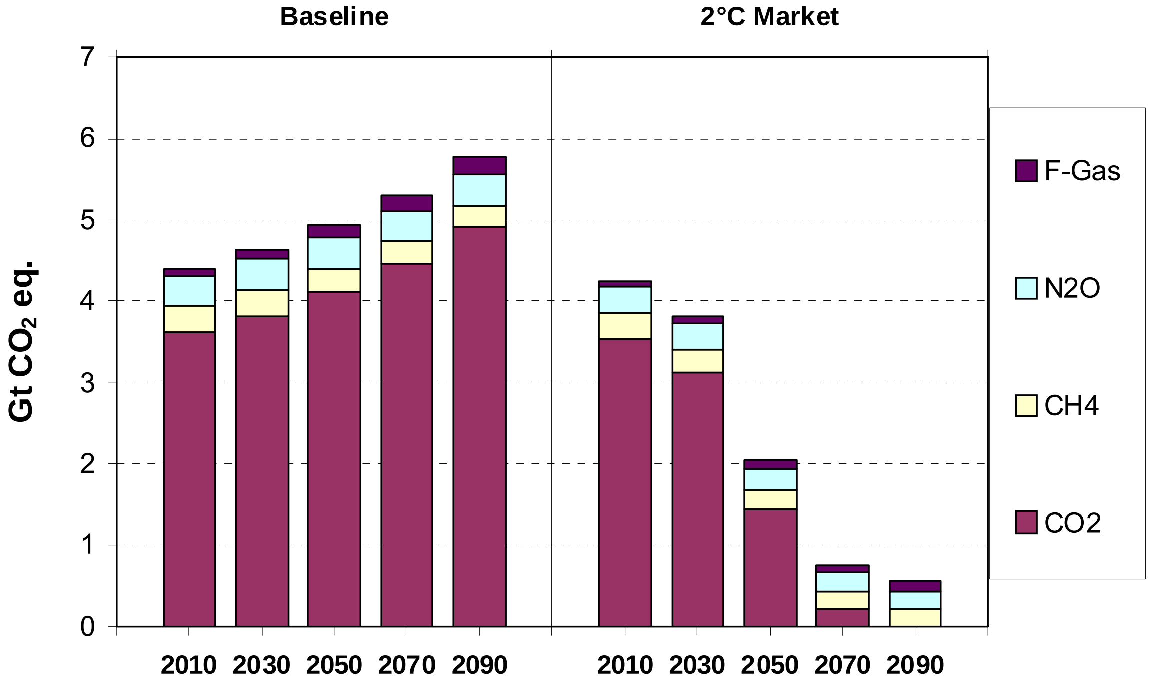

Figure 3. Greenhouse gas emissions in the Western Europe in Baseline and 2 °C Market scenarios

Figure 4 shows the use of primary energy resources in Western Europe in the Baseline and 2 °C market scenarios and figure 5 shows electricity generation with different technologies. Both figures indicate that the share of renewables should increase radically in the 2 °C Market scenario. The use of biomass is at its maximum after 2020. However, in this example biomass import was not allowed from other world regions indicating that the use of biomass could be even higher if biomass would have been imported. The fossil fuels would remain in the energy mix also in the 2 °C Market scenario but after 2020 fossil fuel fired electricity production would be equipped with carbon capture and storage (CCS), when it was assumed to be demonstrated and available. The VTT version of the Global TIAM model allows also CCS investments in biomass fired energy plants resulting in "negative" emissions. In the 2 °C Market scenario this biomass CCS was a cost effective alternative to reduce GHG emissions in the long term.

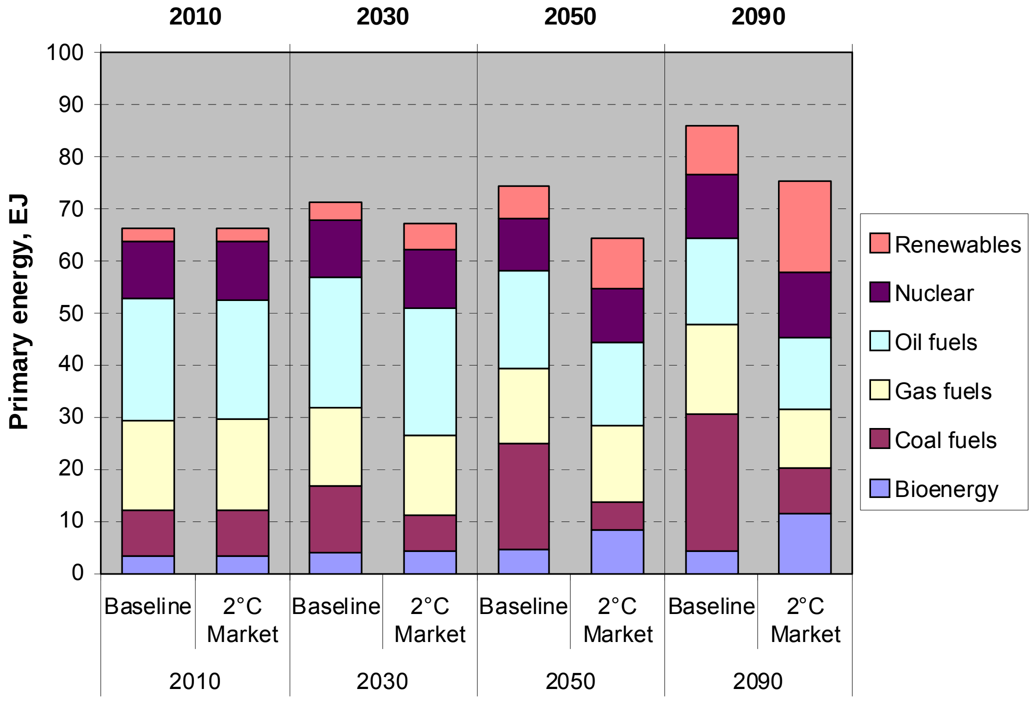

Figure 4. Primary energy consumption in the Western Europe.

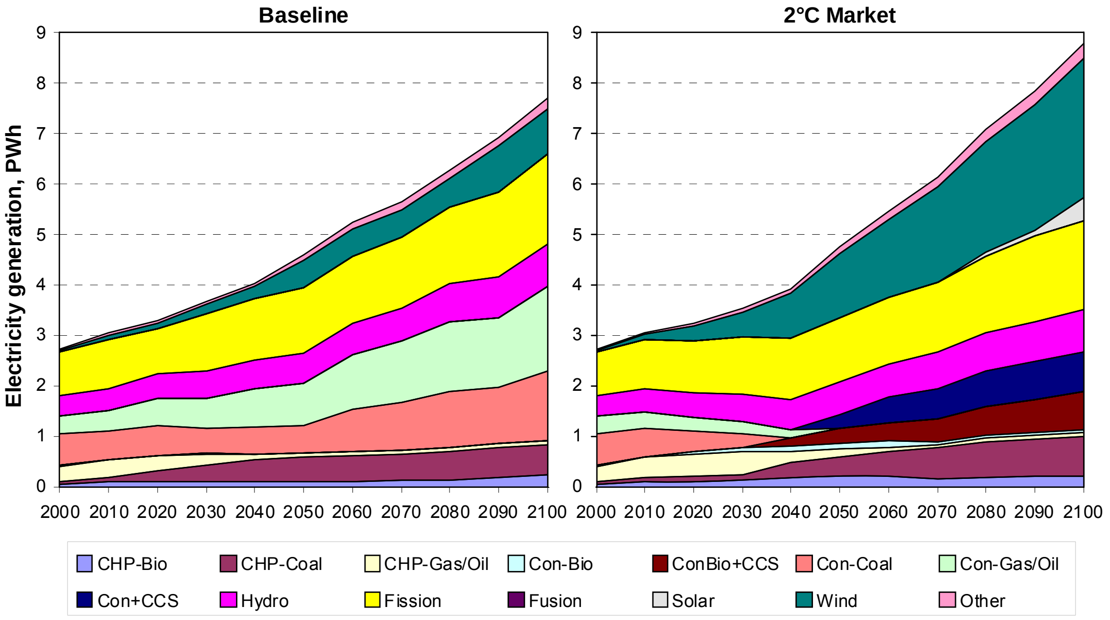

Figure 5. Electricity generation in Western Europe in the Baseline and 2 °C Market scenarios.

3 Studies to increase renewables in stationary energy production in the Nordic countries

3.1 Wind

Denmark has the longest traditions in wind power in the Nordic area. The current installed capacity in Denmark is about 3100 MW and in 2007 about 17% of the total electricity consumption was produced from wind. The planned new capacity by 2012 is 1300 MW[2] of which 400 MW has been planned to be offshore plants (Danish Energy Agency 2008). In the other Nordic countries the shares of wind power production of total consumption are less than one percent, but in Norway and Sweden the investment plans indicate huge increase in wind power production. The national target for wind power investment of Sweden is to increase its wind power production from the current level of 1.2 TWh up to 30 TWh by 2020. The planned investments in Norway would entail about for 20 TWh wind power production. In Finland the new energy and climate strategy targets include 2000 MW increase in wind power by 2020 to fulfill the renewable targets set by the EU. Figure 6 shows the summary of the ongoing investment plans for Nordic countries taken from the country studies. Figure 6 shows the scenarios for wind power investments as reported by the EU Trade Wind project.

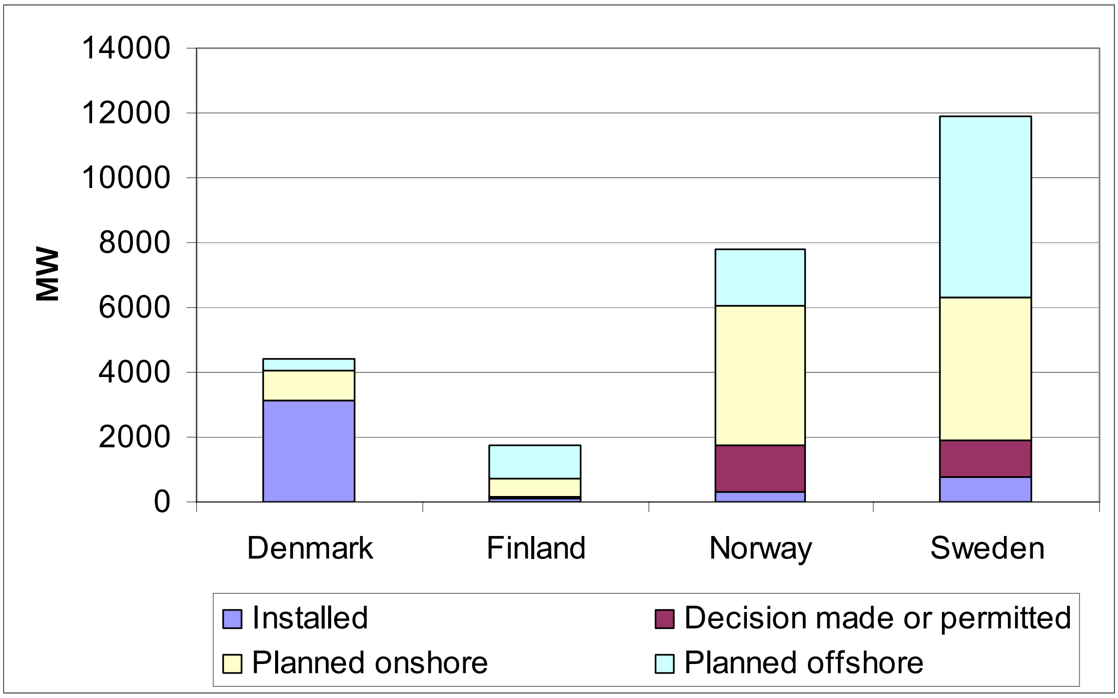

Figure 6. Installed and planned wind power plants in the Nordic countries. Sources: Danish Energy Authority 2008, Energimyndigheten 2008, VTT 2008, NVE 2008.

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[2] Includes Rodsand II (200 MW), Homs Rev II (200 MW), Re-powering (350 MW), onshore plants (75 MW + 75 MW), new offshore plants (400 MW).

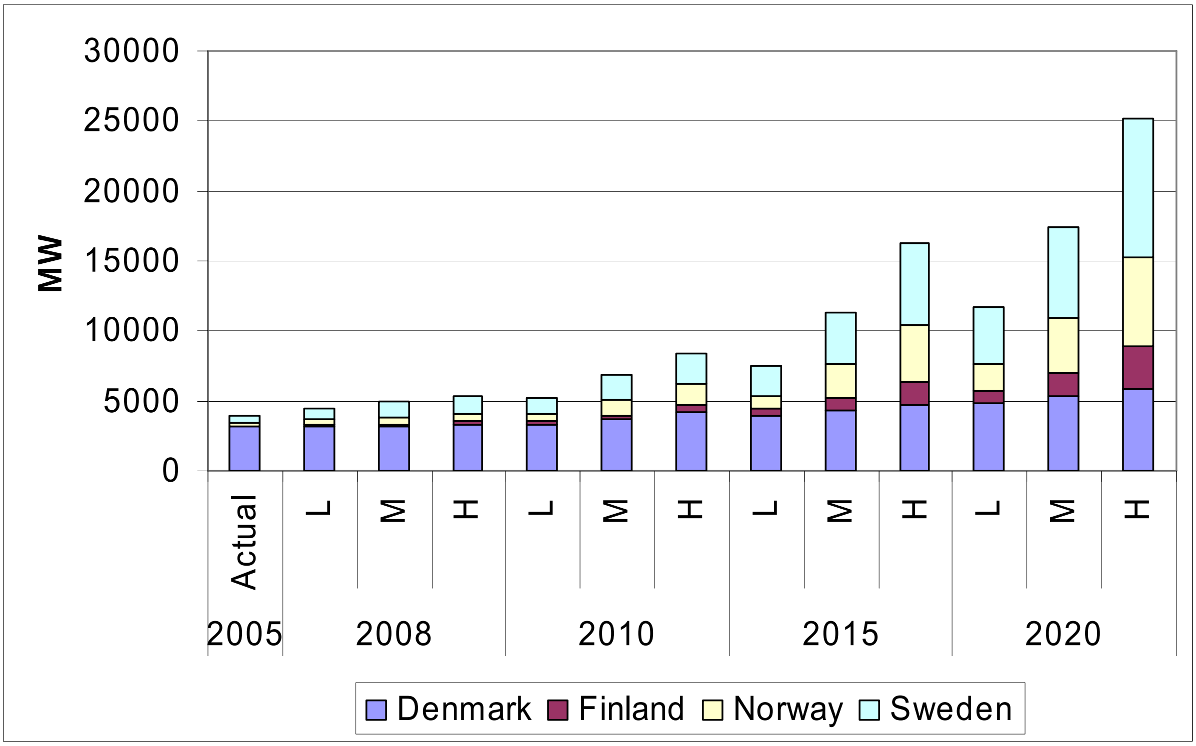


Figure 7. Scenarios for wind power capacities in low (L), medium (M) and high (H) scenarios estimated by the EU Trade wind project (http://www.trade-wind.eu/index.php?id=13).

3.2 Case: Impact of high penetration of wind power on the Nordic energy system

The increasing penetration of wind power in the electricity networks changes the energy balance of the electricity system and the operation of the regulation capacity. Since wind power has very low operation costs, it compensates condensing power and also CHP with higher operating costs. As a result, the average market price of electricity will decrease and also CO_2 emissions of electricity production. On the other hand, the increased share of wind power also increases the need of regulating capacities due to variability and partly unpredictability nature of wind power production. The reduction of CO_2 by investing new wind power is not straight forward due to the impacts of reduced market prices of electricity and its impact on CO_2 emissions at the EU level.

The impacts of increased share of wind power on market price of electricity has been analysed with NEP electricity market models and energy system models and the scenario results are presented in the intermediate NEP report “Reference and policy scenarios”. Below, an additional case study of the impacts of the high share of wind power on Nordic energy systems is shown. The case study is based on the work carried out in IEA Annex on Wind & hydro and PhD study by Juha Kiviluoma from VTT. The simulations have been run with an hourly time-scale energy system market model WILMAR, which includes the Nord Pool area and Germany. The Wilmar model is based on stochastic water value model and time-series for wind are made taking into account the geographical dispersion of large scale wind power.

Table 1 shows the wind power assumptions for different simulation cases. Wind is added as extra production in the systems, i.e. no old capacity is taken away. The fuel prices assumed are: biomass 4.0-4.4 €/GJ, peat 1.5 €/GJ, light fuel oil 7.2 €/GJ, heavy fuel oil 6.2 €/GJ, Coal 2.3 €/GJ, natural gas 6.2 €/GJ and nuclear 0.35 €/GJ.

Figure 8 shows the simulation results for condensing power production for different simulation cases and figure 9 the weekly average electricity production with CHP. According to the simulation results the CO_2 emissions would reduce remarkably in electricity production as the annual operating time of the emission intensive coal and peat condensing power production would be reduced. Table 2 shows the reduction of the operating times of fossil fuel fired electricity production for different cases..

Table 1. Simulation cases with 10%, 20% and 30% penetration of wind power in the Nordic energy system.

Wind capacity (GW)	Base	10%	20%	30%
NO+SE+FI	2,5	17,8	35,7	52,5
Germany	28,6	35,8	35,8	35,8
Genmark	4,1	4,6	4,6	4,6
Wind power (TWh) NO+SE+FI+DK	16	49	87	119

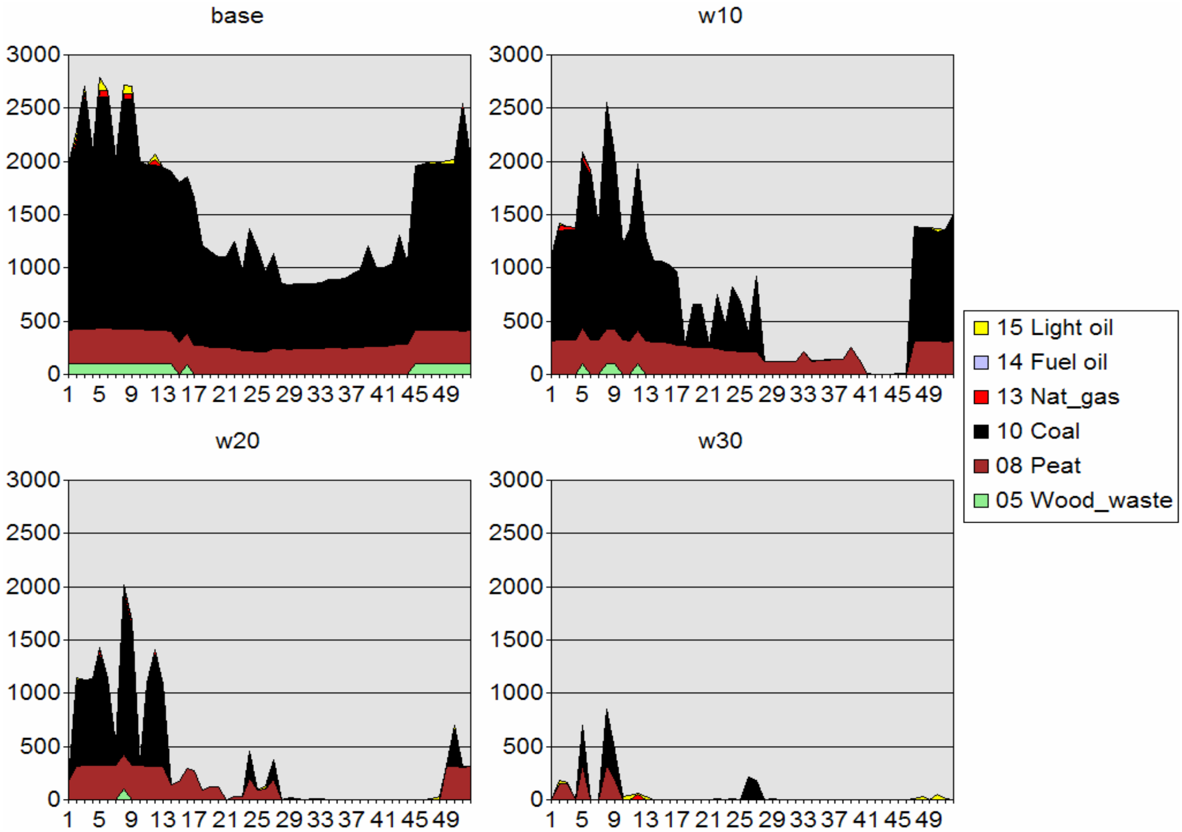


Figure 8. Maximum power form condensing plants with 10%, 20% and 30% penetration of wind power in the Nordic energy system.

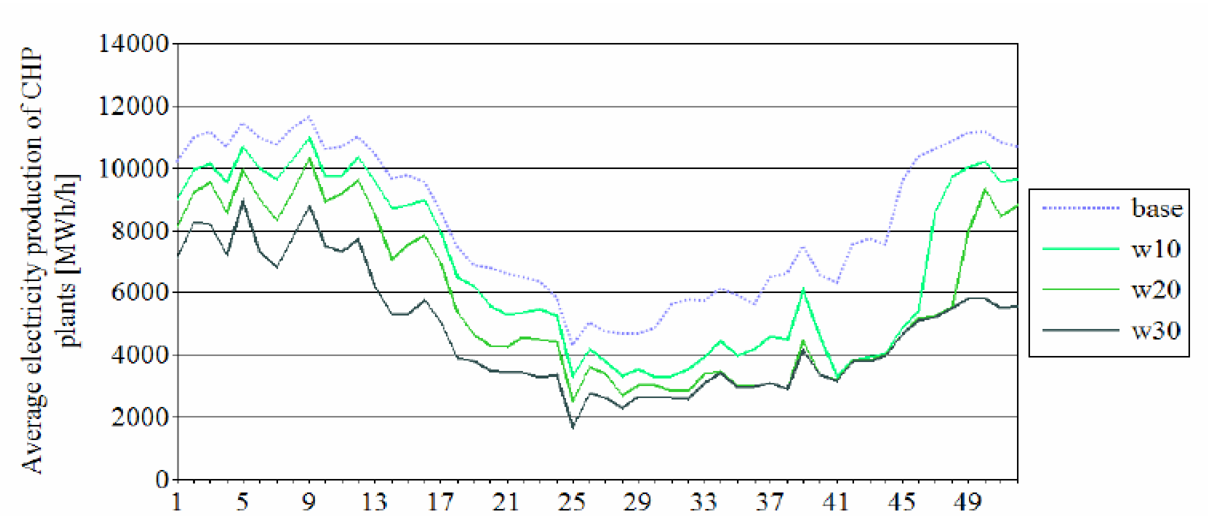


Figure 9. Weekly average electricity production of the Nordic CHP plants with 10%, 20% and 30% penetration of wind power in the Nordic energy system.

Table 2. Calculated changes in fossil fuel fired electricity production with 10%, 20% and 30% penetration of wind power in the Nordic energy system.

	Base h/a	w10 h/a	w20 h/a	w30 h/a
Coal cond.	2705	885	136	3
Peat cond.	7296	5070	2158	79
Coal CHP	4898	3591	2790	2322
Nat. gas. CHP	1497	1285	1063	592
Oil CHP	586	526	469	395

3.3 Biomass

The biomass potentials and biomass markets have been reported in more detail in a intermediate NEP report “Biomass market and potentials” and in this context we present a summary of different scenarios for future biomass potentials to give an overview of the range and the factors influencing the increased use of biomass.

The evaluation of potentials to increase bioenergy production is a challenging task for several reasons:

- The competition for biomass between different end use sectors (industry, energy production, production of transportation fuels)
- Available land area and yield of energy crops (i.e. the competition of arable land area between food production and production of energy crops)
- The future of the forest industry (timber, pulp, paper) in the Nordic countries
- Import and export balance of biomass
- Price levels of fossil fuels and CO_2 allowances, support mechanisms, etc., which influence the willingness to pay for biomass
- Technical limitations such as feasible transportation distances
- In the long term, the impacts of climate change.

Figures 10 and 11 show the bioenergy use and potentials for the EU countries as reported by the EUBIONET II study (Alakangas, 2007).

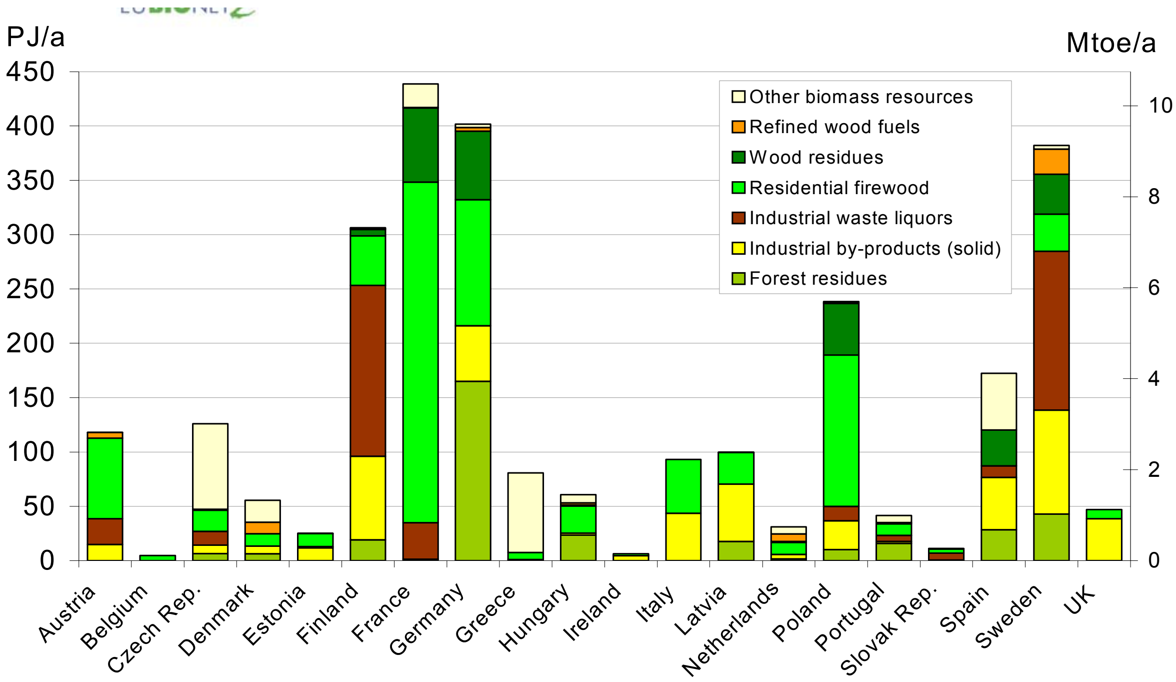


Figure 10. Biomass use in the 20 EU countires in 2004, PJ. Source: EU BIONET II (Alakangas, 2007).

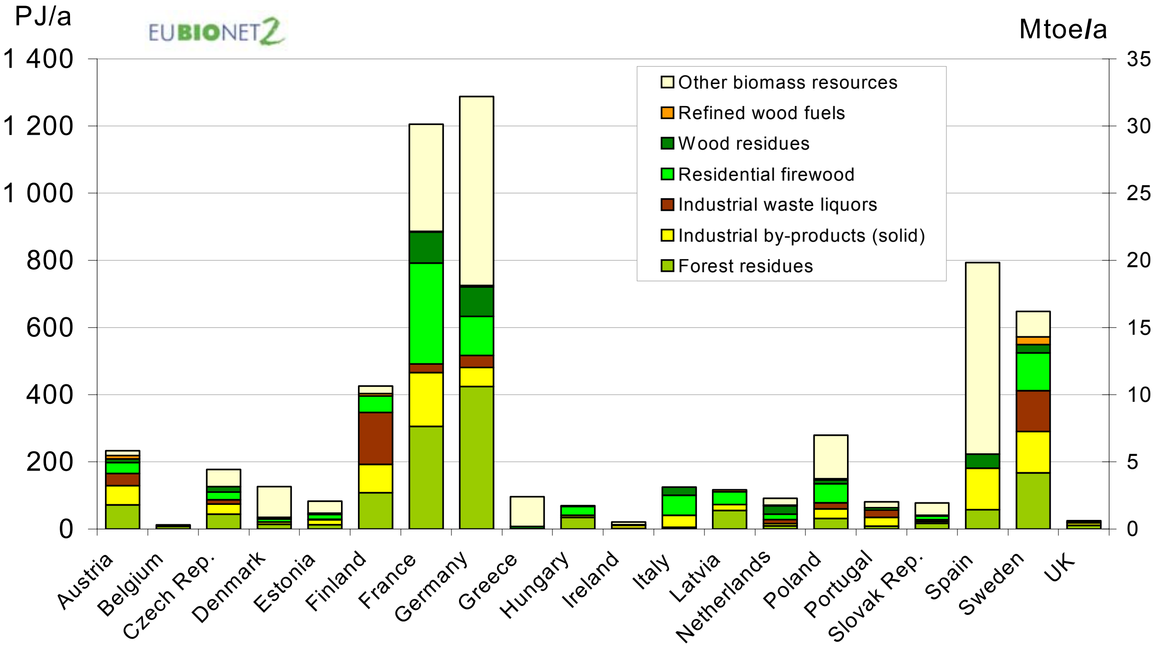


Figure 11. Biomass resources in the 20 EU countires, PJ/a (technoeconomical potential). Source: EU BIONET II (Alakangas 2007).

According to the EUBIONET II results the total potential is approximately 6000 PJ. Much higher potentials have been reported by the European Environmental Agency (from 8000 PJ by 2010 to 10 000 PJ by 2020) and by the Institut für Energie und Umwelt (from 8500 to

10 000 PJ by 2020) (Thrän *et al*. 2006, EEA 2006). According to the EU Commission's Renwables Roadmap for bioenergy (EU 2007), the 20% share of renewables targeted has been estimated to include:

- production of bioelectricity: >1500 PJ biomass (resulting in more than 200 TWh electricity)
- RES-heat: additional 2200 PJ biomass
- biofuels: 2500 PJ biomass needed.

Compared to the present use of biomass for energy (3000 PJ) within EU the RES directive proposal would indicate approximately doubled biomass use. The RES directive proposal also states that only sustainable renewable energy sources would be accounted to the national target. Currently, the sustainability criteria are under development by EU and it is not clear which resources would fulfil these criteria.

It can be seen from the above figures that Finland and Sweden represent top EU countries in bioenergy use and, in addition have large resources compared to many other EU countries. In Denmark and Norway, the current biomass consumption is more modest and so are the potentials. In Finland and Sweden most of the biomass is used by the forest industry. The side products and waste materials are already now largely used in energy production. The side products mainly produced by saw mills, plywood and board industry as well as chemical and mechanical pulp industry include:

- Bark, saw dust, wood chips
- Liquid products (i.e. black liquor) and sewage sludge.

Figure 12 shows an estimate of Swedish bioenergy potentials reported by the Swedish Commission on Oil Independence. Even higher potentials have been reported recently by Svebio (250 TWh by 2020 and 400 TWh by 2050; Svebio, 2008). Norwegian scenarios of the bioenergy potentials are shown in the figure 8 and the estimated increase of bioenergy use in Finland is shown in figure 9. It is evident that each study has different approaches to calculate biomass potentials. The comparison between Nordic countries is therefore extremely difficult without detailed information on assumptions.

In Finland, Norway and Sweden, the largest share of today's biomass use and also the prospected future use is based on wood resources. In Finland, 70% of wood resources for energy production are used in the forest industry. It is therefore evident that in the short term the share of bioenergy is set to decrease if the production of forest industry, especially chemical pulp and saw industries, declines. The situation would be the same if pulp would be imported to the Nordic area as the amount of industrial side products, like bark and black liquor, would be decreased. Figure 9 shows the estimated increase in the use of biomass energy by 2015-2020 in two scenarios for Finland. The figure shows that the use of wood fuels could be considerably increased if the willingness to pay for biomass is increased by accelerated measures or a higher price level of fossil fuels.

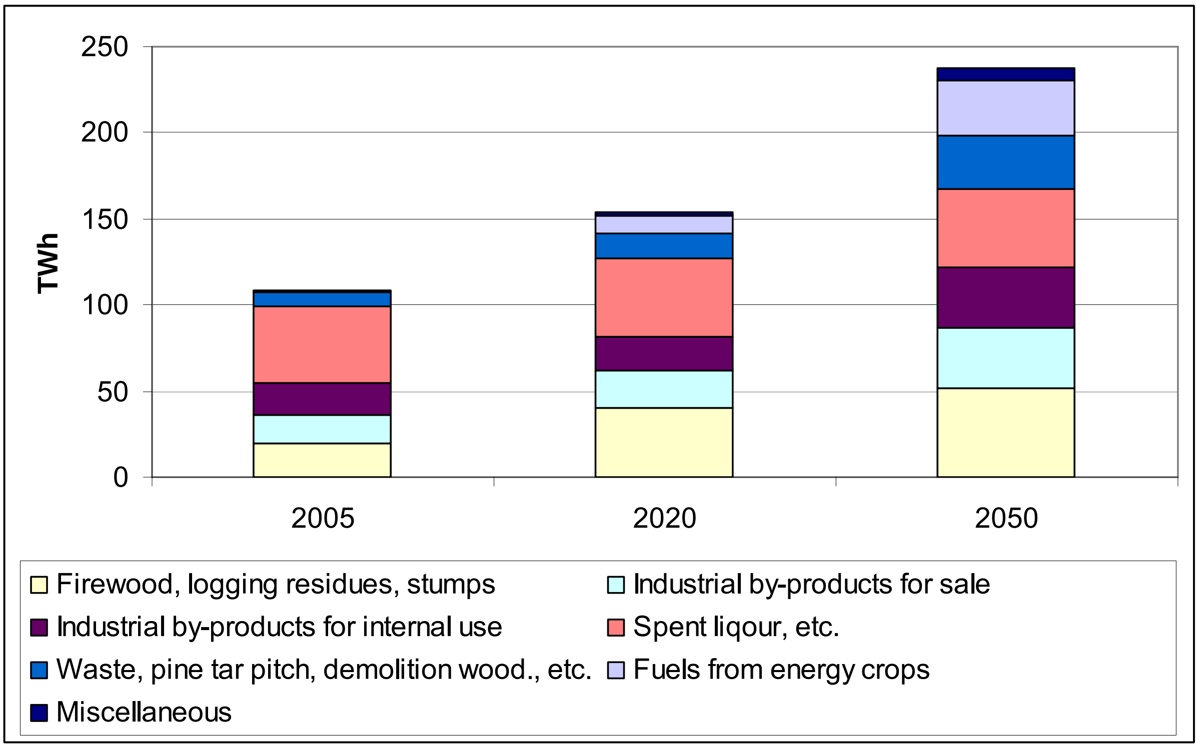


Figure 12. Swedish bioenergy potentials. Source: Commission on Oil Independence, 2006.

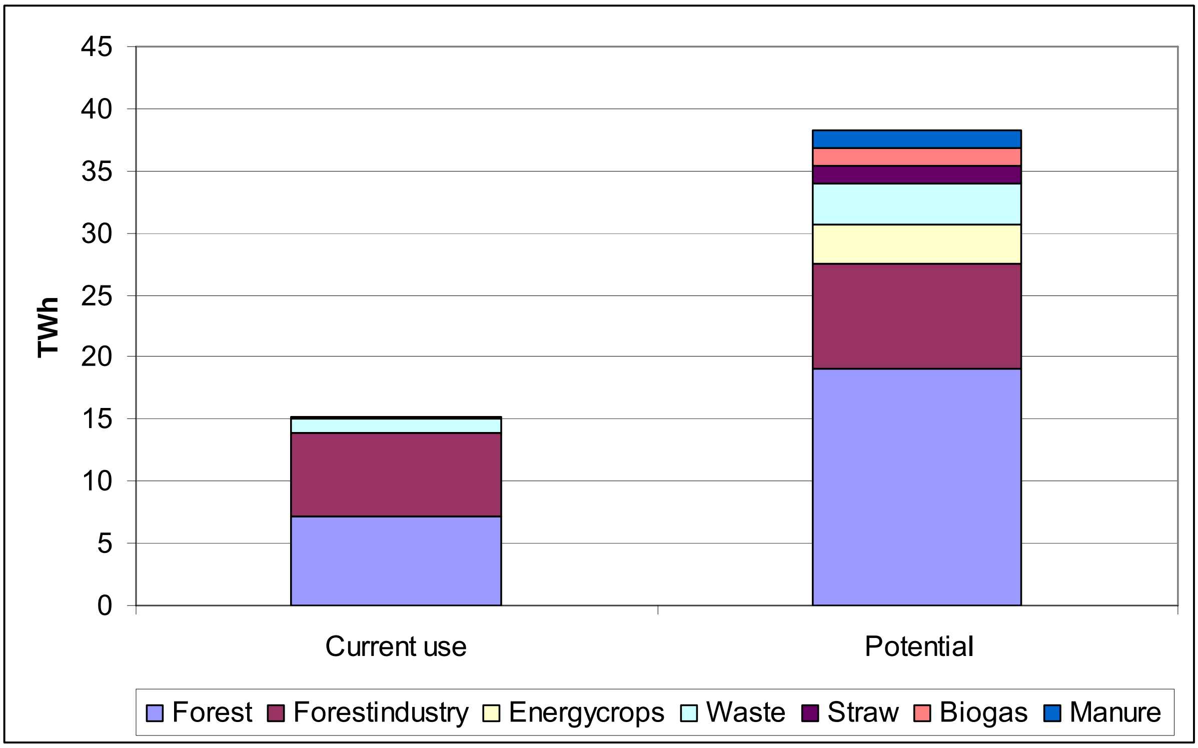


Figure 13. Current use and biomass potentials in Norway. Source: Norwegian Forest and Landscape Institute, 2006.

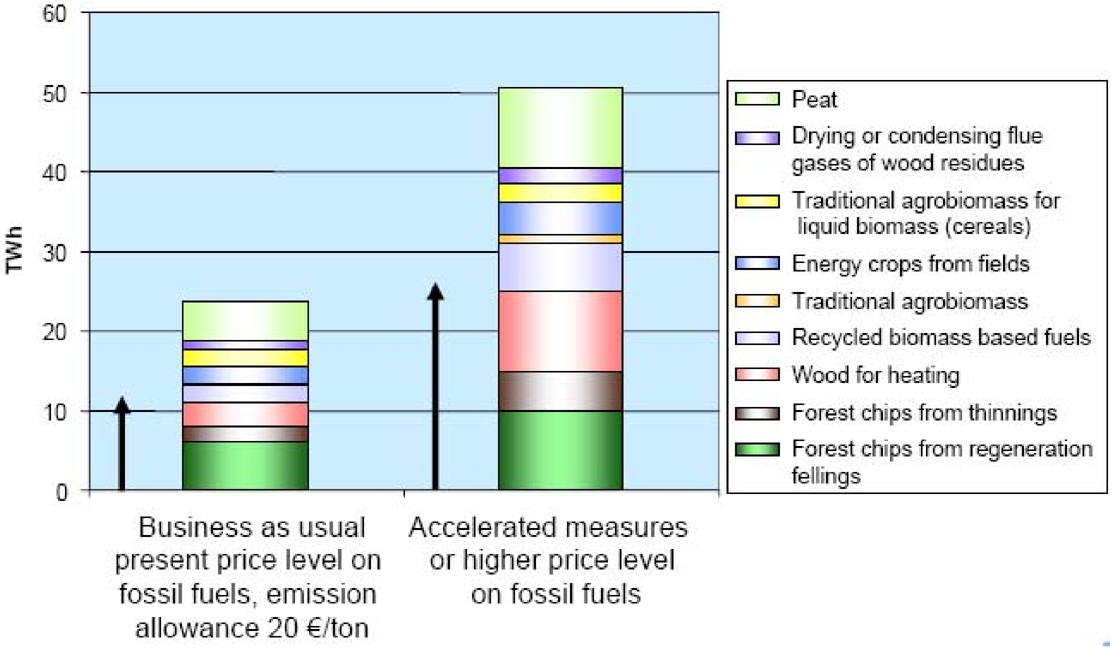


Figure 14. The estimated increase of use of biomass and peat for energy by 2015-2020 in two scenarios in Finland. Source: Rintala biomass working group, 2007.

Biomass products, such as pellets and bio oils, make longer transport distances possible. This means that in the future biomass resources could be better utilised and large amounts of biomass can be exported if the paying ability is higher abroad. Biomass could also be imported, for example from the Scandinavian companies' own pulp mills and plantations in South-America. On the other hand, Finland shares a long border with Russia and good rail transport connections. Traditionally large amounts of wood have been imported to Finland but recently Russia has increased the export taxation of wood which has made the wood import from Russia uneconomical.

Figure 10 shows the estimated increase of biomass use for different sectors by 2015-2020 in two scenarios in Finland. CHP will be the dominant sector in the near future and liquid biofuels have a large market potential. Figure 11 shows the Swedish estimates of the increase of biomass in different sectors.

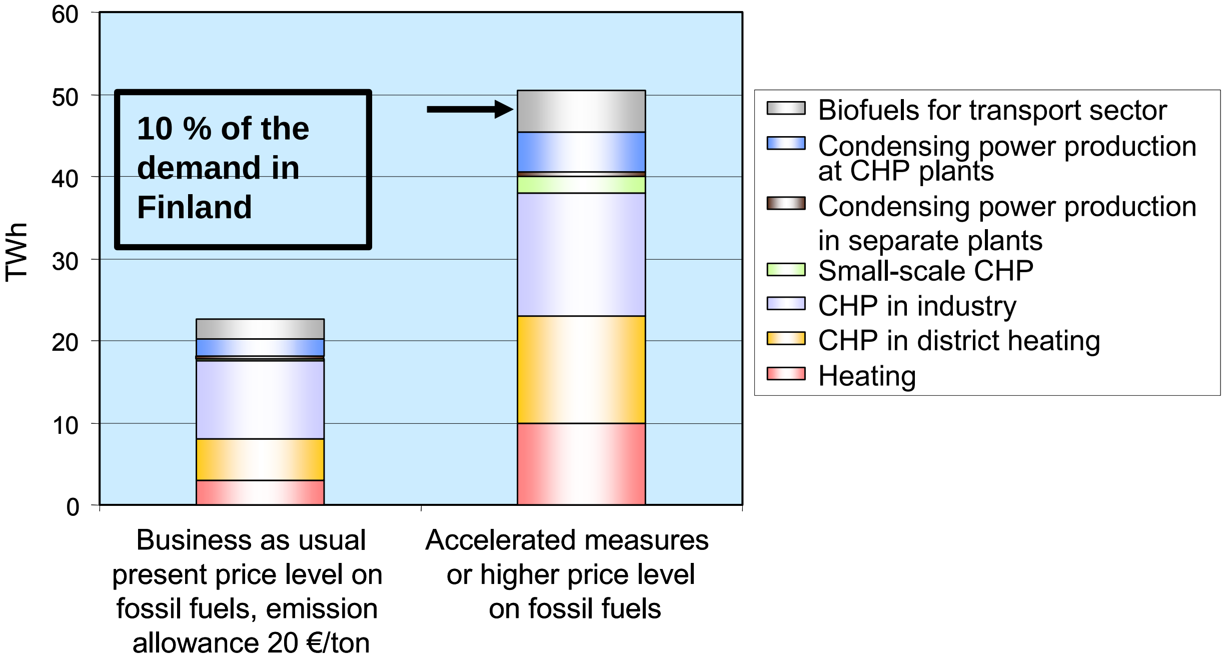


Figure 15. The estimated increase of biomass in different energy sectors by 2015-2020 in two scenarios in Finland. Source: Rintala biomass working group 2007.

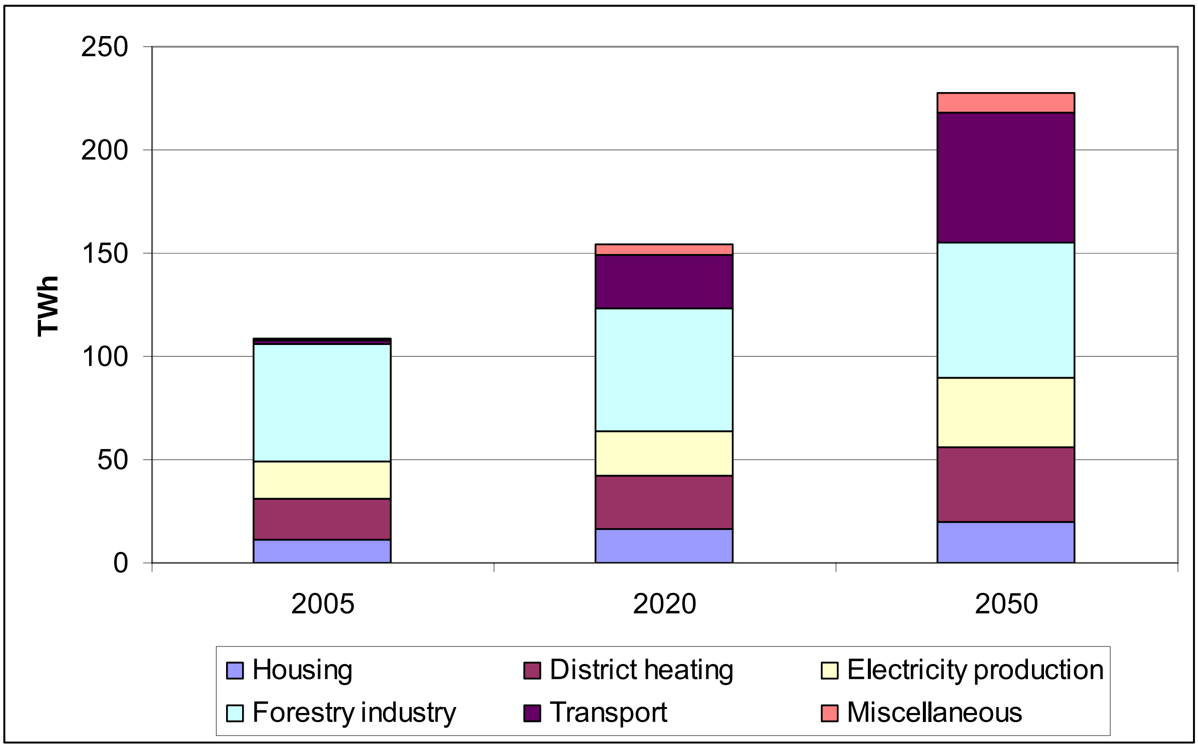


Figure 16. The estimated increase of biomass for different in energy sectors by 2050 in Sweden. Source: Commission on Oil Independence 2006.

3.4 Hydro power

Hydro power potentials are usually well defined but increases in hydro power production are limited due to national environmental protection and legislation. Much of the increase in hydro power production comes from refurbishment and enlarging of existing large scale hydropower plants in Finland, Norway and Sweden. In the longer term climate change could result in increased hydropower production, especially in Norway. For example, the scenarios of the Nordic Grid Master Plan 2008 (Nordel, 2008) assume more than 10 TWh increase in hydro power production in 2025 in Norway in the climate scenario. Approximately 6 TWh of this figure is due to increased precipitation.

Figure 12 shows the hydropower production potential in Norway.

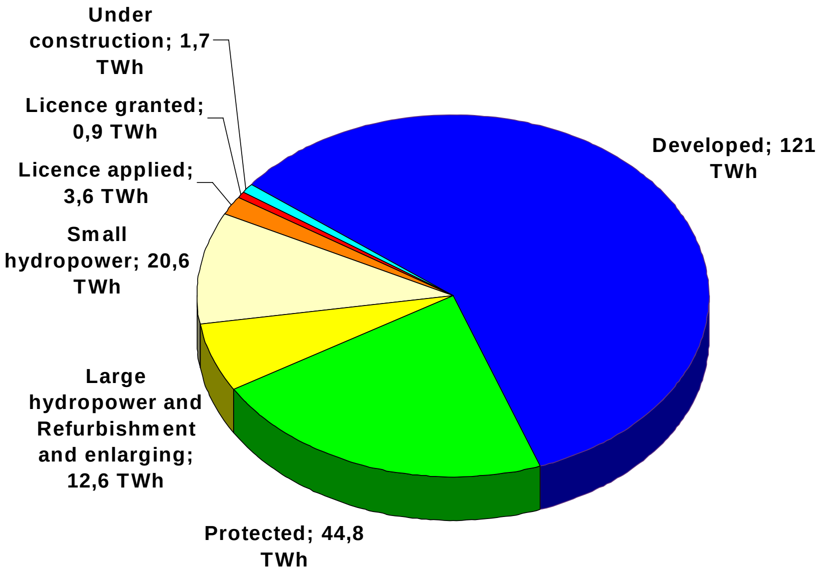


Figure 17 Hydro power in Norway (EBL, 2008).

The most recent Finnish evaluation by the Finnish Energy Industries and Oy Vesirakentaja indicates that an increase of 470 MW (1 330 GWh) would be technically and economically feasible by 2020. Approximately a quarter of this energy (261 MW, 301 GWh/a) will probably be realized by refurbishment of existing large scale hydro power plants. The most important other development projects are located by the Kemijoki, Iijoki and Kymijoki rivers along which over half of Finland’s harnessed hydropower is located. Figure 13 shows the Finnish hydro power potential estimates.

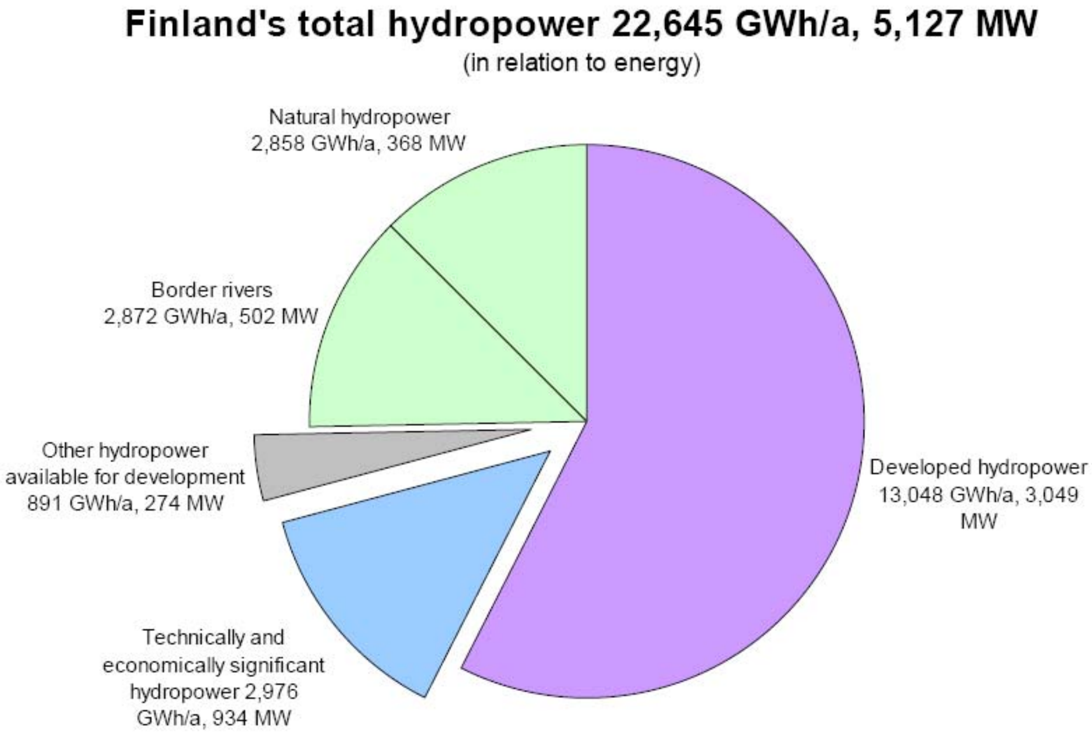


Figure 18. Finland’s total hydropower potential by amount of energy generation. Source: Oy Vesirakentaja 2007.

In Sweden, the Government has drawn up guidelines for the future utilization of rivers for hydropower. These imply that the major part of rivers and individual stretches of rivers, which have not yet been claimed for development, will remain undeveloped. Consequently the four main rivers Vindel, Pite, Kalix, and Tornio-Muonio rivers are excluded for hydro power exploitation. What then remains to be developed include small scale hydro power plants. The unexploited rivers account for about one-third of the hydropower potential that is estimated to be economically feasible, and about half of the technically viable resources.

4 End-user changes affecting CO_2 emissions and the power system

All changes are not only about production or CCS. The end-users can change their behaviour. One of they main topics is energy efficiency, of which there is a separate NEP2 report. Energy efficiency is mostly a question of using better and improved technologies and processes for the same tasks. In the power producing sector it includes among others increasing efficiencies, for example having combined cycle gas turbines instead of just gas turbines or CHP production instead of condensing power plants. In this chapter we take a look at the other side, the demand. There are important demand side measurements, which will lower CO_2 emissions and improve energy efficiency, but will also increase the demand for electricity. We have chosen to here look at electric vehicles (EVs) and heat pumps (HP) and their effect on the power system. One of the main aspects of new loads is their impact on peak load, which will be studied in more detail.

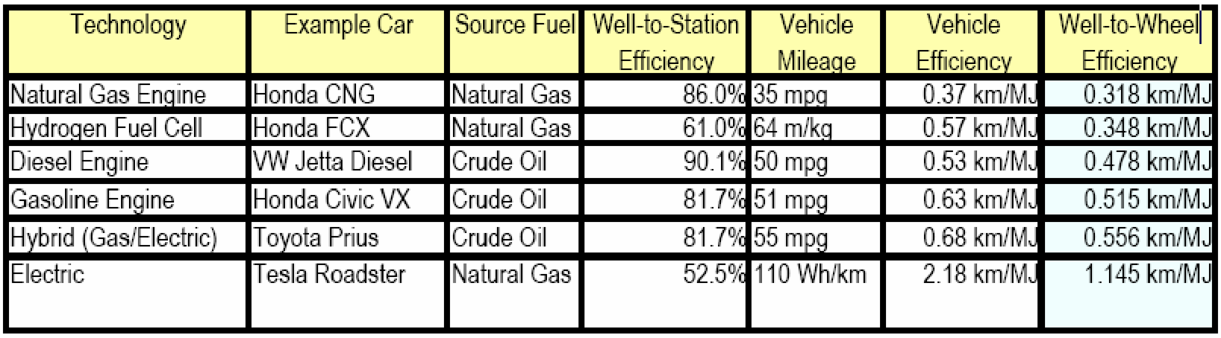
4.1 *Electric vehicles*

4.1.1 Transforming the transport sector

Transportation based on oil faces two major challenges: oil supply has difficulties to keep up with the demand (IEA 2008) and transportation fuel use is a large source of greenhouse gas emissions. In the year 2000 direct emissions from the fuel use were 14.0 % of annual greenhouse gas emissions (GHG) globally. Road transport accounted for 75 % of the transport sector direct emissions in 2000.

Transforming road transport to rely on electric vehicles (EVs) gives a possibility to deal with both of these challenges. Electricity can be converted from several different energy sources and with EVs it would be easy to release road transport from the grip of oil.

Table 3. Comparison of the well-to-wheel efficiency of different cars according to Tesla Motors Inc. The vehicle mileage for Honda Civic VX is (51 miles per gallon, mpg=4.6 l/100 km) is quite low, achievable at highway driving. Newer models of Honda Civic use (Honda 2008) a lot more gasoline, for example 25 mpg = 9.4 l/100 km for city driving. (Source: Tesla Motors 2008)



Technology	Example Car	Source Fuel	Well-to-Station Efficiency	Vehicle Mileage	Vehicle Efficiency	Well-to-Wheel Efficiency
Natural Gas Engine	Honda CNG	Natural Gas	86.0%	35 mpg	0.37 km/MJ	0.318 km/MJ
Hydrogen Fuel Cell	Honda FCX	Natural Gas	61.0%	64 m/kg	0.57 km/MJ	0.348 km/MJ
Diesel Engine	VW Jetta Diesel	Crude Oil	90.1%	50 mpg	0.53 km/MJ	0.478 km/MJ
Gasoline Engine	Honda Civic VX	Crude Oil	81.7%	51 mpg	0.63 km/MJ	0.515 km/MJ
Hybrid (Gas/Electric)	Toyota Prius	Crude Oil	81.7%	55 mpg	0.68 km/MJ	0.556 km/MJ
Electric	Tesla Roadster	Natural Gas	52.5%	110 Wh/km	2.18 km/MJ	1.145 km/MJ

4.1.2 Technology of electric vehicles

Electric vehicles have several sub-categories. Hybrid electric vehicles like Toyota Prius without a possibility to charge the batteries are not usually considered to be electric vehicles although their drive train is partially electrified. If the hybrid vehicle can be charged with an external electricity source, then the vehicle is called plug-in hybrid electric vehicle (PHEV). The battery pack is larger than what would be required in a plain hybrid. Since the vehicle still has an engine and a fuel tank, all-electric range does not need to be large. Even with relatively small ranges the fuel savings are significant especially if there are opportunities to charge the batteries elsewhere in addition to home. An all-electric range of 32 km can result in over 70% savings in fuel consumption. (Thornton 2008).

The progress of automotive batteries will affect the relative merits of different electric vehicle types. As batteries get cheaper, longer all-electric range in PHEVs and full electric vehicles (FEVs) become more viable. Other battery characteristics like energy density, ratio between power and energy, capability for fast-charging, and cycle life are going to have an influence as well.

4.1.3 Charging infrastructure

There are two limits to electric vehicle charging. The first is set by the battery properties, i.e. how much charging power it can withstand without detrimental effects. The second is due to the charging infrastructure. Fast charging a vehicle would require around 100 kW and this is not feasible in residential buildings. Dedicated charging stations would be required and they would need to tap into high or medium voltage transmission grid. Ten thousand outlets in the Nordic countries would increase the power production capacity demand with at most a thousand megawatts, if they are all assumed to be active at the same time.

Most household wirings have rather limited amperage as already noted and this will limit the charging power even if the batteries could withstand larger currents. In the Nordic countries many parking spaces have electric outlets for the cars to enable pre-warming of the engine before use. These could be used also for charging of electric vehicles, as well as charging opportunities at workplaces. Power outlets in these locations could be useful to people living in apartment houses without a household charging possibility. Obviously billing would become an issue. Monetary value of the required annual electricity would not be large, but still large enough to be meaningful. At an estimated average of 2 €/100 km the annual costs would rise to 400 €. It will be necessary to commonly be able to identify the car or the user and measure the charge. The developments in automatic meter reading (AMR) and two-way communications will no doubt lead to the introduction of workable solutions for this.

4.1.4 Driving patterns

Vehicle owners will have different driving patterns. Some people will only rarely drive long distances whereas others will do it frequently. Another aspect in the driving patterns is the timing of the driving and more importantly that of the charge opportunities. Most vehicles are parked for a very large fraction (~ 95 %) of the time. However, charging opportunity is not always present. An estimate for the share of vehicles plugged-in at any given time has been made at VTT and used for these calculations. We assume that there are two possible places where the vehicles might be plugged-in: at work and at home. Most people would be plugging in only at home; some would do it at both locations and only a few at work. The data used for estimating the leaving and arriving of vehicles was derived from the National Travel Survey conducted during 2004-2005 in Finland (WSP LT Consultants Ltd 2006). It gave information on the purpose, timing, and distance of personal travel. The information was processed to give estimates of when cars might arrive at work and at home, and what kind of distances they had travelled before that. Charging concentrates to afternoons and evenings when people arrive from work, shopping and leisure. This is due to the assumption that most people will charge only at home.

Selections made for modelling the charging of EVs in the VTT model were:

- 20% can charge at work
- 2% never charge at home
- Average daily distance driven per vehicle: 52 km
- Average no of trips per day: 3.0
- Average distance driven before plugged in: 39 km

4.1.5 Rate of adoption for EV's

Plug-in hybrid cars are not yet commercially available. Full electric vehicle models are already available, but not for the mass market. Electric vehicles with short range and low top speeds can be bought mostly from small manufacturers. Several large automobile manufacturers have in 2008 announced market introductions of their PHEVs and FEVs to happen in 2-3 years.

Electricity consumption due to electric vehicles will naturally depend on the rate of adoption of different EVs. This is extremely difficult to predict currently, as it is not known whether electric vehicles will truly penetrate the vehicle market. Assuming continuing restrictions on oil supply, pressure to reduce GHG and air pollution emissions from the transport sector, and progress in the battery technology EVs would seem to have a good chance to become a dominant player in the vehicle markets. How fast this could happen will depend on the cost competitiveness of the cars, the performance of the batteries, and even on lithium mining. If the introductory models of the larger manufacturers turn out to be successful, then electric vehicles have taken a big step towards becoming mainstream technology.

4.1.6 Influence of EVs on the electricity consumption

How EVs influence the power system is best described using cases. We study two cases:

1. 5 million EVs in the Nordic countries (excluding Iceland)
2. 5 million EVs with smart charging in the Nordic countries.

5 million EVs sounds very high, but to evaluate the impacts on electricity consumption, enough high nuber was selected. For peak load comparison we use year 2006 Nordel simultaneous peak load week, 16.-22.1.2006 (Nordel 2006). The peak load of 67 800 MW took place at 20th January, between 8:00 and 9:00 o'clock Scandinavian time.

Slow charging, max 12A @ 220V, is assumed for all EVs and all cases. EVs are assumed to be without heating or air-conditioning. Heating and/or air-conditioning would use approximately an extra 10% according to preliminary calculations. The share of different EVs is assumed to be as shown in Table 4.

Table 4. Estimation of electric vehicles' specific electricity consumption, average annual mileage and annual electricity consumption. In addition, a very raw estimate on the share of different types of EVs to be found on the roads in 15-25 years. .

	Electricity consumption kWh/km	Trip km/a on electricity	Annual consumption MWh/a	Share of electric vehicles
Full electric vehicles				
• FEV 0,25	0,25	17 400	4,34	5 %
• FEV 0,17	0,17	17 500	2,97	15 %
Plug-in hybrid vehicles				
• PHEV 0,25	0,25	14 100	3,53	20 %
• PHEV 0,17	0,17	14 000	2,38	60 %

A sedan-sized electric vehicle with reasonable aerodynamics is likely to achieve an average consumption of 0.15-0.25 kWh/km of grid electricity. Tesla Roadster for example has an announced consumption of 0.11 kWh/km.

4.1.7 Case 1: 5 million EVs in the Nordic countries (excluding Iceland)

If half of all personal vehicles in Finland, Sweden, Norway and Denmark were EVs, the annual electricity consumption would rise by 14 TWh, or 15 TWh if the increase in the transmission network losses is also added. For example, it is in comparison just a bit more than the expected annual production, 13 TWh, of the fifth Finnish nuclear reactor.

The effect on the peak load in the Nordic area of 5 million EVs is notable. The peak load moves from Friday morning to Thursday evening (17:00-18:00), as shown in figure 19. The peak load of the system increases with 3 800 MW. The Thursday evening load would have been 4 500 MW lower hadn't it been for the charging of EVs.

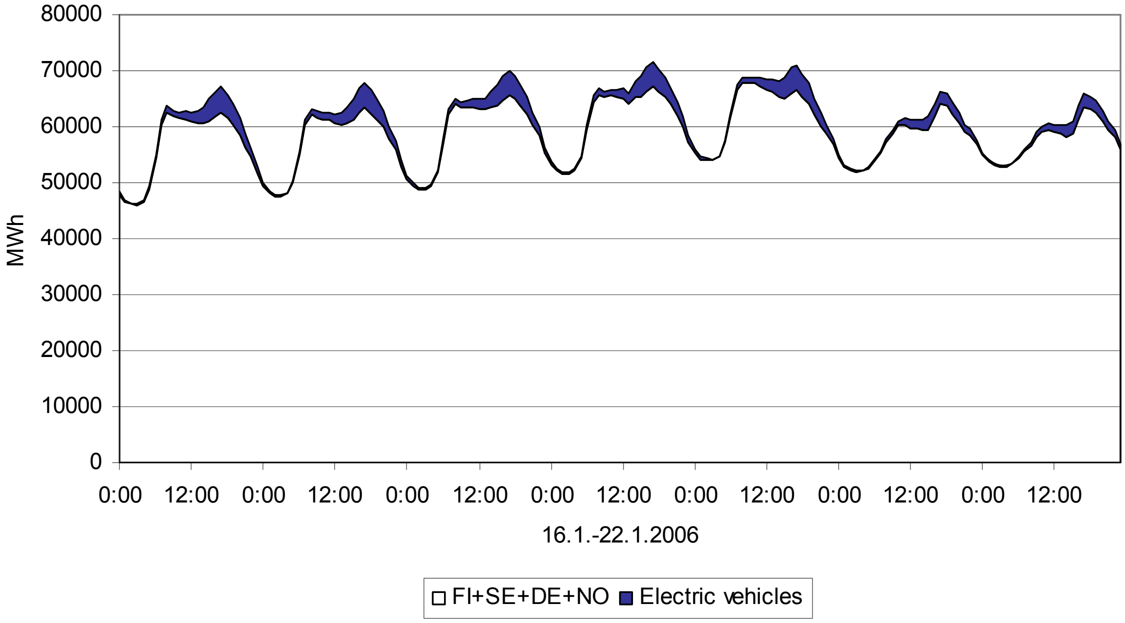


Figure 19. The effect of 5 million electric vehicles on the electricity consumption in the Nordel system. Charging is assumed to happen as soon as vehicles plug-in.

4.1.8 Case 2: 5 million EVs with smart charging in the Nordic countries

The cumulative charging profile would be very different if smart charging takes place and vehicles are charged during hours of cheapest electricity and/or lowest demand. This would be beneficial for the power system as power plants would operate more efficiently. The financial gains of smart charging are quite small for an individual car owner, some tens of euros per year. The price difference between day and night electricity is not that big in the Nordic market. However, a new large peak in electricity consumption is not a small matter for the power system operation. An easy way to avoid this could be to have smart charging as a default option in EVs.

In this case smart charging is simulated with a simple algorithm. EVs are set to postpone evening charging between 16:00 and 23:00 to the consumption void in the middle of the night, 0:00-7:00. Smart charging should be arranged to cause as little discomfort to the user as possible. Therefore the user is assumed to be able to override the postponement, so that as a result only 90% of the evening hour loads are moved to later. To ensure that the smart loads are no worse for the system, the night time loads are restricted to a maximum defined by the previous day’s max dumb load. There are no rules between 7:00 and 16:00. Rules in Finland follow Finnish time and in Scandinavia Scandinavian time.

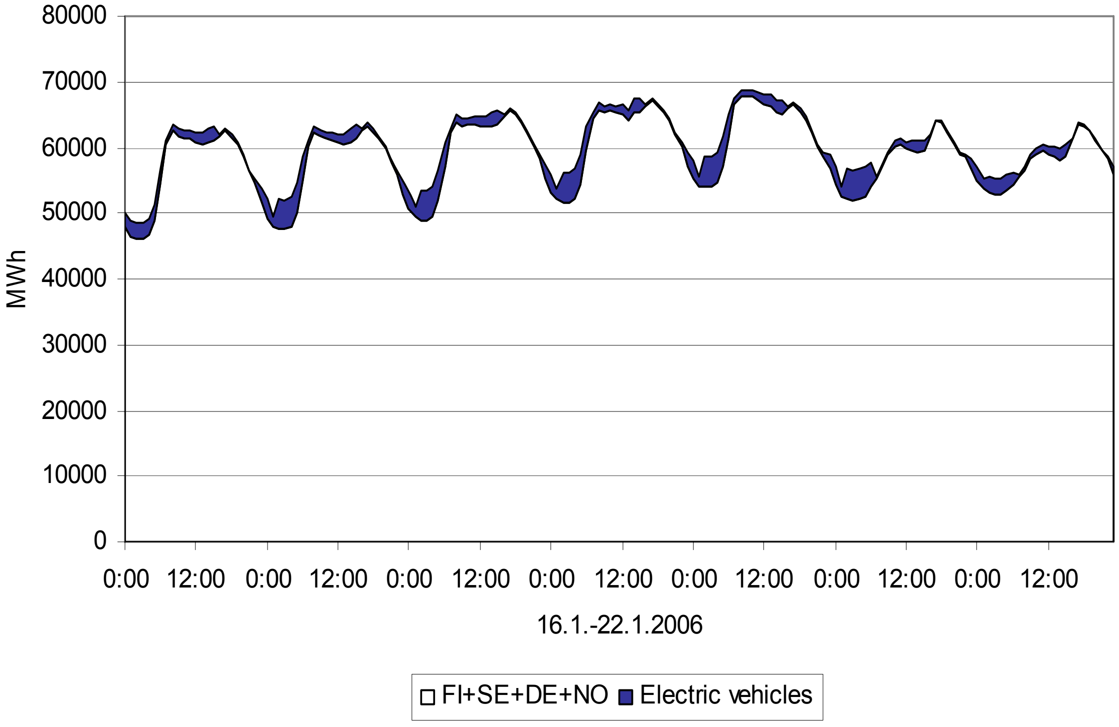


Figure 20. 5 million EVs with smart charging in the Nordic countries (excluding Iceland).The system peak load increases with a measly 1 000 MW to 68 800 MW. The increase is less than 2 %, although half of all personal vehicles are EVs.

EVs impact on the power system peak load can be seen in figure 20. It is very tolerable, considering that smart charging favors both base load power plants as well as variable power production, as explained below.

4.1.9 Effect of 5 million EVs on CO_2 emissions

It is difficult to estimate the changes in CO_2 emissions. If we assume gasoline driven cars to emit 170 g_{CO2}/km, and marginal electricity to be produced with coal condensing power at 900 kg/MWh, we end up with equal emissions. If marginal electricity would be produced with new CCGT having emissions of 376 kg/MWh, the cut in CO_2 emissions would be 7.2 Mt_{CO2} for 5 million electric cars. With an average Nordic electricity production having emissions as low as 670 kg/MWh, the savings would be 3.2 Mt_{CO2}.

4.1.10 Other effects on the power system

Charging behaviour could very well be set to depend on the spot price or some other price indicator. Receiving fresh price signals is no problem with two-way communication expected to be inherent in EVs with smart charging capabilities. If the power system has large amounts of variable production like wind power, then the hours with lowest prices are not necessarily during the night and charging would adjust accordingly within the limits of plug-in periods and user preferences.

EVs could even help to balance the power system. There has to be a balance between production and consumption in the system at all times. If a power plant or a transmission line suddenly trips, or expected production is less than expected, reserve production is needed. EVs offer an alternative. At times when up-regulation is needed they could slow down or stop charging. Full benefits are achieved if the vehicles are also capable of discharging, either during disruptions or when power prices are very high. EVs could even provide support for a local or residential micro grid in blackout or in high peak load situations.

4.2 Heat pumps

Heat pumps are here scrutinised more closely and especially their effect on the power system. To get a more realistic estimate of different heat pump load curves, hourly load profiles were calculated using a sophisticated household heating flow model (VTT House Model) and a realistic temperature time series. The estimated changes in hourly system load due to households converting to heat pumps are studied using year 2006 realised system peak loads as basis.

4.2.1 Heat pump types

There are several types of heat pumps, both depending on from where they pump heat and where they deliver it. Some combinations are expensive investments, as ground source heat pumps, some less expensive, as air-air heat pumps. The lower the distribution temperature of a heating system, the greater is its efficiency. For example, low-temperature floor heating has a significantly higher efficiency than a conventional radiator heating system.

Compressors and pumps in the system consume electricity. The ratio of produced heat to consumed electricity is described by the Coefficient of Performance (COP) of the heat pump. The momentary COP for a specific heat pump varies second by second, but in the statistic sense COP must be understood as the yearly average. The yearly average COP is often referred to as the Seasonal Performance Factor (SPF) just to indicate that it has been integrated over a year. Although COP can be quite high under ideal conditions, the annual average is more moderate due to less than ideal conditions as well as the use of auxiliary electric heating element. Heat pumps are usually equipped with an extra electrical heating element, which can supply heat for peak load especially during the coldest winter days.

Ground source heat pump

Ground source heat pump systems are becoming more and more competitive, and increases in electricity and oil prices will definitely improve their position. Moreover, as the global market for heat pumps has not yet matured and the technologies are still evolving, the investment cost per heat output can be expected to fall.

There are several ways to install heat collectors, as shown in Figure 21. One way is to bury collector pipes at the depth of 0.7-1.2 m, and 1.5 m apart. As the heat demands extensive piping, it is suitable only if the plot is large enough and the ground appropriate. Another solution is to bore 100-200 m deep holes, and a third to put pipes in lakes. Lakes should be deep enough not to freeze to the bottom in the winter. (SULPU 2008)

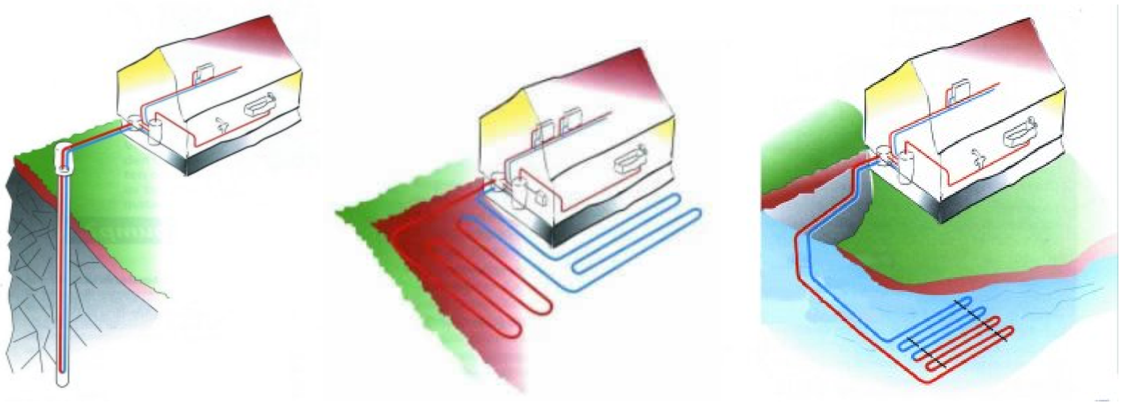


Figure 21. Different types of ground source heat pump installations: bore hole, in the ground, in the lake. (Source: SULPU 2008)

COP is currently in the range 2.6-3.6 in the Nordic climate. Calculated from statistics at Finnish Heat Pump Association SULPU, the average Finnish COP of all installed ground source heat pumps is 2.9. (SULPU 2008, Heljo 2008a)

Air heat pumps

Air heat pumps, using ambient air as heat source, represent an alternative option for reducing external energy consumption in buildings, but they typically represent supplementary heat sources only. Both investment and assembly costs of an air heat pump are, under present market conditions, substantially lower than that of a ground heat pump. The more so for an air-air heat pump than for an air-water heat pump that delivers its heat to a water-based heating system including or excluding domestic hot water (DHW). COP of air heat pumps varies strongly in relation to outdoor temperature. When the outdoor temperature falls down to below -20…-25°C, modern air heat pumps have only a small advantage.

Based on statistics from (SULPU 2008), the Finnish COP -average of installed air heat pumps is 1.9. The air heat pump technology has made great progress in recent years and new air heat pumps have decidedly better COP than older ones.

Exhaust air heat pumps

Exhaust air heat pumps are integrated into the exhaust air side of the ventilation system, and the heat recovered can be used for water-based heating and for domestic hot water.

Based on statistics from (SULPU 2008), the Finnish COP -average of installed air heat pumps is 1.8.

4.2.2 Heat pumps in the Nordic countries

Sweden is the European leader in heat pumps with total of 700 000 installations in 2007. Using 7.5 TWh of final energy in the form of electricity a total of 22.5 TWh useful heating energy is made available. A sizeable share is though produced in the district heating sector.

Exhaust air/heat recovery heat pumps hold a strong position in new construction of single family houses. Their market share in this segment is exceeding 90%. Recent developments for air-water heat pumps have resulted in a number of new highly efficient models, which have led to an increased interest for this type of heat pump. Due to technology improvements of air heat pumps, air-air heat pumps have become the most obvious choice to improve energy efficiency in the large share of electric heated houses in Sweden. (EHPA 2008)

Finland is quite successful in implementing heat pumps on a European level. The amount of heat pumps in Finland is approximately 150 000, whereof 100 000 are air-source heat pumps and 40 000 ground source heat pumps. Ground source heat pumps are nevertheless clearly more influential if we look at the produced heat. The amount of heat pumps increased in Finland with 40 % in 2007. Yearly annual sales are approaching (and will in 2008 surpass) 50 000 heat pumps. Heat pumps gathered 2.8 TWh of “free” heat in 2007 (see Figure 22).

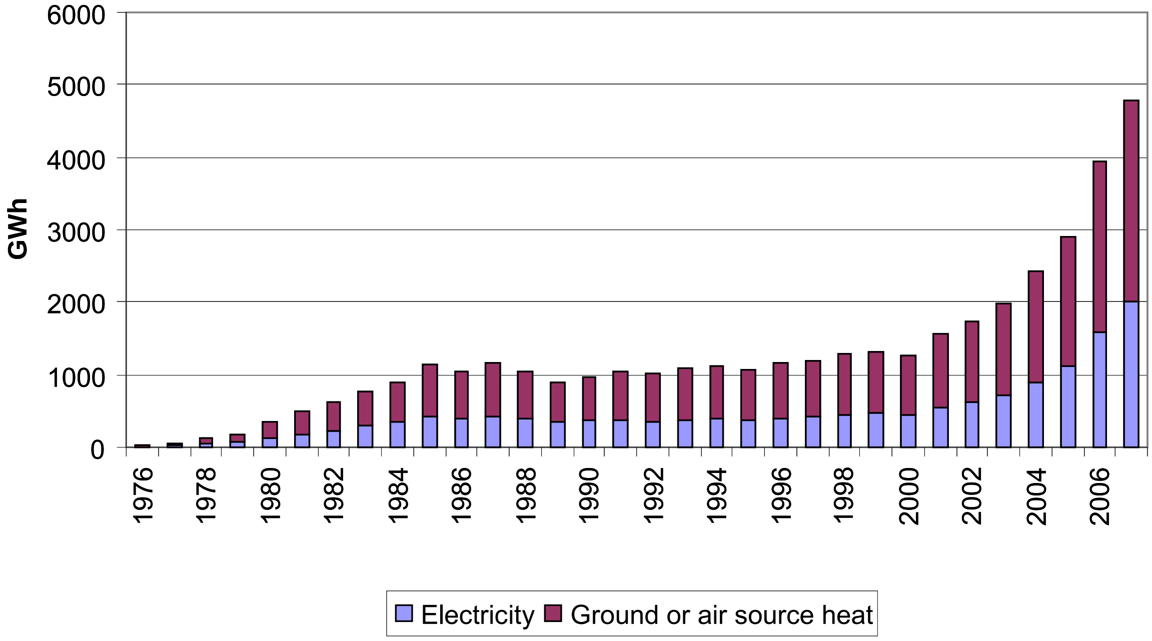


Figure 22. Heating produced by heat pumps in Finland 1976-2007. The useful energy (heating) from heat pumps is more than double the electricity used as input. Most energy production is from ground source heat pumps, although air heat pumps are more numerous. (Data from SULPU 2008)

There are 40 000 heat pumps in Denmark, whereof 5 000 are ground source heat pumps. Heat pumps in Denmark suffered from a bad reputation after the initial introduction in the early 1970'ies, which thanks to quality assurance programs in the 1980's has been slowly overturned. (EHPA 2008)

Norway had 55 000 new heat pump installations in 2006 and 70 000 in 2007, over 90 % of which was air-air heat pumps. The rate of installations is a bit higher in Norway than in Finland. On the other hand, the installed stock of ground source heat pumps amounts to just 16 500, only one-third of that of Finland. (EHPA 2008)

4.2.3 Method for load profile of heat pumps

The hourly heating demand, including domestic hot water (DHW), of a selected single family house was generated using dynamic simulation program VTT House. VTT House Model is a dynamic simulation tool for building simulations. The House Model combines air infiltration and ventilation, as well as heat and moisture transfer processes. The detailed description of the program is in (Tuomaala 2002).

The modelled building is a ridge roofed single-family house with a gross area of 163 m^2 and its insulation is typical of a 1970's house. The building is located so that its living room is facing to the north and the kitchen to the south. The house is inhabited by a four-person family, 2 adults and 2 children. The indoor climate of the simulated single family house was assumed to be good, which equals minimum air change rate 0.5 1/h and an indoor temperature of 21 °C during the heating season. The space heating energy demand of the house is 29 MWh/a. The domestic hot water demand with 4-person family is 3.6 MWh/a. The oil consumption of an oil heated house is correspondently approximately 3 800 litres oil/year.

The hourly heat demand profile was applied against various heat pump cases. The heat pump performances were modelled according to outside temperature. The calculated cases were as followed:

- **Case 1a**. oil heated house will be changed to a ground source heat pump house
- **Case 1b**. oil heated house will install the air-to-air heat pump as an auxiliary heating system parallel to the oil heating system
- **Case 1c**. oil heated house will be changed to a air-to-water heat pump house, the backup heating is direct electricity
- **Case 2a**. direct electric heated house will install the air-to-air heat pump as an auxiliary heating system parallel to the direct electric heating system
- **Case 2b**. direct electric heated house will be changed to a ground source heat pump house
- As a reference for cases 2a and 2b, the consumption of a direct electric heated house without heat pumps was also calculated. The direct electrical heating system had a hot water storage for a domestic hot water with 3 kW heating resistor. The hot water heating was set on every day at 22:00. The daytime backup usage was not assumed.

The analysis of the heat pump systems combined with the heating systems of the house did not contain any other auxiliary heating systems (for example fire places) that are typically used in single family houses and can shave the peak demand in extreme weather conditions. The study was assumed to be a worst case analysis from the electricity peak-demand point of view. Weather data from 1979 from the city of Jyväskylä in Mid-Finland was selected to be the representative average weather.

4.2.4 Description of heat pump systems used

The properties of the ground source heat pump system

The ground source heat pump was located in the technical room. The heating energy delivery system was radiator heating. The ground source heat pump served both space heating and domestic hot water heating.

The model of the ground source heat pump was linear proportional to the outside temperature (Figure 23).

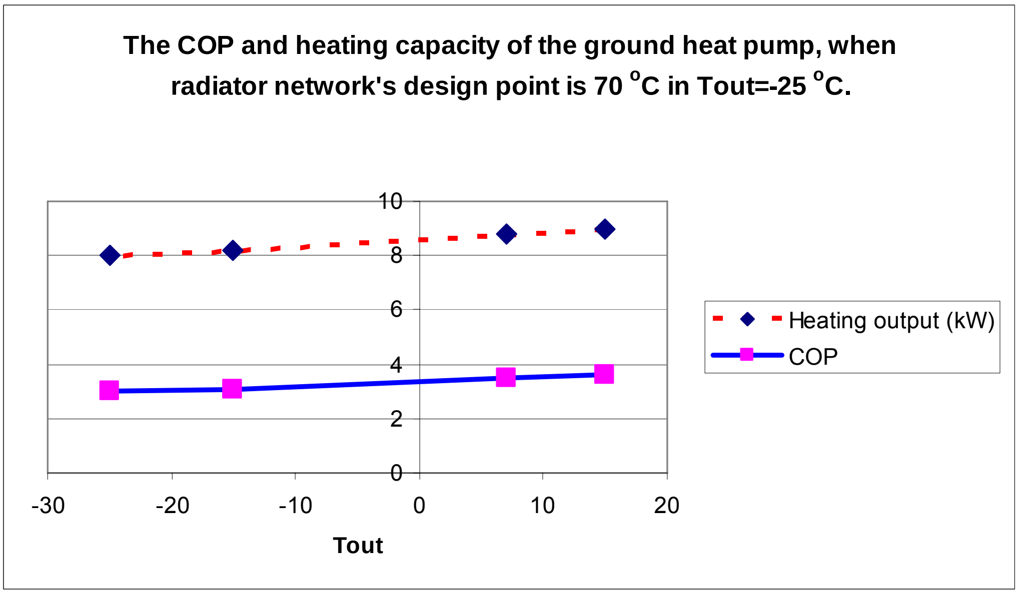


Figure 23. The linear model of the ground source water heat pump system.

The properties of the air-to-air heat pump system

The air-to-air heat pump was located in the living room, from which its heat was delivered to other spaces of the house by natural buoyancy forces through the open doors. The air-to-air heat pump was not capable to produce the DHW.

The capacity model of the air-to-air heat pump was proportional to the outside temperature (Figure 24).

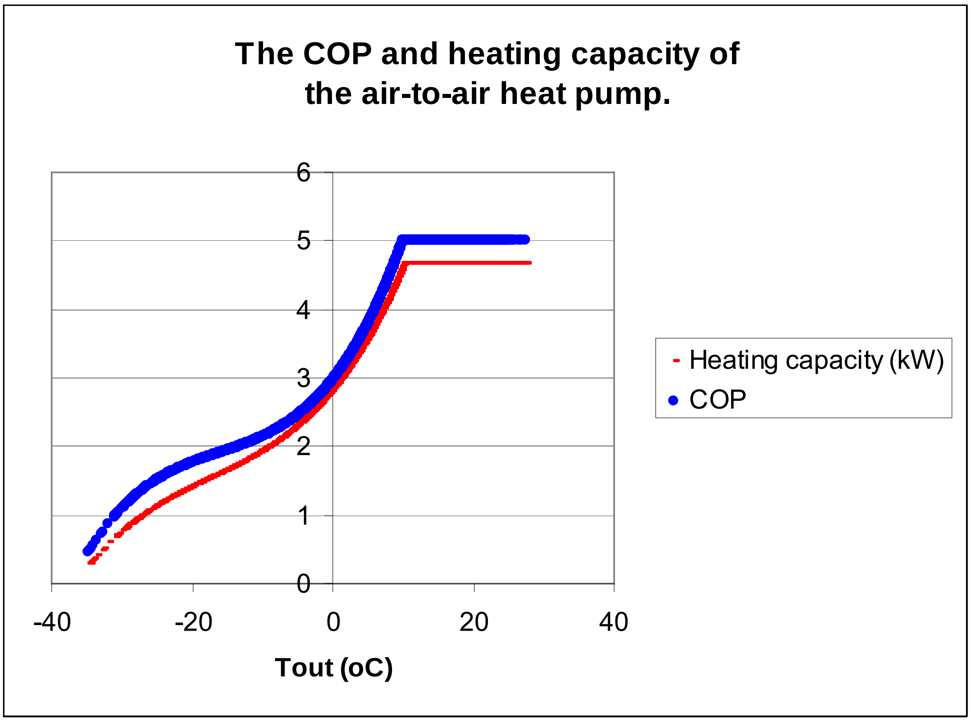


Figure 24. The model of the air-to-air heat pump system.

The properties of the air-to-water heat pump system

The air-to-water heat pump was located in the technical room. The heating energy delivery system was radiators. The heat pump can serve both space heating and domestic hot water heating. Direct electric heating was assumed when COP was less than 1.1 during extreme weather conditions in winter.

The model of the air-to-water heat pump was linear according to the outside temperature (Figure 25).

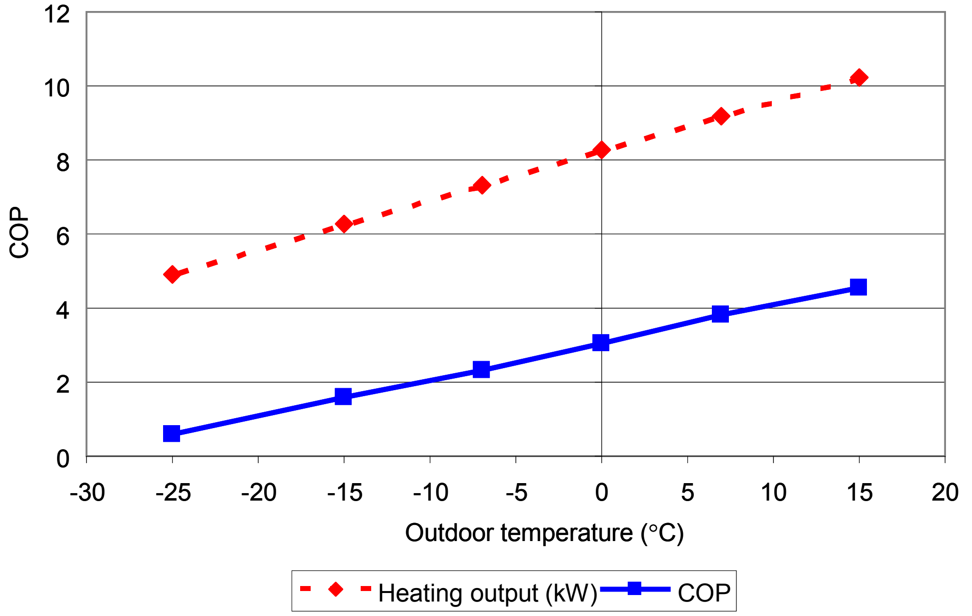


Figure 25. The COP and heating capacity of the air-to-water heat pump, when radiator network's design point is 80 °C.

4.2.5 Results for converting to heat pumps

The results of converting different oil or electric heated houses to wholly or partly heat pump heated houses are summarized in Table 5.

Table 5. Converting old oil heated (Base case 1) or direct electric heated (Base case 2) houses to different types of heat pump houses. GSHP=Ground source heat pump, AAHP= Air-to-air heat pump, AWHP= Air-to-water heat pump.

Case	Base case 1	Base case 2	Case 1a	Case 1b	Case 1c	Case 2a	Case 2b
Heating type	Oil	Dir. electr.	Oil			Dir. electr.	
Heat pump	-	-	GSHP	AAHP	AWHP	AAHP	GSHP
Electricity (MWh/a)	0,0	33,2	10,7	5,9	16,9	25,4	10,7
Peak (kW)	0,0	14,2	7,3	1,9	12,3	15,1	7,3
Peak hours (h/a)	-	2346	1455	3030	1368	1682	1455

4.3 Heat pump impacts on system load in Finland

4.3.1 What-if analyses A

There are 260 000 oil heated houses in Finland at the moment. If we assume that 200 000 oil heated houses were changed, whereof

- 100 000 to ground source heat pumps,
- 50 000 to have air-air heat pumps as supplement, and
- 50 000 to air-water heat pumps,

the electricity consumption would increase by 2.2 TWh.

The effect of the 200 000 new heat pumps on the Finnish system peak load week is simulated in . The Finnish peak load week from 2006 is used as basis. A quite cold week is selected from the VTT House Model results to represent the additional heat pump loads, as system peak load and cold weather go hand in hand. The simulation shows that the power system peak increases with 1100 MW due to the new heat pumps.

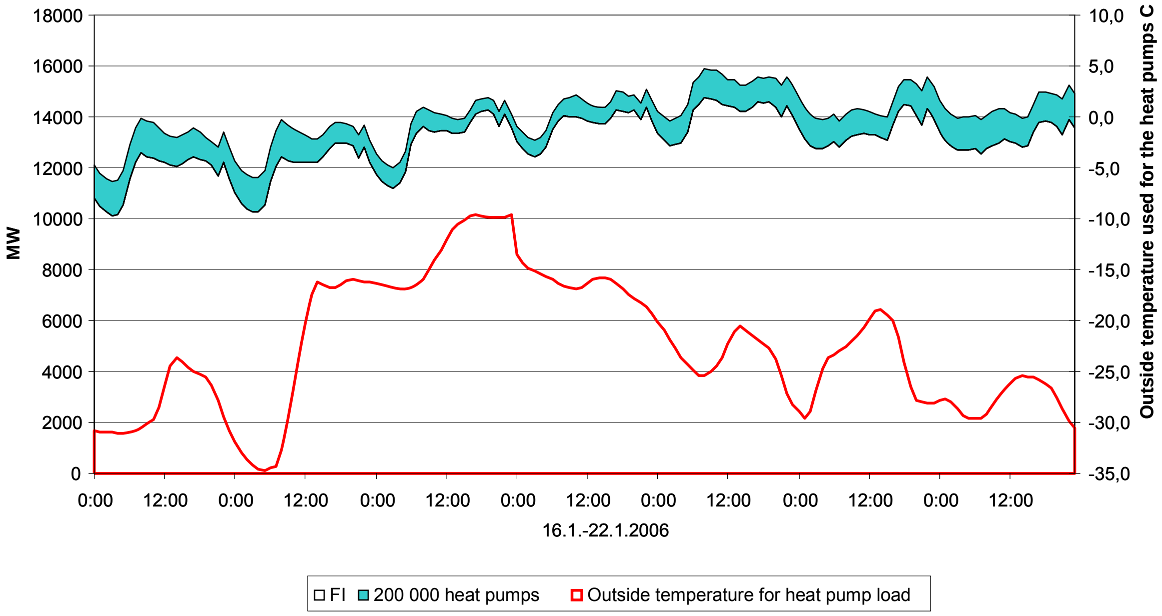


Figure 26. If 200 000 oil heated houses in Finland are changed to heat pumps, it will have an increasing effect, even as high as 1100 MW, on the system peak load.

4.3.2 What-if analyses B

We assume that the majority of air heat pumps installed in Finland are in detached electric heated houses, although detached houses with other fuels, semi-detached houses and service sector buildings have their share of air heat pumps. There are nevertheless a lot of direct electric heated houses in Finland, so only a minority can be already equipped with air heat pumps. Therefore it is only fair to have a case studying new heat pumps in 200 000 direct electric heated houses, whereof

- 50 000 would be changed to ground source heat pumps and
- 150 000 would get air-air-heat pumps as supplement.

This case in turn would bring electricity savings of 2.3 TWh. Combining case 1 and case 2 results in a net increase of 0.1 TWh.

The effect that 200 000 new heat pumps in direct electric heating houses have on the Finnish system peak load week is simulated in Figure 27. Again, the Finnish peak load week from 2006 is used as basis, and the same methodology is used for heat pump loads as in case 1. The result: the peak decreases with 400 MW thanks to new heat pumps in direct electric heated houses. But, combining case 1 and 2 still leaves a net increase of 700 MW for the system peak load.

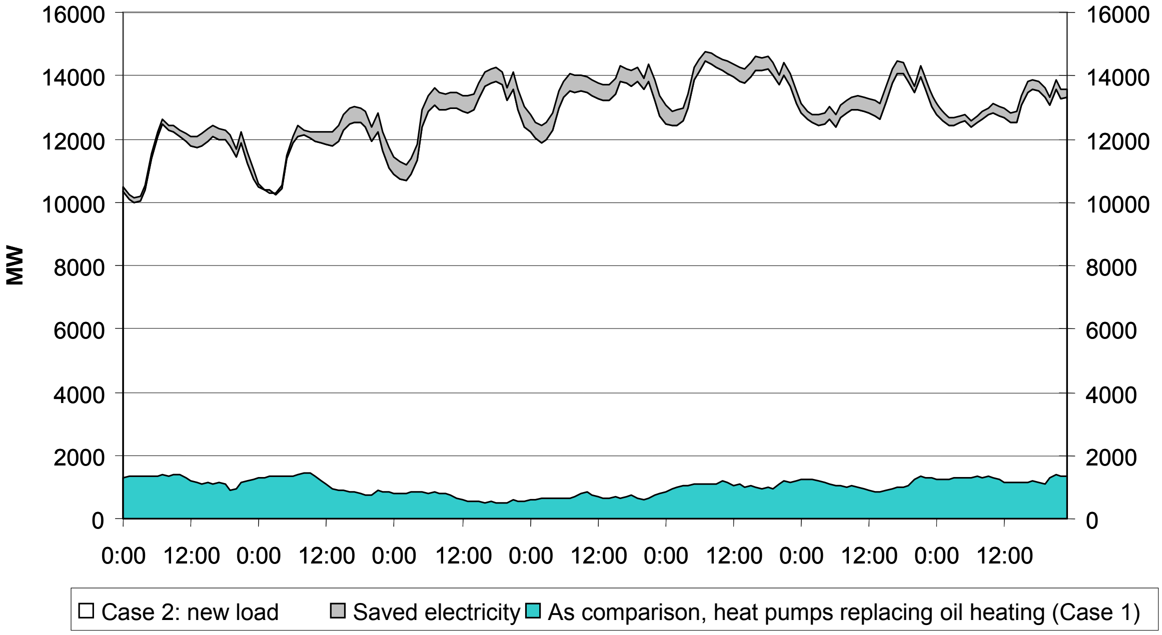


Figure 27. If 200 000 direct electric heated houses in Finland get heat pumps as supplements or as new heating systems, it will decrease the system peak load with 400 MW.

4.4 Nordic aggregate load case studies

Here we compare on a Nordic level the loads of EVs and heat pumps to the total Nordic loads in 2030. The hourly total Nordic load in 2030 is estimated using load index series for different end user types. The index series are originally made for end-users on the distribution network level in Finland. Their use has been successfully calibrated for the country specific load of Finland, Norway, Sweden and Denmark for the year 2006 (calibration year).

Each country’s load curve for year 2030 is modelled using index series for different end-users in combination with estimated annual energies of same. The effects of EVs and heat pumps are studied in two different cases, aggregate case A and aggregate case B.

Aggregate case A: Nordic electric load in 2030 with
- 5 million electric vehicles and
- 400 000 heat pumps to compensate other fuels, mainly oil heating (200 000 new ground-source heat pumps, 100 000 new air-source heat pumps and 100 000 new air-water heat pumps)

Aggregate case B: Nordic electric load in 2030 with:
- 5 million electric vehicles,
- all the heat pumps from aggregate case A and
- additionally 600 000 heat pumps to compensate direct and storing electric heating (450 000 air-source heat pumps and 150 000 ground-source heat pumps).

Case A can be seen as a worst case scenario with regard to load impact and case B as a more realistic alternative. In case A, heat pumps compensate other fuels, mainly oil heating (half of them for Finnish oil heaters, half for Sweden and Norway). Case B includes those heat pumps which are in case A, but also additional heat pumps that are installed in houses with electric heating. In both cases electric vehicles are smart-charged.

A summary of the cases is given in Table 6.

Table 6. Summary of the case studies.

	Estimated energy (TWh)	**Estimated change in peak load* (MW) in -10 °C**	**Estimated change in peak load* (MW) in -25 °C**
Aggregate scenario for 2020	435,3		
Aggregate scenario for 2030	453,8		
Case A:			
5 million electric vehicles	14,0	970	970
Case A heat pumps total	4,4	1 200	3 300
- 200 000 ground-source heat pumps	2,2		
- 100 000 air-source heat pumps	0,6		
- 100 000 air-water heat pumps	1,6		
Case 1 total for 2030	**472,2**	**2 170**	**4 270**
Case B:			
5 million electric vehicles	14,0	970	970
Case A heat pumps total	4,4	1 200	3 300
Case B heat pumps total	-6,9	-1 300	-990
- 150 000 ground-source heat pumps	-3,3		
- 450 000 air-source heat pumps	-3,6		
Case 2 total for 2030	**465,3**	**870**	**3 280**

*peak load at simultaneous system peak load third Wednesday of January 8:00-9:00

The impact of cases A and B on the load of the 3rd week in January are simulated in Figures 28-31. However, it is to be noted that only the heat pumps are temperature dependent, as the base load is simulated without temperature dependency.

The impacts are simulated using different outdoor temperatures, −10° C and −25° C for the heat pump load curves. Both cases show substantial peak load increases at −25° C, whereas peak load increase is quite small for case B at −10° C. A simultaneous cold spell simultaneously in the Nordic countries is in our opinion better described by −10° C than by −25° C. The Nordic countries form a widespread geographical area. It is unlikely that the whole area faces extremely low temperatures at the same time. So all in all, heat pumps and EVs will not have a very big adverse effect on the peak load.

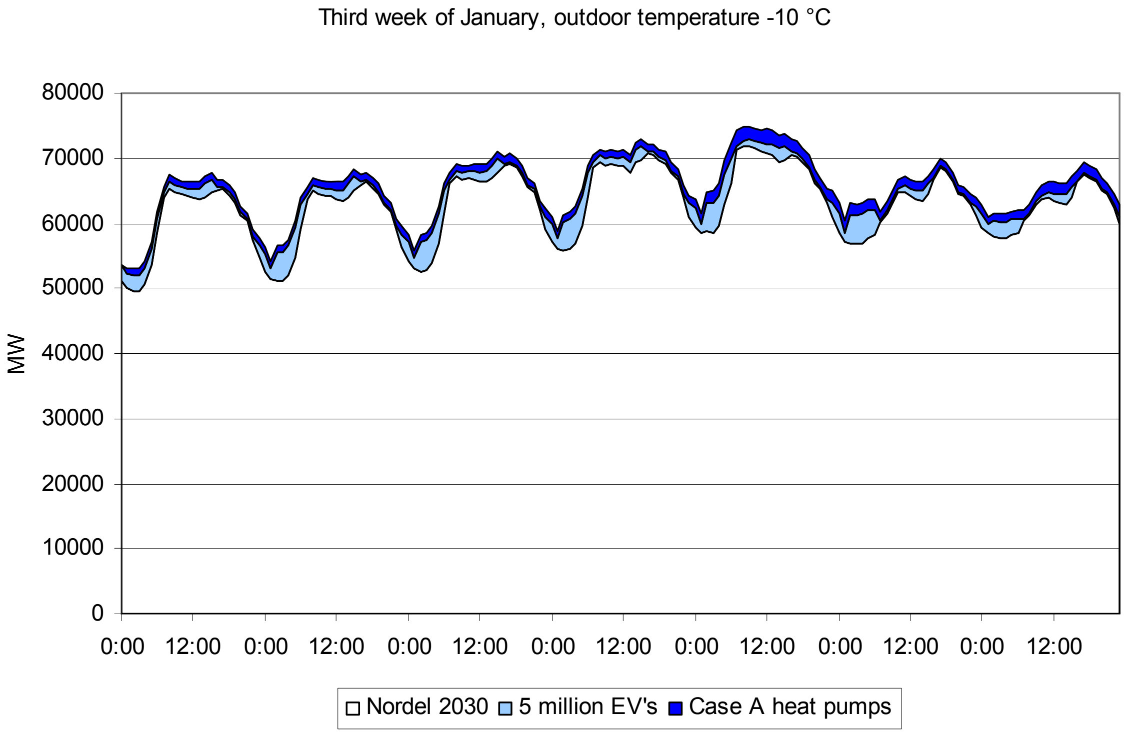


Figure 28. Case A, outdoor temperature -10 ° C.

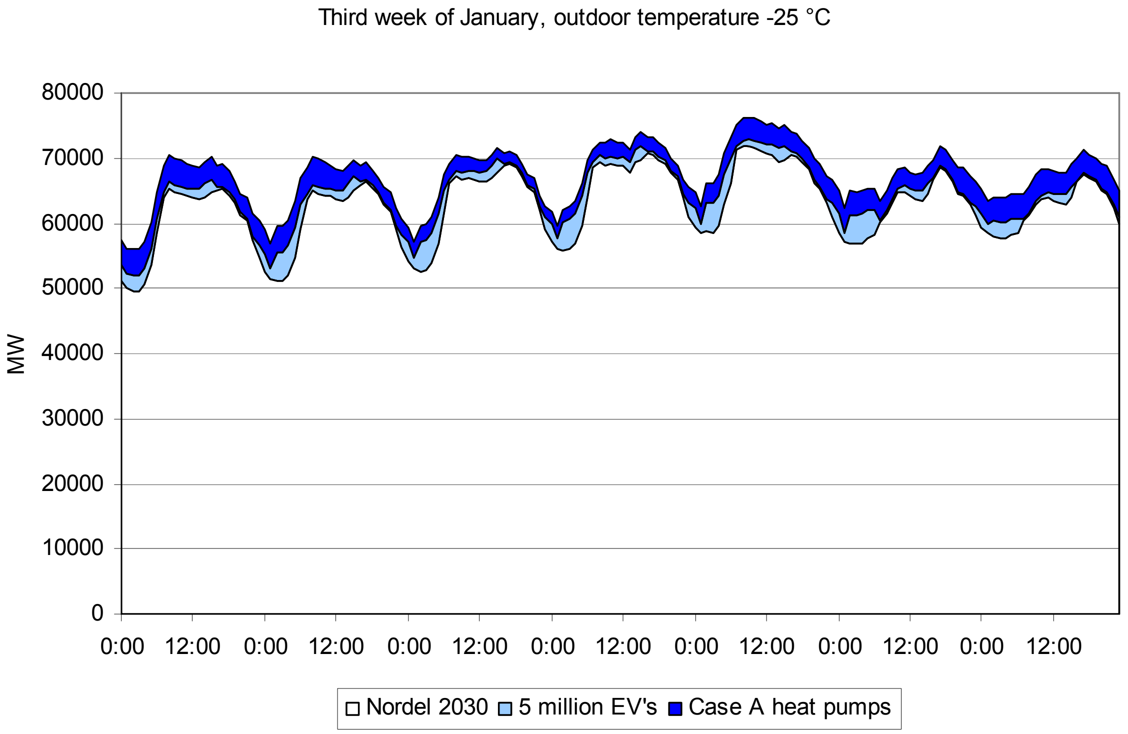


Figure 29. Case A, outdoor temperature – 25 ° C.

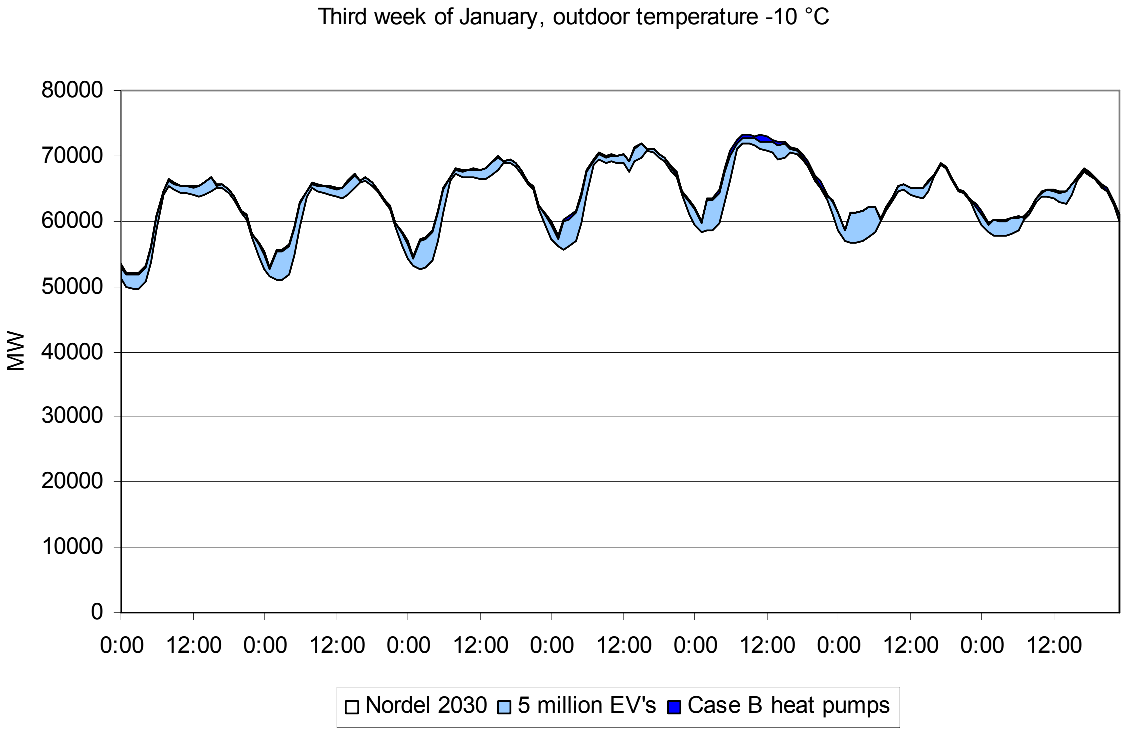


Figure 30. Case B, outdoor temperature -10° C.

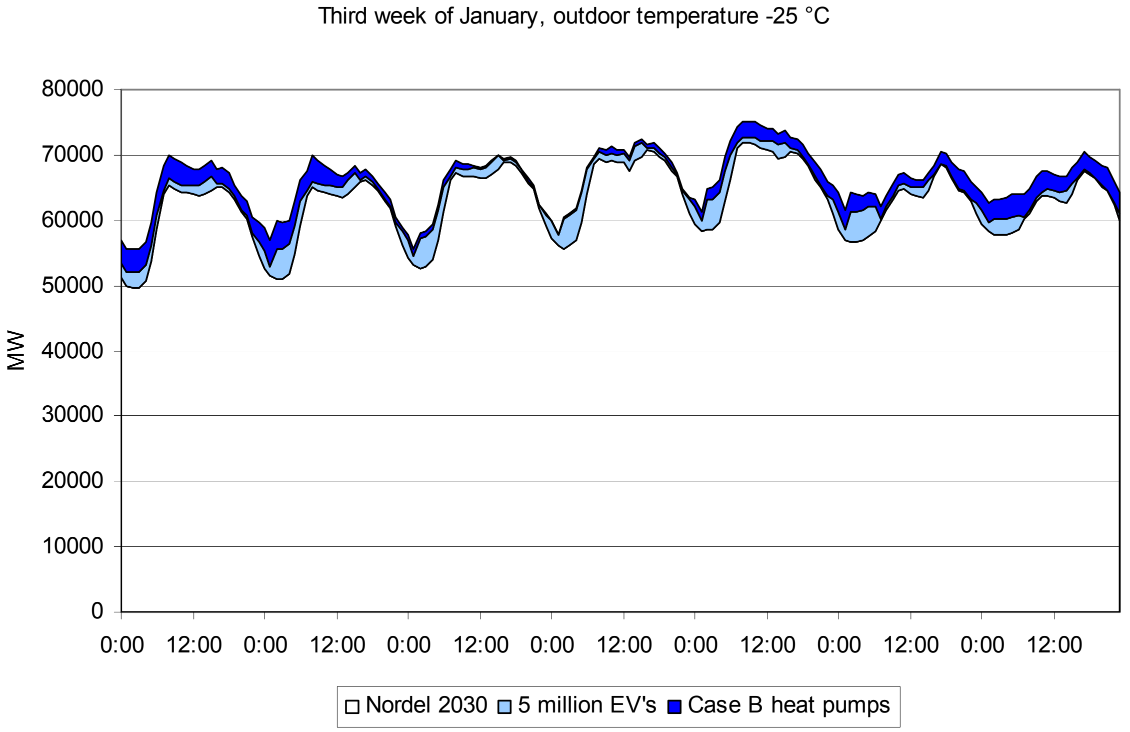


Figure 31. Case B, outdoor temperature -25 ° C.

4.5 Changes to CO_2 emissions due to heat pumps

Heat pumps are assumed to replace heating oil. The example oil heated house is perhaps not that common in the Nordic countries that there will be 400 000 of them to replace the heating system of. On the other hand, a lot of different houses and buildings are heated with oil, so it will not be that difficult to find present consumptions of 1520 million litres of heating oil that could be changed to heat pumps as in the case shown previous.

If the heating oil has a CO_2 emission of 2.64 kg_{CO2}/litre, then the cut in CO_2 emissions for the equivalent of 400 000 houses will be

- -0.6 Mt_{CO2} if electricity is produced with coal condensing power (900 kg_{CO2}/MWh),
- 1.7 Mt_{CO2} if electricity is produced with new CCGT (376 kgCO2/MWh), and
- 0.4 Mt_{CO2} if electricity is produced with average Nordic production (670 kgCO2/MWh).

In addition, if similarly 600 000 houses (or roughly 20 TWh direct electric heating) change to heat pumps, the cut in CO2 emissions will be

- 6.2 Mt_{CO2} if electricity is produced with coal condensing power (900 kg_{CO2}/MWh),
- 2.6 Mt_{CO2} if electricity is produced with new CCGT (376 kg_{CO2}/MWh), and
- 4.6 Mt_{CO2} if electricity is produced with average Nordic production (670 kg_{CO2}/MWh).

5 Discussion on the nuclear power

5.1 Current political atmosphere in Finland and Sweden

The renaissance of nuclear power in Western Europe started with the building of Finland's 5th nuclear reactor, Olkiluoto 3 (OL3). Nonetheless, nuclear power has increased in Finland and in Sweden since the 1980's quite significantly even before OL3, thanks to upgrades of old reactors. Even the shutdown of the Barsebäck units has not been a severe set-back for nuclear power. It is expected that nuclear capacity in Sweden will reach 10 100 MW by 2020.

Capacity will start to phase out by 2030. It is up for debate whether Sweden will replace old nuclear plants with new nuclear plants. The public opinion is not set against nuclear at the moment, but might of course change once again.

Three companies are seeking permission to invest in a new reactor in Finland. The Finnish government will probably grant at least one new licence, possibly even two. Nuclear is seen as one of the most powerful tools to mitigate CO_2 emissions in Finland. Future development, i.e. 2030 and onwards, is on the other hand up for debate, just as in Sweden. Old phasing-out capacity needs to be replaced.

It is difficult to say how many plants would be viable in the Nordic system in the long term. This depends on the growth in electricity demand and the contribution from other sources, especially renewables. Although the growth in energy demand is set to decrease, energy efficiency does not necessarily mean a lower share for electricity, it might even mean the contrary. Energy is a lot of times saved by switching to electricity, especially in the transportation sector. Car engines have quite low operating efficiencies, and running on electricity would improve the energy efficiency significantly. A partial switch to electric cars would increase the demand for electricity, well matching the production of a new nuclear plant. Electricity demand increase could also take place in the heating sector if, for example, old oil boilers of detached houses would be replaced by heat pumps. It is also likely that increased emphasis on security of supply would benefit nuclear power, but this depends on the impact of renewables on energy balances and system stability.

5.2 The cost of nuclear plants

5.2.1 General aspects

Nuclear power plants come in a lot of types and sizes, and this discussion is not meant to be an all embraising study on the cost of all nuclear power plant alternatives. Two new nuclear power plant types, European Pressurised Water Reactor (EPR) and AP1000, are studied.

EPR is built by Areva, of French-German origin. One EPR is at the moment being constructed in Finland (Olkiluoto 3, OL3) and another in Flamanville, France. Net electricity output is 1600 MW_e, net efficiency is 38 % and thermal capacity is 4300 MW_{th}. The OL3 thermal capacity may very well be uprated to 4500 MW_{th} some years after startup, and later versions of EPR may also have higher thermal capacity. The maximum thermal capacity with EPR lies in the vicinity of 4800-4900 MW_{th}.

AP1000 is Westinghouse's answer to future demands for new and robust nuclear capacity. AP1000 is simpler, lighter, smaller and cheaper to build than EPR. Net electricity output is 1090 MW_e, net efficiency is 33 % and thermal capacity 3400 MW_{th}. As with EPR, thermal uprate, with e.g. 200 MW, might be possible.

5.2.2 Investment costs

Olkiluoto 3 has reported total costs (incl. interest during construction, owner's estimated project cost, 2 first cores) of 3 000 M€ (2003 money), but is generally seen as a bargain. The EPR built in Flamanville to EdF has overnight capital costs of 3300 M€ (2005 money), including the owner's project costs but excluding interest during construction, of course, and first core. Estimated total cost, including all investment related costs, for 2008 is about 4 000 M€. It gives a comparative cost of 2500 €/kW. All construction costs have experienced a price hike in recent years, and the investment cost may currently very well be a bit above the mentioned sum for new plants. On the other hand, Areva has sold 2 EPRs for a total of 8 000 M€ to China on Nov. 26, 2007, but that deal includes a long-term supply of uranium according to the Bloomberg website.

AP1000 is estimated to be cheaper than EPR. Price class has been marketed at 500-1000 US$/kW, but it is also estimated to be a lot more expensive than that. In July 2007 Westinghouse clinched a US$ 5 300 million deal with China to build four AP1000 reactors according to Bloomberg. It is unclear what is included in the different estimates, and how optimistic they have been. One expert estimate for total cost of AP1000 is 2100 €/kW.

Decommissioning costs are usually estimated to be of the size of 9-15% of the initial capital cost of a nuclear power plant. But when discounted, they contribute only a few percent to the investment cost and even less to the generation cost.

Decommissioning cost might be as high as 280 €/kW_e for EPR. AP1000 is estimated to be cheaper to decommission, with one estimate being 200 €/kW_e.

5.2.3 Operation costs

Burnup is assumed to be 45 MWd/kgU, as e.g.OL3, but might very well increase even to 60 MWd/kgU. A higher burnup gives more energy for the same fuel. On the other hand, there have been issues about brittleness of fuel rods with higher burnup, which could have more severe security implications.

Additional fuel back-end cost in excess of the decommissioning cost could be estimated to be around 0.5-1.0 €/MWh_e.

Operation and maintenance are together approximately in the same category, or a bit higher, as the fuel costs, with present uranium prices. Taxation of nuclear power may be quite high, for example as in Sweden resulting in even higher costs than the fuel costs.

The price of uranium has increased strongly during the last couple of years. The spot price as of December 31, 2007 was 90 US$ per pound of U3O8. It has come down in the spring of 2008, being now approximately 65 $/lb. In the long-term new mines will be opened and the production is expected to better meet the demand. Hence the price can be forecasted to settle down.

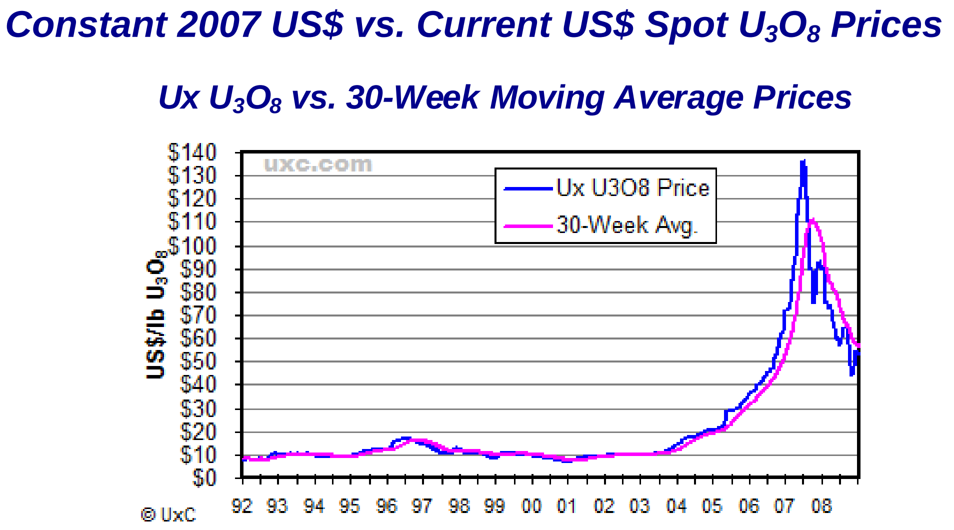


Figure 32. Price development of uranium. Source: The Ux Consulting Company, LLC (UxC), http://www.uxc.com/review/uxc_g_30wk-price.html

Using price levels from January 2008 we get uranium fuel prices as shown in Table 7.[3] On the other hand, the US dollar is weak (1.56 US$/€ in January 2009). These price levels result in fuel costs of 4.2 €/MWh$_e$ per produced MWh of electricity for EPR. The fuel costs for AP1000 are higher, 4.8 €/MWh$_e$.

Table 7. Uranium fuel cost by components. Price levels from beginning of 2008. The share of each fuel component of the resulting uranium fuel cost is shown to the right. With a as high raw uranium price level as in recent years the share of raw uranium is roughly half of the total fuel cost.

Uranium fuel cost by components

Natural uranium cost	Need (kg) of natural U3O8 per 1 kg of U fuel 8,9	Price (US$) of pound U_3O_8 65	Price (US$) of kg U_3O_8 143,0	Raw uranium cost (US$/kgU) 1273	48 %
Conversion cost	conversion coefficient 7,5		Price of fuel conversion US$/kg U as uranium fluoride (UF6) 10,5	Conversion cost (US$/kgU) 78,75	3 %
Enrichment cost	Enrichment need in Separative Work Units (SWU) per 1 kg of U 7,3		Enrichment cost (US$) per SWU 143	Enrichment cost (US$/kgU) 1044	39 %
Fuel fabrication				Fabrication cost US$/kgU 275	10 %
Total fuel cost				Total cost US$/kgU 2670	100 %

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[3] For raw uranium a price of 65 US$/lb U3O8 from 21.4.2008 is used. Sources: The Ux Consulting Company, LLC http://www.uxc.com/review/uxc_Prices.aspx WISE, Nuclear Fuel Cost Calculator http://www.wise-uranium.org/nfcc.html.

5.2.4 Production costs

Different sources give different estimates for the cost of electricity generated by nuclear power plants. Parameters that have an impact are among others total investment costs, capacity factor, discount rate and price of fuel. The question of what is included, and what not, in the calculations has a significant impact. For example taxes have a very strong impact on the costs in Sweden.

Bernard Salha, senior vice president of EdF, in an interview in Nucleonics Week, November 12, 2007, announced a production cost of 46 €/MWh (in 2005 euros) for the Flamanville plant.

VTT's nuclear cost model gives a production cost of 30.7 €/MWh for EPR, and a few euros lower for AP1000. A real discount rate of 6% is assumed, as well as a lifetime of 60 years and an average capacity factor of 90%. Annual average production is estimated to be 12.9 TWh for EPR and 8.9 TWh for AP1000.

Of course, using a higher real discount rate will increase the production costs tremendously as nuclear power is capital intensive. E.g. an interest rate of 10% results in a production cost of 42.43 €/MWh, an increase of more than 30%. Another uncertain cost factor is taxation to compensate the increased profits caused by the EU ETS (i.e. windfall taxation). If Swedish tax on nuclear (thermal capacity and real estate) is included, the production price will be well above 36 €/MWh.

5.2.5 Production cost of old nuclear plants

Old nuclear power plants have about the same fuel costs as new plants. The net efficiency is around 33%. Operation and maintenance costs might be a bit higher. On the other hand, decommissioning (seen as an annual fixed cost) is more or less paid for.

Swedish nuclear power plants have had an average capacity factor of 81% during 1996-2006; Swedish outages have included coast downs and even voluntary down-regulations, as well as very long revisions. These all have been improved in recent years, e.g. outages due to revisions have been approximately 6% between 2004 and 2006. Unplanned stops on the other hand have increased, being for example over 11% in 2006. The Swedish nuclear power plants will probably achieve better capacity factors, with an optimistic, but realistic expected value of 86%.

Finnish nuclear power plants have had an average capacity factor of 94% during 1996-2006. The Finnish track record has been probably the best in the world, and there is no reason to assume that it would deteriorate in the future.

5.3 New nuclear power plants affect the market

Nuclear power plants (NPP) have low variable costs and will therefore be running as much as they can in the Nordic electricity market. The question is how deeply will they influence the market?

5.3.1 The setup

The new nuclear power plants will move some CHP and especially the condensing power plants on the merit order, to be used less, but at the same time making more capacity available at peak load. We study how new nuclear power plant capacity affects both the price of the market and balances, if all other aspects are kept constant, all other aspects being fuel prices, neighbour area prices (Germany, Estonia, Poland, the Netherlands), other production capacity and the price of CO_2 (20 €/t).

The study was done for three separate situations: the situation as it is 2008, the situation in 2020 assuming capacity development according to NEP preference case, and the situation in 2020 assuming capacity development according to NEP policy scenario. All fuel and export area prices as well as the CO2 price are kept unchanged in all the situations. In each situation three different nuclear developments are studied. For 2008, the base case is no new nuclear power plants, while there is one - Olkiluoto 3- in 2020. The base case is compared to 1600 MW extra nuclear capacity and to 3200 MW extra nuclear capacity.

5.3.2 The results

The market price reacts likewise in all the three situations as shown in Figure 33. The decrease in the market price is 4% ±0.5% per 1000 MW new capacity. This results in 600 M€/a savings for the consumers per each 1000 MW of new nuclear capacity.

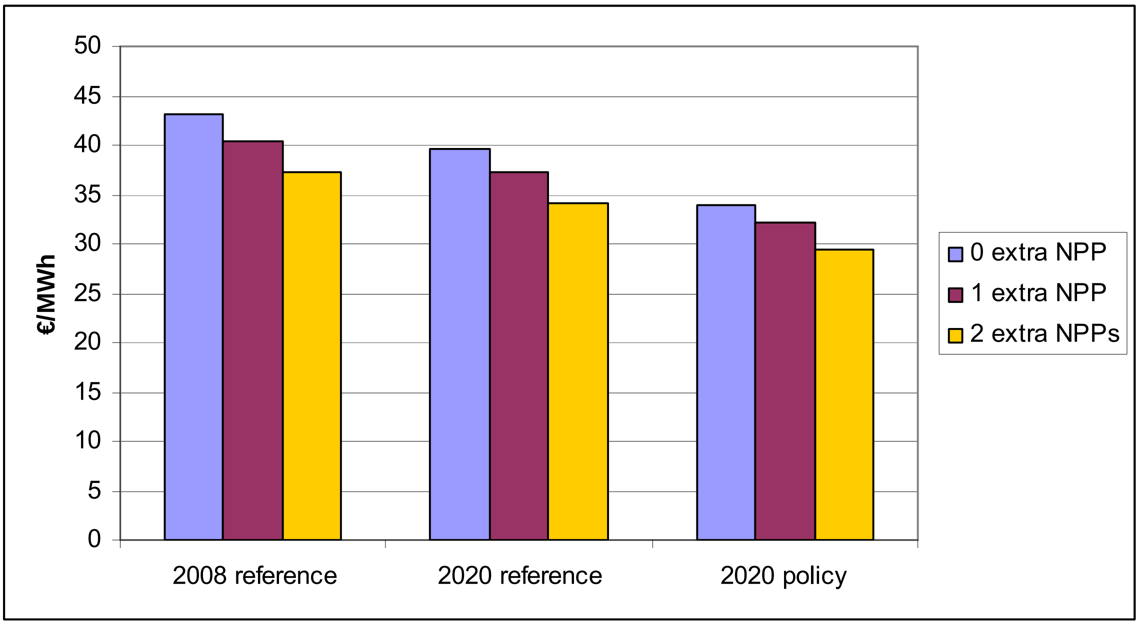

Figure 33. The effects of additional nuclear power plants (NPP) on the Nordic market price in three different scenarios.

The new nuclear based electricity both replaces other Nordic production and is exported. The changes in the exports are shown in Figure 34. The 2008 capacity and production constellation has still expensive domestic production to be replaced, while the situation is much better in 2020 in both scenarios. The increase in renewables will be substantial by 2020 in both cases, the reference and the policy scenario, leaving less room for condensing power. The exports increase with 16 TWh in 2020 in the case that two new NPPs are set up.

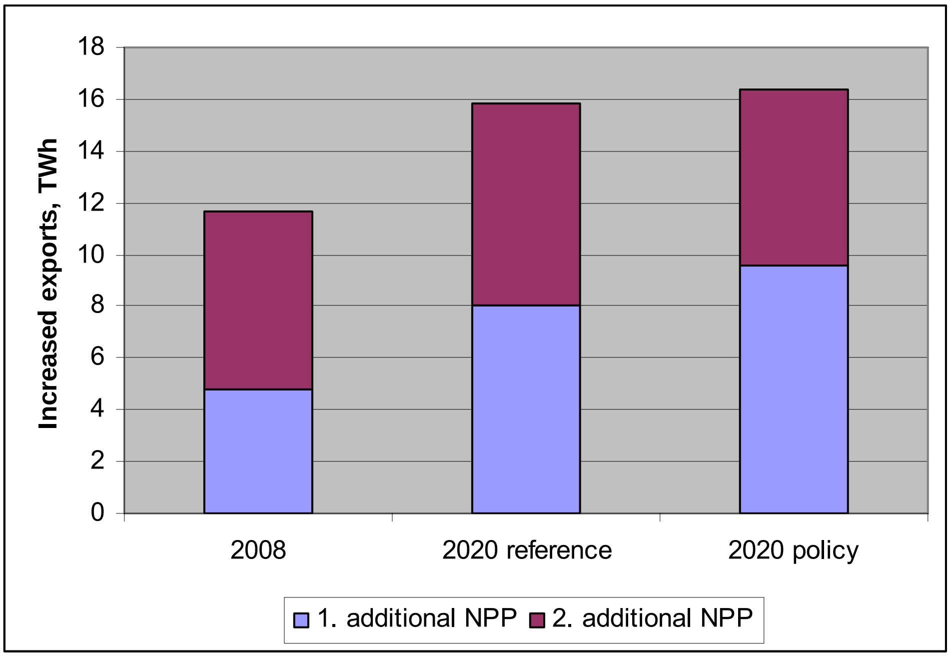

Figure 34. Increase in exports according to new NPPs in the different situations. As seen in the 2008 situation, less than half of the new NPP capacity would result in exports, whereas the share is well above 50% in 2020.

Condensing power production (expect nuclear) in 2020 in the reference scenario is already down to 14 TWh, but in the policy scenario it is barely 7 TWh. New NPPs have less and less impact on condensing power production, as it is becoming a very narrow peak capacity. The new NPPs in the policy scenario decrease condensing power production with only 2 TWh each, while the decrease in CHP is even more substantial, being even 3.5 TWh for the second NPP.

5.3.3 Changes in CO_2 emissions

The changes in Nordic CO_2 emissions will not be as large as the total electricity production of one unit could give reason to believe. As shown previously, condensing power production is already very low in the policy scenario. Saving in condensing power CO_2 emissions will be less than 2 Mt_{CO2} for each new NPP unit. If we calculate with average marginal CO_2 emissions for Nordic electricity production, then the savings are roughly 1.3 M t_{CO2}. It might be less, if the NPPs are eating away at the production of CCS units. There are, though, savings also from the fossil CHP emissions, so the effect will probably be even larger than given above.

The overall savings made in the European CO_2 emissions will be substantial, corresponding to the electricity production. The exports will replace fossil condensing production, approximated at 6 Mt per new NPP.

6 Status of the carbon capture and storage within EU

The EU Strategic Energy Technology Plan (SET-Plan) has recognized the demonstration of carbon capture and storage (CCS) in fossil fuel-based power generation as one of the focus areas of European technology development. The Commission's proposal for a CCS Directive (EU, 2008c) aims to resolve all the major CCS-related legislative issues and to provide a comprehensive regulatory framework to ensure the safety of CCS deployment. Furthermore, the Commission confirms that the current ETS can recognize CO_2 captured and safely stored as not emitted, which means that CCS projects can be opted in to the ETS in the 2008-2012 period. The Directive examines the implications of making CCS mandatory. Power plants built after the launch of the CCS Directive should be *capture ready*. The IEA Greenhouse Gas Programme has proposed that capture ready greenfield plants should reserve space for capture plant, carry out feasibility studies, and identify the potential storage sites and transmission routes to the storage sites.

The problem with CCS is that currently the technology has not been demonstrated on the scale of power plant producing millions of tonnes of CO_2 per year. The costs of capture are also still high. A capture plant consumes in addition energy and therefore the efficiency of electricity production would decrease. This contradicts the EU targets to increase energy efficiency. Also, high uncertainties are related to underground storage potentials. CO_2 can be injected and stored in underground geological formations, such as old oil and gas fields, saline aquifer formations and coal beds. Norway and Denmark have access to their own oil and gas fields but with current knowledge neither Finland nor Sweden have suitable storage sites for CO_2. Implementing CCS in those countries would require CO_2 transport abroad via pipeline or by ship. The CO_2 tankers built by StatoilHydro have a capacity of 1000 m^3 but the largest existing LNG tankers could transport about 230 000 tonnes of liquid CO_2.

Norwegian StatoilHydro has operated CCS since 1996 in the North Sea. On the Sleipner gas field 1 million tonnes of CO_2 is captured from natural gas every year and injected to the saline aquifer under the sea belt. Statoil has also further demonstration plans, like in Snøhvit and Mongstad. Vattenfall has also been very active to implement CCS and has a pilot plant for CO_2 capture in Germany. EON has plans for CCS in Denmark and Sweden, and DONG Energy is also operating a small pilot plant in Denmark. Recently Fortum has announced that they have started feasibility studies to implement CCS in Meri-Pori coal fired condensing power plant in Finland. Also Pohjolan Voima from Finland has plans for CCS demonstration facilities.

6.1 New CCS barely affects the market

CCS has high fixed and variable costs compared to plants without it. The gain is in saved CO_2 emissions and thus EUAs. How will CCS succeed in the Nordic market?

6.1.1 The set-up

We study the effects using two cases in NEP policy scenario surroundings. In the first case Norwegian gas CCGT's in Kårstö and Mongstad are assumed to be turned into CCS-plants by 2020. This is in accordance with NEP scenarios. Their capacity will drop from a combined 700 MW to 560 MW at the same time, an efficiency drop of 10 percentage units. The second case is a coal condensing power plant (coal PP) with its capacity dropping from 550 MW to 440 MW due to CCS, an efficiency drop of 8 percentage units.

The calculations settings are as follows: NEP policy scenario assumes that there will be new renewables power production fulfilling EU 20% target for renewables, and low CO_2 power production meeting the EU 20% decrease target for CO_2. This makes it a tough surrounding for new CCS technology, as the Nordic fossil fuel use will be quite low in the electricity sector. The price level in Germany is low in 2020 (assumed CO_2 price of 20 €/t), but higher in 2030 (assumed CO_2 price of 40 €/t).

The cases here are, however, studied in relation to CO_2 prices of 20 €/t and 50 €/t, and in comparison to a situation where there is no CCS. We have not let German price levels fluctuate according to CO_2 price levels, but kept them unchanged matching the policy scenario. This means that the results are better viewed as changes, not absolutes.

6.1.2 The results

According to the policy scenario, the plants are not much in use in 2020, with or without CCS as the need for condensing power is quite low. The savings in CO_2 emissions are therefore quite low 2020, at best 0.7 Mt $_{CO2}$. A higher CO_2 price of 50 €/t CO_2 doesn't increase the savings in our model runs.

The coal PP is running at full capacity both with and without CCS in 2030 with a CO_2 price of 20 €/t. The power output is less with CCS, as the efficiency is impaired. This influences the CO_2 savings, being 3 Mt_{CO2}, but only slightly. The difference in plant emissions with and without CCS is shown in Table 8. The differences come not only from CCS, but also from how well the different plants fit into the market, and from the changes in their capacities.

The production of electricity in 2030 is greater with CCS than without in the case of a CO_2 price of 50 €/t, but the other way around with a price of 20 €/t. CCGT is producing less electricity with CCS than without in all the four cases. CCGT with CCS is fairing better at high CO_2 prices, whereas it is vice versa with coal PP/CCS. Overall, CCGT/CCS is not as competitive as coal PP/CCS in this set-up.

Table 8. Changes in CO_2 emissions for the different CCS cases compared to emissions from same plants without CCS.

	20 €/t		50 €/t	
	2020	2030	2020	2030
Coal PP Mt CO2	-0,8	-3,0	0,0	0,2
Gas CCGT Mt CO2	0,0	-0,5	-0,1	-0,7
SUM Mt CO2	-0,8	-3,4	0,0	-0,5

The market price is not much affected by these two plants turning CCS. The changes to the market price due to CCS are shown in Figure 35. The price increase for the combination 20 €/t and year 2030 has to do with the study set-up. Neighbor areas (Germany et al) have price levels more matching a CO_2 price of 40 €/t in 2030 in the NEP2 policy scenario. Therefore the exports just explode in 2030 with a low CO_2 price, with the extra production in the Nordic countries being condensing power.

Otherwise condensing power is very marginal in the case calculations, being at the most 9.1 TWh (2030, 50 €/t), including 4 TWh of CCS-production. In 2020, with a CO_2 price of 50 €/t, the results show a condensing power production below 2.5 TWh. That is, in turn, because the low German price level matching a CO_2 price of 20 €/t in 2020.

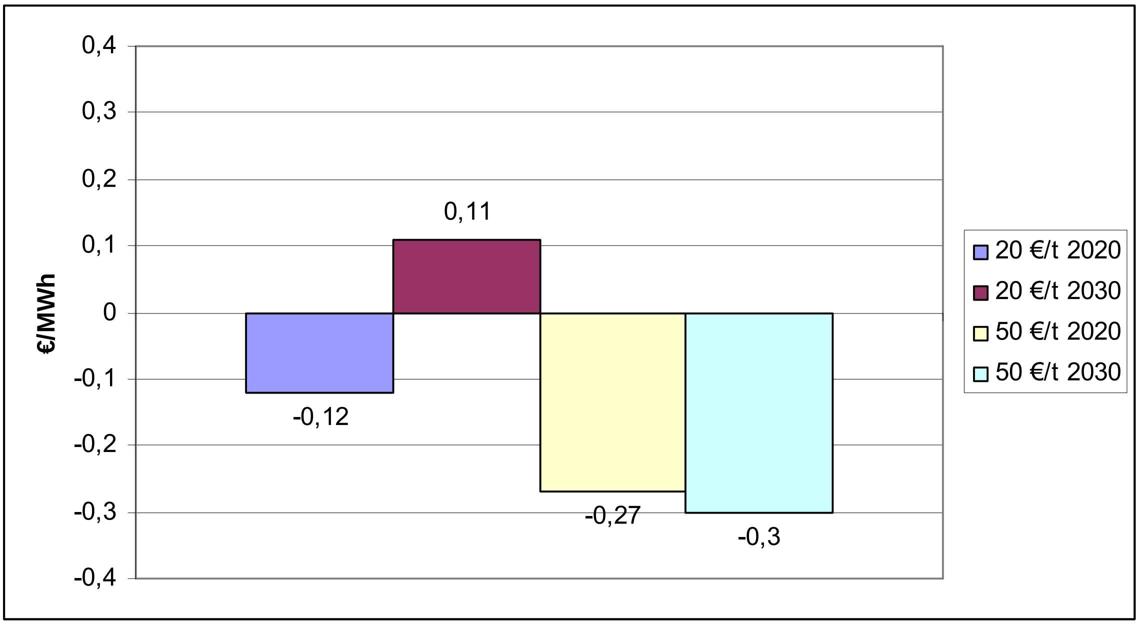

Figure 35. The changes to market price in four different situations due to adding CCS to CCGT in Norway and to a coal power plant.

7 Conclusions

In this report some of the major technology options to reduce CO_2 emissions in energy production, residential heating and in transport sector are given with a Nordic perspective. The reported technology options include increased use of renewables (wind and biomass) and nuclear power, carbon capture and storage (CCS), electric vehicles, and heat pumps. In addition to these examples, there are naturally several other options to reduce CO_2 emissions, which are included in NEP scenarios and other NEP reports.

The theoretical potential to increase renewable energy use in the Nordic area is large but techno-economic potentials depend on:

- Accelerated support mechanisms and/or increased fossil fuel prices
- Changes in environmental legislation for the future utilization of Nordic rivers for hydropower
- Changes in the regulations and permitting procedures for land use (wind power)
- Sustainability criteria for biomass
- The future of forest industry (biomass).

In Norway and Sweden large number of wind power projects is under development but there is no guarantee that these projects will be realized. The theoretical potential to increase hydropower production is also large but bearing in mind the political situation and the attitude of many people, a further hydropower development would be limited.

Biomass is feasible for heat, electricity and liquid biofuels production, but the techno-economical potentials are very difficult to estimate and therefore the reported Nordic estimations have very large variations. Also the biomass potentials of Russia, Americas and other exporting areas are difficult to estimate, although their effects on the biomass market volume and price could be dramatic. As wood resources for large scale energy production are limited by feasible transportation distances the use of wood fuels as a main fuel can be complemented with agricultural residues, energy crops and commercial, industrial and industrial recovered fuels. Production and trade of pellets can be increased significantly. As national incentives on bioenergy have significant variations, biomass trade would be increased as the demand increases. It can be expected the in the near future, bioenergy is not anymore only local, but widely utilised source of energy. A competition of wood raw material with the forest industry already exists in some countries, and the competition for agricultural land will become fiercer.

End-user technologies like heat pumps and electric vehicles diminish CO_2 emissions. Changing oil heating to heat pumps, or gasoline cars to electric vehicles are a couple of solutions for the future. If the electricity is seen as produced with old coal condensing power plants (900 kg $_{CO2}$/MWh_{el}), then the savings are none-existent or negative. Using average marginal Nordic power production (670 kg_{CO2}/MWh_{el}), there is a small positive effect for the heat pumps, but already a 3 Mt_{CO2} saving for 5 million electric vehicles. But if more and more electricity is produced using renewables, nuclear and CCS in the future, then the emissions of the marginal production will decrease, resulting in larger CO_2 emissions savings. On the other hand, changing direct electric heating to heat pumps will decrease CO_2 emissions strongly, but the more the higher the marginal production emissions are. If we use an average CO_2

emission for the Nordic electricity production of 50 kg_{CO2}/MWh_{el}, then the consumer side savings (5 million EVs, 400 000 oil heated detached houses to heat pumps) would reach 15 Mt_{CO2}.

The renaissance of nuclear power in Finland and Sweden is up for debate. The fifth reactor is under construction, and three companies are seeking permission for a new reactor in Finland. The Finnish Government is targeting to make the decision concerning construction permits for new reactor(s) by the end of fall 2010. A sixth and a seventh reactor would have similar affects on the CO_2 emissions. Over half of the production 2020 would go to lowering the continental marginal emissions, approximately with 6-7 Mt_{CO2} each. Nordic emissions would decrease relatively less, as nuclear energy would not only suppress condensing power production, but also CHP. On the other hand, if demand for electricity would increase much steeper due to environmental reasons (heat pumps, electric vehicles, etc.), the savings in CO_2 emissions would be a lot more significant even in the Nordic countries.

Implementing CCS would largely depend on the development of international legislation and also large scale demonstrations to prove that CCS is safe and technically viable. Also, implementing CCS would require supporting schemes to make it economically viable. From the Nordic countries only Norway and Denmark have suitable storage sites, which means that international collaboration would be required before CCS could be implemented in Finland or Sweden. In the presented case study CCS and condensing power plants was not a very effective solution for the Nordic countries, if and when the EU target of 20% renewables is fulfilled in 2020. The need for condensing power may be high, but also very narrow, in the future. Thus the savings in CO_2 emissions would not be that striking, unless, once again, the production would replace continental high-emission condensing power production. CO_2 saving-wise it might be better to introduce CCS to CHP than to condensing power in the Nordic countries. On the other hand, in the case of minimum investments on new nuclear (and phasing out of old nuclear), CCS could be solution for deep emission reductions in energy production.

It is evident that none of the above technology options would solve the climate change issue alone as the global energy system should be practically emission free in this century. All the possible solutions should be available to find the best solutions towards carbon free energy systems.

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