Climate Change and the Future Nordic Energy System

-with focus on the electricity system

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Executive summary

The Climate and Energy project analyses the consequences of climate change for the Nordic energy system. Human activities influence the global climate and this will have serious impacts. How serious the consequences will be, depend on geography, which sector is in focus and with which references the changes are compared.

In this report, impacts of different types of climate changes are compared to other possible developments for the Nordic energy system. The main focus of the report is on the electricity system. Several types of climate-change impact are considered:

- Changes in average climate properties (average values for temperature, wind and precipitation) influence e.g. the demand for electricity and the electricity production from hydro and wind power. The changes in average climate properties are described in many studies, and the results show common trends.
- Changes in extreme climate events, like storms, heavy rain and long periods with unusually high or low temperatures, can have serious impact on the function of the energy system. Security of supply is threatened by extreme climate events. Dam security, backup for wind power and reliability of overhead lines are challenges by extreme events. Limited information exists about the long-term development of extreme climate events, and no consensus is found.
- Climate change may have a major impact on the future energy system due to energy policy. As a response to the global consequences of climate change, the energy system may (or may not) be revolutionised. Ambitious energy policy may limit CO_2 emissions, tax fossil fuels and support renewable energy sources and energy efficiency.
- Economic activities may be directly influenced by climate change, e.g. agricultural production may expand or relocate as a result of climate change. Economic activities in energy-intensive industry may be reduced because the climate change motivates altered energy policy.

While the first type of impact (direct impact of changes in average climate variables) seems to be limited compared to the technical and economical development that can be foreseen in a 50 years perspective – the other three types of impact can have a vast influence on the energy system.

In this study the long-term development of the energy system is described by three scenarios:

- A medium scenario that can be regarded as a continuation of current trends with modest economic growth and balanced energy policy.
- A (extreme) free market scenario with high economic growth and little environmental regulation, with large commercial power plants and a high energy demand.
- An (extreme) environmental scenario with low energy demand due to firm policy.

The three scenarios are used to illustrate how economical and technological conditions can be radically different compared to today. For all scenarios, it can be concluded that the direct impact of changes in average climate variables are marginal compared to other changes that are expected. One key factor for the robustness of the energy system is the relative share of hydropower, which is high in the environmental scenario (with low energy demand) but lower in the free market scenario (with high energy demand).

Average climate variables

Regional climate scenarios were developed within the Climate and Energy project. They indicate that the annual mean temperature for Scandinavia and Finland will be 4-5 degrees higher during the period 2070-2100 compared to 1960-1990. The warming is larger in winter than in summer. At the end of the century, precipitation is probably reduced in southern Scandinavia (most clearly in summer) but probably about 30% higher in the north, especially in winter but also in spring and autumn. Wind may increase by around 5%, primarily in winter (Rummukainen et al., 2006).

These results indicate that the regional consequences in the long term include higher temperatures, more precipitation and more wind, which brings about melting glaciers but also better conditions for biomass production. Climate change enables more electricity production from hydropower and wind power and enhanced energy supply from biomass (Venäläinen et al., 2004). In a Nordic perspective, these changes will be in the order of 10% of current electricity production.

Increasing temperatures will influence the energy demand by reducing the need for energy used for space heating. An increase in temperature would reduce the electricity demand in the order of 1% per degree in the Nordic area at present share of electric heating. This demand reduction will take place in fall, winter and spring. The electricity used for air conditioning in summer may increase, but this increase would be much less than the reduced electricity use for heating (in the order of 1/30).

Possible economic and technological development

However, the consequences due to climate change seem small compared to economic, technical, and political changes that can take place:

- Electricity demand is expected (by EU) to increase by 1 to 2% p.a. In 45 years, this will be an increase of 60 to 140%, but present Nordic electricity consumption per capita is much higher than the EU average.
- Wind power and biomass supply 8% of the current Nordic electricity demand. This share may multiply before year 2050. Fossil fuel reserves are large but limited and their use may be restricted due to climate change policy.
- New technologies, such as flexible AC transmission systems (FACTS) and superconducting cables, may revolutionise the transmission system. Long distance transmission between countries may increase and electricity flow may be controlled systematically, allowing a high share of intermittent power production, e.g. wind power.
- New communication and computation technologies make it possible to activate small-scale generation and demand to react in real time on system needs. Demand may be delayed for some hours and in that way reduce the need for peak production.

The described changes in energy demand and supply directly due to climate change can with little difficulty be absorbed by the energy system during a 50 years time span. However, the electricity system is vulnerable in relation to extreme weather events. Storms, floods and extreme temperatures can disrupt the power supply. The frequency and seriousness of extreme weather may be more critical for the energy system than changes in average climate values.

The three scenarios in this report outline developments for the Nordic energy system with promising technologies during the next 50-100 years. The study encompasses the stationary energy system with focus on the electricity system. First, the main, medium-path scenario is presented in the next two sections.

Energy demand in 2050

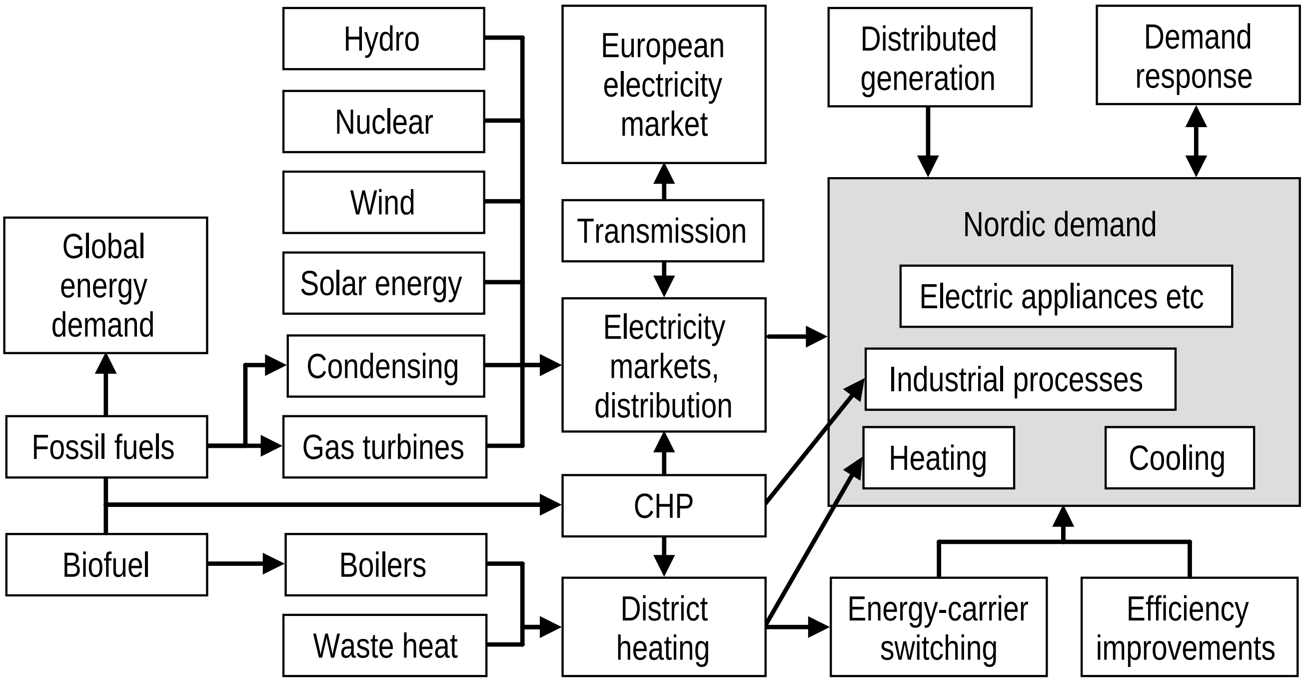
Global energy demand is likely to increase due to industrialization and enhanced standard of living in many countries. Increased energy demand and limited cheap energy supplies make energy carriers more expensive, which makes new technologies, renewable energy and energy conservation more profitable. Fossil-fuel use may be limited by environmental concern and cost increase (cf. Azar and Lindgren, 1998). Utilisation of renewable energy sources may increase, primarily in the forms of biofuel, wind power and solar energy, for which technologies already are more or less commercial (cf. IEA, 2003). Harmful climate-change consequences may emphasise the use of policy instruments.

Taxes and emission allowances can raise the cost for fossil fuels and green certificates and feed-in tariffs can promote renewable electricity.

Energy is likely to be used more efficiently in Nordic industry, buildings and electric appliances (cf. IEA, 2003). Heat can be recovered for repeated utilisation in industrial processes and for heating. Thus, primary energy supply may decrease without reducing the comfort, benefit or utility owing to energy use (Azar and Lindgren, 1998, cf. IVA, 2003; Eon, 2006). Climate change will reduce space-heating demand and its seasonal variations (e.g. Skaugen and Tveito, 2002).

An integrated system

Nordic power grids will be more linked to the continental power system and the Nordic electricity market is a part of a common European market. This will raise Nordic electricity prices to levels that are similar to continental Europe, which dampens electricity consumption (cf. Eon, 2006), especially for purposes where other energy carriers are rather easily applicable. The interplay between power generation and electricity consumption in the Nordic countries and continental Europe also means that Nordic electricity use normally increase operation and carbon dioxide emissions from the committed power plants with highest operation cost, which now are mostly coal-fired (and in the future probably natural-gas-fired) condensing plants.



There is continuous interplay among various components in the stationary energy system, from energy sources, via conversion and distribution units to demand, which may be influenced in several ways.

The level of the electricity consumption in 50 years is very uncertain. Until then, the complete stock of power plants and transmissions lines can be renewed. New electronic equipment and information and communication technologies can enable consumers as players in the electricity system and influence the demand for energy supply. Demand response and advanced markets with dynamic nodal pricing can reduce the required peak generation capacity (Nordel, 2004). With nodal pricing each location has it own price, dependent on the marginal impact of losses, capacity constraints, and general energy markets. Surplus or deficit because of local production, like wind power or micro generation, can be signalled though the price. Since the prices show larger variations, the motivation to adapt demand to actual prices is strong, and e.g. micro generation can benefit from timing the production to the highest prices.

Electricity consumption for heat production can often be replaced by fuels, district heating or solar energy, which have sufficient quality for heating. In secluded low-energy houses, electric heating can be preferable. Switching from electricity to other energy carriers for space heating reduces the seasonal variations of electricity consumption. Industrial electricity consumption becomes more similar to continental Europe, where less electricity normally is used by manufacturing. Swedish industries can reduce electricity consumption substantially (e.g. Trygg and Karlsson, 2004).

Condensing power production will be reduced when its low efficiency makes the generated electricity too expensive as fossil fuel costs increase. Distributed electricity generation can become widespread. Efficient combined heat and power (CHP) production with wood fuel, municipal waste or, possibly, natural gas increases (cf. IEA, 2003). District heating can become common in all Nordic countries (cf. Eon, 2006). Switching from electricity to district heating for heat supply increases the heat sink for CHP production.

New energy supply technologies emerge, such as photovoltaics (solar cells) and fuel cells (IEA, 2003). Through carbon dioxide capture at power plants and storage in oceans or geological formations, fossil fuels could possibly be used without climate degradation. Hydrogen can be derived through gasification of biomass or electrolysis and may be used as energy carrier where it is advantageous to electricity, for example as vehicle fuel.

To secure energy supply, many different energy sources and technologies can be used with preference for local resources, which often are renewable. Hydropower dams can balance fluctuating wind power output but transmission capacity may limit control possibilities. Possible wind power capacity is primarily an economical trade-off that depends on the interplay between wind power and hydropower, transmission capacities, electricity demand and generation in the same and neighbouring areas and, possibly, spillage (Söder, 2004). Adaptation of electricity consumption through demand response can help absorbing wind variations. New technologies, such as high temperature superconducting materials, power electronics, electricity storage and automated demand response from consumers can revolutionize the way the electricity system is working (EPRI, 2003).

Electronic equipment can automate the control of electric demand in order to avoid expensive periods. The picture shows a product marketed in 2006 that uses wireless communication to control equipment within a house. It is connected to the Internet and can receive SMS and e-mails and can play radio. It can also be used for surveillance. In this way, home automation can be economic (energy savings and demand response) as well as serving for entertainment and security (Tell-it-online, 2006).

High growth scenario

In a second scenario, the growth in demand for electricity and other energy forms is very high and new technology is used to transport electricity over long distances as competition takes place on an European scale. The development of the energy system is left to the market. Large generation technologies dominate and demand is part of the competition. Fossil fuel use and condensing power production increase. New large hydroelectric and nuclear power plants are built. Global warming makes air condition common. Energy efficiency is just slightly improved.

Greener scenario

In the third, environmental scenario, energy and electricity demand is lower than today mainly because of high energy efficiency but also due to less heavy industry. Renewable energy, such as wind power, photovoltaics and biofuel, is common and is promoted by firm policy instruments, which have effectively hampered fossil fuel combustion and, thus, reduced CO_2 emissions. The use of, primarily, domestic energy resources brings security of supply. Nuclear power is no longer required but there is extensive distributed generation (e.g. fuel cells) in low-energy buildings with internal DC micro grids.

Concluding discussion

The scenarios illustrate that the way forward is difficult to predict and can take many forms. It is most probable that events occur that we cannot even imagine today, such as shocks concerning international relations.

A moderate increase in hydropower and wind power production or decreased heating demand and increased air-conditioning demand due to climate change will only have marginal consequences for the energy system. This holds for all of the three scenarios and because the two latter reflect extreme futures, it is likely to be a plausible conclusion. Global trends, such as presumable transition from fossil to renewable energy sources and emerging technologies, are likely to have a much larger influence on the Nordic energy system.

Contents

1 Climate change and the energy system

Climate change scenarios operate with very long time spans – looking 50 or 100 years into the future. In the project "Impacts of Climate Change on Renewable Energy Sources and their Role in the Energy System", the climate scenarios are described for 2050 and 2100, as are the consequences for the renewable energy resources.

The majority of the existing power production plants, transmission lines and electrical appliances and other the electricity-consuming equipment will all have been replaced by this time. So, the question is what the energy system will look like 50 or 100 years from now?

To supplement the analyses on energy resources and climate change in the Climate and energy project, some perspectives on the development of the energy system in the long term are made in this study. The study encompasses the stationary energy system with focus on the electricity system but does not consider transportation.

The core of this analysis is:

- Review of existing studies describing the energy system in a long perspective (section 4)
- Description of important issues for the development of the energy system (section 5)
- Review of new technologies that are considered important in a 50 years perspective (section 6)

On this basis and together with the other sections, three scenarios are developed (in section 7) and the overall impact of climate change is compared with other possible or probable development of the energy system.

1.1 Current energy system in the Nordic area

The current power generation in the Nordic countries is described in table 1.1. One-half of the total generation is from hydropower and besides this only Iceland and Denmark have considerable fractions of renewable energy. Wind power and biomass supply 8% and nuclear power 25% of the electricity. The hydroelectric power production in Sweden and Norway in 2004 was 8% lower than normal, whereas it was 5-13% higher in Iceland and Finland. Current electricity transmission capacities between Nordic countries and with continental Europe and Russia are described in section 5.4.

	Denmark	Finland	Iceland	Norway	Sweden	Nordic
Nuclear		22			75	97
District-heating CHP[a]	27	30		0.4	3.5	61
Industrial cogeneration	1.8	4.2		0.2	1.8	8.0
Hydro		15	7.1	109	60	191
Wind	6.6	0.1		0.3	0.8	7.8
Biofuel	1.4	10		0.3	7.0	19
Waste	1.4	1.0		0.1	0.8	3.3
Geothermal			1.5			1.5
Total power generation	38	82	8.6	110	149	388
Electricity consumption	36	87	8.6	122	146	400
Total final energy consumption[b]	180	310	27	230	400	1100

Table 1.1. Electricity generation and consumption (Nordel, 2005) and total final-energy consumption in the Nordic countries in 2004, TWh

[a] Including condensing plants, gas turbines

[b] Sources: www.ens.dk, www.stat.fi, www.statice.is, www.ssb.no, SEA 2005a, respectively

Table 1.1 also shows the total electricity consumption in the Nordic countries. Iceland, followed by Norway, has the world's highest electricity consumption per capita (29 MWh/year, Nordel, 2005). Finland and Sweden take place four and five, respectively (Fig. 1.1, Elforsk, 2006).

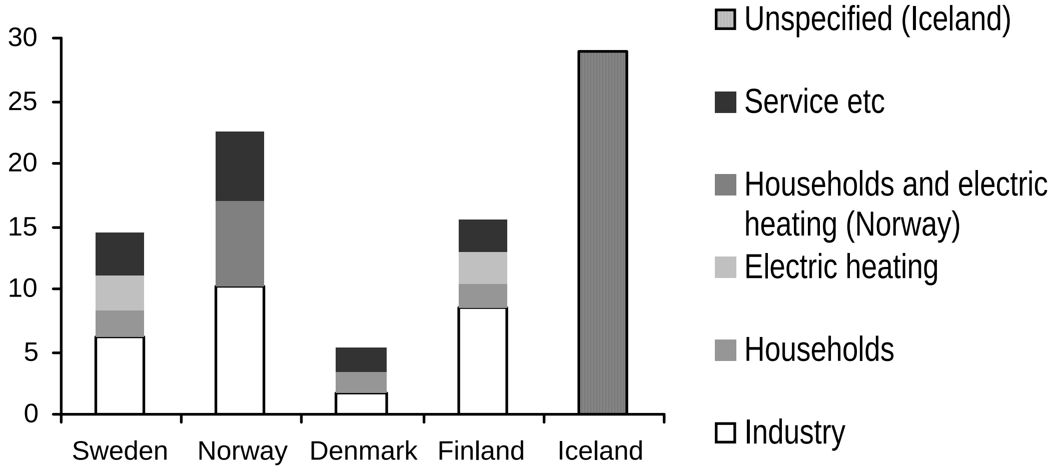


Figure 1.1. Annual electricity consumption per capita (MWh, Elforsk, 2006, Iceland: Nordel, 2005)

Nordic forest, ore, iron, steel and chemical industries use 120 TWh of electricity a year, whereof 50 for pulp and paper production (Elforsk, 2006). In Swedish industry with low energy use, much electricity is used for ventilation, lighting and compressed air (Henning, 2005). The total Nordic electricity consumption for space heating in households is 60 TWh per year. This electricity use is largest in Norway, both in absolute numbers as in share of the heat market, but it is very small in Denmark (see table 1.2).

	Electricity use for domestic space heating TWh/year	Fraction of total domestic space heating %
Norway	30	60
Sweden	20	30
Finland	10	20
Denmark	1	3

Table 1.2. Electric space heating in households (Elforsk, 2006)

1.2 Introduction to climate change

Human activities, such as fossil-fuelled power plants and transportation, release large amount of carbon dioxide (CO_2). This has lead to an increase in the carbon dioxide concentration in the atmosphere (Fig. 1.2). A growing scientific consensus indicates that this influences the global climate, which will have serious consequences for low land areas due to sea level raise and may influence food production and other vital parts of modern life (IPCC, 2001).

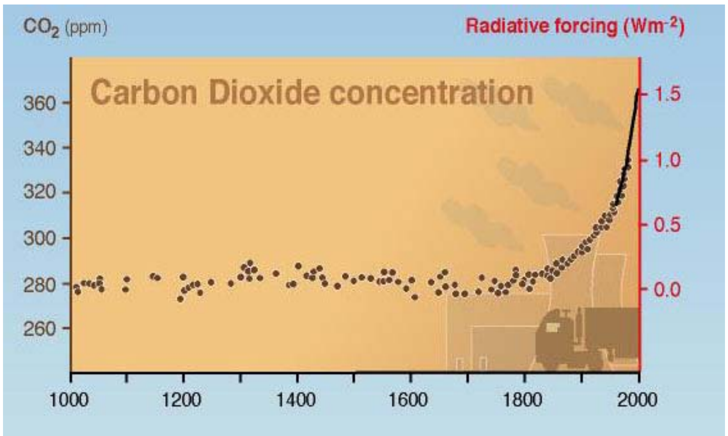


Figure 1.2. The carbon dioxide concentration in atmosphere as an indicator of the human influence on the climate (www.ipcc.ch)

UN IPCC describes the situation this way: “Future changes in atmospheric composition and climate are inevitable with increases in temperature and some extreme events, and regional increases and decreases in precipitation, leading to increased risks of floods and droughts. There are both beneficial and adverse effects of climate change, but the larger the changes and rate of change in climate, the more the adverse effects predominate with developing countries being the most vulnerable.” (Watson et al., 2001).

The climate group within the Climate and energy project have elaborated regional climate scenarios, which have been used by other researchers in the project to assess possible impact of climate change on, primarily, hydropower and biomass production (Rummukainen et al., 2006). The climate scenarios are based on the larger A2 and lower B2 emissions scenarios (IPCC, 2001), as well as global and regional climate models. Emissions scenarios indicate alternative plausible implications for climate change, whereas climate models represent alternative sensitivities of the climate system, but they suffer from incomplete knowledge and lack of measurements.

Compared to the period 1961-1990, the annual mean temperature for Scandinavia and Finland is estimated to be about 3 degrees higher in the middle of the century and 4-5 degrees higher toward 2100. The warming is larger in winter (3-7° in 2071-2100) than in summer (2-5° in 2071-2100) in northern Europe. Precipitation in Scandinavia and Finland is estimated to have increased by 10% in 50 years compared to 1961-1990. At the end of the century, precipitation is probably reduced in southern Scandinavia (most clearly in summer) but probably about 30% higher in the north, especially in winter but also in spring and autumn. Wind is estimated to increase by around 5%, especially in winter, but some simulations predict no particular wind changes (Rummukainen et al., 2006, Parkpoom et al., 2004).

2 Physical impact of climate change on the energy system

The energy system is influenced by climate changes. More precipitation enables increased hydropower generation. There will be more wind and better conditions for biofuel production. Higher temperatures reduce the energy demand for heating, reduce the efficiency of thermal power plants and reduce the capacity of transmissions lines. In this section, possible impacts are described.

2.1 Changes in average climate properties vs. changes in extremes

Climate change can influence the average climate properties, such as temperature, wind, insolation and precipitation. Changes in average values are likely to have moderate impact on the electricity system. As described below increased temperature will result in higher electricity demand for air-conditioning and lower demand for heating in winter. Power generation will be marginally less efficient. But e.g. a 4^oC higher temperature will not have extreme impact on demand or system stability.

If climate change influences the frequency and severity of extreme weather events, the impact can be much more severe. Extreme weather events include droughts, floods and associated landslides, storms, cyclones and tornadoes, ocean and coastal surges, heat waves and cold snaps.

Long periods of droughts are a serious threat to hydro-dominated electricity systems, like the current Nordic electricity system. Short periods of reduced precipitation can be levelled out by the hydro reservoirs. The critical period is in spring when reservoir levels are low. A very cold spring may result in low water flow to the reservoirs because the snow sheet is maintained on the mountains. Extreme rain in the fall can lead to overflow of hydro dams without generation of power. Skaugen, Astrup et al. (2002) have studied precipitation in the period 2030-2049 with focus on extreme rainfall. Although the results are uncertain a tendency to an increase in extreme rainfalls has been found. Timing of the precipitation can also be critical if e.g. the precipitation falls as snow in the late fall instead of rain earlier, then the dams will not be filled up until springtime thaw.

High wind speeds, such as the December 3, 1999 storm in Denmark or the January 8-9, 2005 *Gudrun* storms in southern Sweden, can be damaging to the distribution system. For example, falling trees can tear down distribution lines. If maximum wind speed is increasing, more trees will fall, which may result in serious consequences with long periods of outages. Larger investments in distribution systems (e.g. underground cables) are needed if the distribution system must be more robust against storms.

The Swedish *Gudrun* storm in 2005 destroyed more than 20 000 kilometres of electricity grid lines and more than half a million households suffered from power outages. For one-half of the affected consumers, the outage was less than 24 hours but more than 50 000 lacked electricity for more than a week and 12 000 thereof for three weeks or more. The storm affected a larger area than most storms. The highest mean wind speed attained hurricane force (33 m/s) but maximum velocities in gusts reached 42 m/s. Old and new electricity grid lines were affected. Fallen trees broke cables and damaged isolation and poles fell or got broken. Local grids were primarily concerned but also some regional grids with narrow or insufficiently cleared areas around the lines in the forest. The grid owners experienced a total cost of more than 200 000 euros, mainly for clearing and reconstruction (SEA, 2005c).

For wind power, high wind speeds can result in sudden emergency stops of the generators. Typically, windmills are designed to be operated at wind speeds until 25 m/s. If this limit is exceeded, the windmills are stalled and stop producing electricity. In a system with much wind power this can be problematic, since it is difficult to predict wind speeds. When expecting full production from windmills, the result can be zero if the wind speed is higher than predicted.

In inland thermal production systems, as in central Europe, combinations of high temperatures and little water in the rivers can limit the power production (because of environmental concern, the rivers cannot be used fully for cooling for the power plants). This can be critical since the electricity demand can be high due to air-conditioning in such periods. In 2003, France and central European countries experienced such an event. Long distance transmission of electricity may alleviate such situations.

2.2 Direct Impact on Demand

Higher temperatures could lead to reduced energy demand for heating in winters and less seasonal variations of space heating demand, but could also increase the amount of energy used for air-conditioning during summers.

A simple calculation is carried out of the impact of a general 4°C increase in temperature (see appendix). Such a temperature increase could be the impact of climate change in year 2100. It would result in a reduction of the energy needed for heating by one-third. The increased need for air-conditioning would be in the order of 1/30 of the reduced need for electricity for heating. Note that these values are measured in degree-days, which indicate the physical needs for heating and cooling.

Skaugen and Tveito (2002) indicate a 10-20% reduction in heating degree-days in Norway in the period 2021-2050 due to climate change. For the same period, Venäläinen et al (2004) indicate a 10% reduction of heating degree-days for Finland. Forsius et al (1996) have also estimated the climate change impact on the electricity demand for heating in Finland. They find an 8% reduction in 2025 and 25% reduction in 2100.

In a 100 years perspective, such changes in energy used for heating are relatively small. Building codes for new buildings are expected to lead to a greater reduction. The temperature increase would also increase the electricity use for air-conditioning. The current level of air-conditioning is low in the Nordic countries and the increase in air-conditioning due to economic growth and demand for higher comfort is expected to be much larger than the increase due to climate. This development will lead to higher energy use in summertime and lower consumption in wintertime.

Sailor and Pavlova (2003) have analysed the saturation of air-conditioners in the US and find a less than 20% saturation in cities with less than 100 cooling degree days, 50% saturation in cities with 300 cooling degree days, and 80% saturation in cities with 700 cooling degree days. With 10 millions houses in the Nordic area, a 20% saturation with air-conditioners (with a typical system impact of 1 kW per unit on a hot day) would increase the Nordic summer demand with 2 000 MW. Today the Nordic peak demand in winter is about 60 000 MW and in summer 35 000 MW, so with an additional 2 000 MW summer demand, the Nordic area would still be a winter-peaking area.

2.3 Impact on Energy Supply

Concerning electricity generation, climate change primarily influences hydroelectric power production. More precipitation means that water supplies increase. More evaporation during summer due to warmer climate has a weaker influence. The mean annual Swedish water runoff is calculated to increase by 5 – 20% until 2100. The largest increase in runoff will take place in northern Scandinavia, especially in the north-western Swedish mountains where up to a 40% increase until 2100 has been calculated. The amount of snow in Finland will be reduced by one-half until 2050 and the duration of snow cover will be shortened by two months. Spring floods will be decreased but autumn and winter runoff will be larger. In the south, water supplies will decrease, especially during summer, whereas winter runoff will increase (Andréasson et al., 2004, Venäläinen et al., 2004).

Scandinavian and Icelandic glaciers and ice caps will essentially disappear during the next 200 years due to higher temperatures. Initially, the melting increases glacier runoff substantially (up to 50%) but later runoff becomes smaller again because the ice caps shrink (Jóhannesson et al, 2004). Hydropower production may increase more than runoff because water spill at hydropower plants during spring can be smaller when the snowmelt is more intermittent. Finnish hydropower production will increase by 10% until 2050 (Venäläinen et al., 2004).

The mean wind speed will be increased by climate change and the probability that the wind speed exceeds 10 m/s will become more than ten times as high toward the end of the century. Until 2050, the potential for wind power production can increase with up to 10% in Finland, especially in the Baltic Sea and during winter (Clausen et al., 2004, Venäläinen et al., 2004).

Increased rainfall due to climate change stimulates forest growth and makes Finnish wood fuel supplies up to 15% larger in 2050 (Venäläinen et al., 2004). Elevated temperatures increase coniferous wood production, especially in Sweden and Finland, because the growing season starts earlier but in Denmark the higher temperature causes water deficit. Higher CO_2 concentrations increase wood production because they stimulate the photosynthesis (Bergh et al., 2003). Peat production can increase by 20% until 2050 in Finland because the temperature rise increases evaporation, which promotes peat production (Venäläinen et al., 2004).

2.4 Impact on Transmission

The capacities of overhead transmission lines are influenced by outdoor temperature. Transmission lines have a security distance to the ground and when the power flow increases in a line it is heated. The combination of heating from power flow and the cooling from ambient air determines the temperature of the lines and the security distance to the ground. Increasing outdoor temperatures decreases the effective capacity of the lines. The impact of this can be severe if it is coincident with peak load or periods with large transport of electricity.

As mentioned in section 2.1, transmission and distribution lines are vulnerable to storms. Falling trees can break the lines or the poles can break. Extreme weather, like storms, can reduce the security of supply and may demand investments in new line capacity.

3 Climate policy – applied instruments

A central goal of current energy policy is to reduce CO_2-emissions. A 50% reduction of CO_2-emissions has been mentioned as a long-term goal. Such a goal can only be realized with a total change in the energy system – regarding energy demand as well as energy supply. The future energy system can take many forms. Coal-fired power plants can be expected to be phased out and wind power can be expected to be expanded. The use of efficient CHP production and renewable biofuel should increase. Potentials for additional hydropower capacity exist, but are limited. Sweden has decided to phase out its nuclear power, while Finland is building a new nuclear power plant. However, Swedish nuclear capacity is currently increased through reconstruction of the ten reactors still in operation and the total capacity will even be larger than before the shutdown of the *Barsebäck* nuclear plant.

Policy instruments influence the development of energy supply. Increased international energy trade influences the effectiveness of environmental policy instruments (cf. Rydén, 2003). Policy instruments can increase energy-carrier prices, which restrains the demand for primary energy supply and promotes energy efficiency enhancements that can maintain the benefit of energy use. Policy instruments should make actors, such as companies and households, choose the solutions that are most beneficial for the whole of society. There are basically five kinds of monetary policy instruments that are linked to amounts of energy: taxes, fees, feed-in tariffs, certificates and allowances. The two latter kinds are market-based policy instruments, which can be traded.

Taxes on energy carriers should ideally reflect the external cost that is caused by the use of an energy carrier (Carlson, 2002). There are minimum taxes on oil and electricity in the European Union (EU). In Sweden, there are energy, carbon-dioxide and sulphur taxes on fuels. There is also a tax on electricity consumption. Therefore, there is no tax on fuels that produce electricity. To promote CHP production and to support industry, fuels that are used for heat production in a CHP plant or for an industry have no energy tax and lower CO_2 tax. The sulphur tax is on oil, coal and peat and is independent of how the fuel is used. In Denmark, energy taxes have been used for years to promote energy efficiency and other energy policy goals. For a household, the current electricity tax is 0.09 €/kWh. For companies, the tax is lower (e.g. 0.015 €/kWh for small companies) (Danish Energy Regulatory Authority, 2006).

Taxes collect money for the government but fees may only mean a redistribution of money among actors. In Sweden, there is a fee on nitrogen oxide emissions. Owners of nitrogen-oxide-emitting plants pay for their emissions but get money back according to the annual plant output. For a plant with low emissions but large production, the transactions total to a revenue for the owner, whereas plants with high emissions in relation to their yields experience a net cost.

To promote more sustainable power supply, there are feed-in tariffs (e.g. in France) or *green* certificates (e.g. in Sweden) for renewable electricity in many EU countries. With feed-in tariffs, a transmission system operator must feed in all renewable electricity at either a fixed tariff or a fixed bonus, which is added to the market price that the producer is paid. The tariff may differ among the included generation sources, e.g. wind and hydropower. With an electricity market, the financial burden of paying the tariff should be equal for all grid operators. In Germany, operators with a share of renewable electricity that is below the national average, have to buy *green* electricity from the other operators (Ringel, 2006). The German feed-in tariffs have, for example, contributed to an expansion of solar cells. In Denmark, favourable tariffs have been used to promote both district heating and wind power. These tariffs have recently been revised and the future expansion of (on-shore) wind power and combined heat and power (CHP) production is uncertain.

Some countries that previously had feed-in tariffs have now introduced green certificates instead. With such a system, a governmental body normally gives producers a green certificate for every MWh of generated renewable electricity. Electricity consumers or distributors are obliged to buy certificates that correspond to a certain quota of their consumed or distributed electricity, respectively. The obligation creates a demand and market for the certificates, and a producer can sell his certificates and obtain an additional revenue besides the market price of the electricity itself. Some renewable electricity generation may be exempted from the system, e.g. large hydropower plants (Ringel, 2006).

The European Union must reduce its greenhouse-gas emissions with 8% until 2010 compared to the 1990 level, according to the obligations in the international Kyoto protocol on reduction of greenhouse-gas emissions. Since the beginning of 2005, there are emission allowances for carbon dioxide in the EU as a means to reach this goal. Companies that emit large amounts of CO_2 must have an emission allowance for every tonne of CO_2 that is emitted. The emission allowance system comprises combustion plants larger than 20 MW or smaller plants connected to a district-heating system larger than 20 MW, refineries and industries that produce coke, iron, steel, glass, glass fibre, cement, ceramics, pulp, paper and cardboard. The system comprises nearly one-half of the CO_2 emissions in the EU but just one-third of Swedish emissions (SEA, 2004). Energy suppliers and industry have become allowances primarily according to their previous emissions. Companies with more allowances than required can sell them, and a company that wants to emit more CO_2 than it has allowances for has to buy additional allowances. The allowance price is decided by supply and demand in the allowance market and has become much higher than predicted before the system was introduced. Measures to reduce emissions are ideally taken if they cost less than buying allowances. Companies where emission reductions are expensive can buy allowances from companies where it is cheaper to reduce emissions.

The emission allowances have raised the cost for electricity generation in fossil-fuel-fired power plants and increased the electricity price in continental Europe and in Nordic countries, which has made relations between power production and electricity consumption in different countries more obvious (cf. SEA, 2005b). There is a certain amount of emission allowances in the EU and the total emissions from the companies that are included in the allowance system should, presupposed that the system works as intended, end up at the level that corresponds to the total amount of allowances. However, the CO_2 emissions from these lines of business cannot be lower than the level that the amount of allowances prescribes if there is not a surplus of allowances. Measures that reduce electricity consumption in Nordic countries (except Iceland) reduce the operation and CO_2 emissions from coal-fired condensing power plants but not really the total CO_2 emission under the present emission trading regime. But CO_2 emissions have to be reduced and increased renewable electricity generation and measures that reduce electricity and fossil-fuel consumption can contribute to the required reduction of CO_2 emissions within the EU. Such measures can often be more cost-effective solutions than building natural-gas-fired condensing power plants, which is the way to reduce CO_2 emissions that seems to be closest at hand for continental power producers. The emission allowances increase fossil-fuel costs and promote, therefore, biofuels and efficient CHP production and make condensing power production less beneficial.

The Kyoto protocol includes the two flexible mechanisms joint implementation and clean development mechanism, which means that if a country takes measures that reduce greenhouse gas emissions abroad, the emission reduction can be included in the country’s (or EU’s) reduction of greenhouse gases.

The current EU emission trading period ends at the end of 2007. For the next period 2008-2012, new allowances will be allocated, which should ascertain that EU reaches the 8% reduction goal. However, the Kyoto obligations are only a first step toward a CO_2 concentration level in the atmosphere that is not harmful for climate and mankind. For the period after 2012, there are no binding agreements concerning greenhouse gas emissions neither on European nor on a global level. In the future, an emission trading system may include other greenhouse gases than CO_2, such as methane, additional lines of business, such as transport, and more countries, possibly the whole world. Norway may, for instance, enter the EU emission trading system.

With a CO_2 tax, the cost of emitting CO_2 is known but not the resulting total CO_2 emissions. With emission allowances, on the contrary, the total CO_2 emissions are prescribed but the price of the emission allowances is not known beforehand. In a similar manner, subsidies can be compared to certificates. Economic support to the building or operation of renewable power plants means a known cost but unknown outcome concerning the amount of produced renewable electricity. Electricity certificates, on the other hand, require a certain total amount of renewable electricity generation but the certificate price depends on the market.

But policy instruments need not be monetary. In Denmark, utilities for electricity and natural gas are working actively with demand side management (DSM) to promote energy efficiency. The arrangement with mandatory DSM activities will probably be expanded in 2006 to cover district heating. Governmental requirements concerning energy supply and use for new and modified buildings, industries and products could be introduced. For example, new Danish building codes came into force in 2006 with strict requirements concerning the overall energy demand in new houses.

Iceland has large energy resources in the form of geothermal energy and hydropower. Only a small fraction of the potential is used today (www.os.is). If energy prices increase and CO_2 policies are strengthened in other countries, more energy intensive industries may be established in Iceland. Two-thirds of the current electricity is used in industry, e.g. in aluminium plants.

4 Review of long term studies of energy supply and use

Today the electricity flow in the network is mostly one-way from central power plant to consumers. Several studies predict radical changes in the future with power and information flowing in many directions, e.g.: “Every node in the power network of the future will be awake, responsive, adaptive, price-smart, eco-sensitive, real-time, flexible … and interconnected with everything else” (Wired Magazine, 2001, Economist, 2004). This is a possible ingredient in the future energy system.

Many analysts have tried to grasp the development of energy supply and use in various scenarios. The future will not look like in any one scenario but scenarios can provide valuable guidance concerning favourable or undesired development paths for the energy system. Here, some long-term studies with foci ranging from global to national level are reviewed. But first, a quick look back at a study made 50 years ago. Ljungdahl (1951) showed the difficulties in making Sweden less dependent on imported fuels. He noticed that a more rational utilisation of energy sources would require continuous research and extensive technical-development efforts with long-term aims. He thought, for example, that the national benefit of combining district-heating distribution and power production must be evaluated., At that time, nuclear power did not seem to become of crucial importance for Swedish power supply. Twenty years later, the first large Swedish nuclear reactor was put into operation. Twenty years may be regarded as a fairly foreseeable time frame. This should be kept in mind by the reading of this report and reviewed studies that aim at an even more distant future.

4.1 European SmartGrids

The European Commission (2006) has initiated a so-called technology platform for electricity networks of the future. This includes a vision for the European electricity grid of 2020 and onward. In the vision, it is pointed out that the most distinguishing feature of the future grid will be the ability for the users to play an active role in the supply chain. Both the information and electricity network will be of Internet-style. Each element can communicate at low cost with all other elements by broadband and power is traded in a European-wide market.

Balancing electricity network is done in real-time and e.g. the Nordic hydropower supplies balancing power to most of Europe. It is stressed that European-wide solutions for balancing power are more efficient than national ones. Long distance transport of electricity is supported by superconducting HVDC cables (high voltage direct current). Wide area monitoring systems (WAMS) and Wide area protecting systems (WAPS) are used to improve the security of supply. Advanced power electronics allow variable speed operation of generators and motors leading to increased energy efficiency.

4.2 International Energy Agency

The International Energy Agency developed energy scenarios until 2050 which, among other alternatives, included that increasing demand for scarce fossil resources (primarily oil) provokes price spikes and geopolitical security risks (IEA, 2003). Increasing gas demand may raise gas prices. The economic development in developing countries continues. Energy demands, and average incomes, become more similar to developed countries.

The report then outlines a desirable vision of sustainable development and argues that it is possible to achieve secure energy supply, climate change mitigation and access to energy services for all, if appropriate policies are applied while sustained economic growth is maintained. Electricity should, as an example, be supplied to 95% of world population. Sources that do not emit carbon increase but natural gas can be a transition fuel to a low carbon world (IEA, 2003).

Significant changes in fuel mix are necessary but have been made before, for instance by nuclear capacity expansion. Many technologies needed are already available or at the stage of development but other should emerge rapidly. Development of new technologies, which are environmentally benign from a comprehensive viewpoint, must be promoted through research expenditures, market incentives, price signals and international collaboration. Critical supply technologies include combined heat and power (CHP) production, photovoltaics, hydrogen production and cleaner coal technologies, such as carbon capture and storage. Among robust demand-side actions, there are energy efficiency improvements (e.g. more efficient appliances) use of information and communication technologies (ICT) to optimise performance, passive heating and cooling building architectures, as well as manufacturing and services requiring little energy and materials (IEA, 2003).

In the World Energy Outlook 2004, IEA (2004) predicts that the global energy demand will be 60% higher in 2030 than today and the CO_2 emissions will increase even more. Two-thirds of the increase in global energy demand is expected to come from developing countries. The report express concern about the energy security as the energy supply will depend heavily on infrastructure like ships, ports and refineries. These installations are vulnerable to terror attacks. The average oil price is expected to be around US$ 25 per barrel for the whole period (can be compared with the current price of US$ 70, Fig. 4.1).

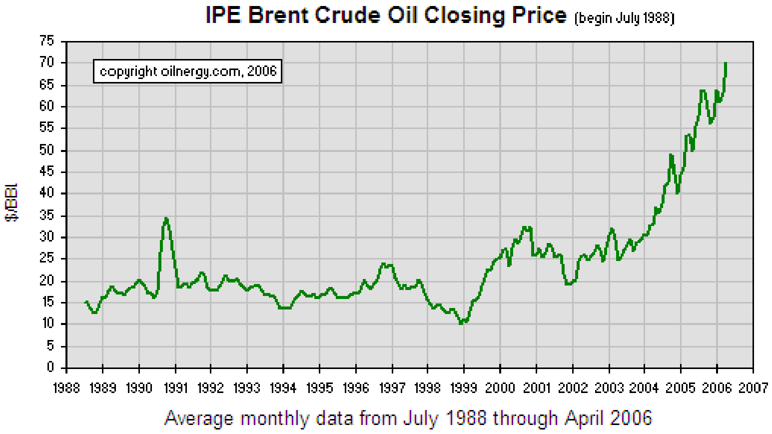


Figure 4.1. Development in oil prices since 1988 (www.oilnergy.com, 2006-05-08)

In an alternative policy scenario, the IEA studies an energy efficient and more environment-friendly future. In this scenario, the global primary energy demand is reduced by 10% compared to today. Global CO_2 emissions are reduced by 16%. As a regional example, it is mentioned that the electricity prices in Europe will increase by 12% compared to the reference scenario.

In the World Energy Outlook 2005, IEA (2005) estimates the global annual growth in CO_2 emissions to be 1.6% from 2003 to 2030. In Europe, the growth will be less: 0.4% p.a. (per annum).

4.3 European Commission (2003): European energy and transport trends to 2030

In 2003, the EU Commission published a baseline projection of electricity demand and production until year 2030. In table 4.1 some key findings are presented. The growth from year 2000 to 2030 is expected to be between 28 and 42% for the four Nordic countries included in the study. Sweden is expected to have phased out its nuclear power and to have substituted it by thermal power production (incl. biomass). The annual growth in consumption is between 1 and 2% p.a.

TWh	2000				2030			
	Nuclear	Hydro and wind	Thermal (incl. biomass)	Total	Nuclear	Hydro and wind	Thermal (incl. biomass)	Total
Denmark	0	5	32	36	0	14	36	51 (+42%)
Finland	22	14	33	70	34	16	48	98 (+40%)
Sweden	57	79	9	146	0	79	107	187 (+28%)
Norway	0	142	1	142	0	165	21	186 (+31%)
EU-15	863	343	1 366	2 574	745	642	2 458	3 846 (+49%)

Table 4.1. Projected electricity generation, year 2000 and 2030 (European Commission, 2003)

4.4 Energy in 2050: Three Swedish studies

On request from the governmental Swedish climate delegation, Azar and Lindgren (1998) calculated possible Swedish energy supply and use that reduce CO_2 emissions with 50-75% by 2050. Industrial manufacturing and the demand for heating (larger apartments) and electricity-specific services have increased. More efficient energy utilisation reduces the need for energy supply for a certain purpose with 40%. Depending on the desire for enhanced services, primary energy demand is maintained or increased.

Biofuel dominates energy supply but is within what nature can withstand. It is used for heating, industrial processes and cogeneration (e.g. black liquor gasification). Fossil fuel combustion is drastically reduced. Hydropower capacity is maintained but nuclear power is phased-out. Wind power generation is much larger than today. Solar heating and solar cells make minor contributions. To reduce CO_2 emissions substantially by high demand for energy services, fossil vehicle fuel must be replaced by renewable energy (e.g. methanol) and hydrogen derived through solar energy in more solar-rich countries is bought in the international hydrogen gas market and used for transportation and cogeneration (Azar and Lindgren, 1998).

A working group within the Royal Swedish academy of engineering sciences outlined energy supply and use in Europe and Sweden in 2050 (IVA, 2003). The European economy is growing and increases the inhabitants' material standard of living. More equipment is made smaller and mobile, which requires energy efficient technology. Light emitting diode (LED) lighting and energy lean electronics reduce electricity demand, which reduces the need for cooling. Higher comfort requirements increase the demand for air conditioning and appropriate indoor temperature but isolation, control systems and smart windows reduce energy demand in buildings. There is a potential of large energy conservation in the manufacturing industry. Pulp and paper mills can make better use of the wood and supply electricity and heat to other consumers.

Natural gas is the dominant energy carrier in Europe but later hydrogen will have a central role. The hydrogen may be produced through electrolysis with renewable electricity. Electricity becomes an even more important energy carrier. Electricity is generated in fuel cells, solar cells, wind and wave power plants and with bioenergy and, possibly, fusion. CO_2 free electricity is generated with natural gas and coal through CO_2 capture and storage. IT enables cooperation in the grid among small and large electricity suppliers and consumers. Swedish energy use remains at current level with economic growth and increased material standard of living due to more efficient energy utilisation (IVA, 2003).

The Swedish branch of the large European energy company E.ON made five scenarios for the energy system in 2050 focusing on Sweden (Eon, 2006). Common features for the scenarios include that global energy use increases considerably due to the economic growth in Asia. Fossil fuels dominate global energy supply. It is unlikely that global emissions of greenhouse gases have decreased radically. In Sweden, existing large hydroelectric power plants are still in operation but current nuclear power plants are shut down. Oil use is drastically reduced and district heating has expanded. In most scenarios, the Swedish natural gas consumption increases whereas electricity demand and total energy use decrease.

4.5 Electricity sector framework for the future

EPRI (2003) contains a broad work on future possibilities for the electricity sector. The project is developed in dialogue with a large number of stakeholders.

As a part of the study, innovations in new technology are described. Six key points are highlighted:
- Electronic control of the transmission and distribution network: It is anticipated that the existing, relatively slow electro-mechanical switches will be replaced by power electronic equipment. This new technology can react in real-time, and can be the backbone of a “smart, self-healing power delivery system”. Self-healing starts with intensive monitoring of the system (e.g. a large number of electric flows and temperatures in transformers and cables), real-time automated calculation of power flows and of a worst case scenario and optimal corrections. FACTS (Flexible AC Transmission System) controllers can react in real-time to disturbances and redirect power flow as needed. WAMS systems (Wide Area Measurements System) can be used to predict system instabilities that cannot be detected locally.
- Strengthened information infrastructure to support interactive real-time transactions. The information infrastructure is needed to activate the retail energy markets for delivering demand response and to ensure the needed quality of supply (witch may differ from end-user to end-user).
- Develop a consumer gateway to allow prices, communication and decisions to flow to and from households. It is stressed that the social benefit of an efficient energy use will outweigh the cost of the portal technology. This includes advanced metering allowing for real-time pricing.
- Increased energy efficiency in all sectors through use of advanced communication and control systems.
- Fully integrate distributed energy resources, like fuel cells, wind power and even electric or hybrid automobiles.
- Ensure fuel diversity through technology development, including coal, nuclear and renewables.

4.6 Grid 2030

The US Department of Energy (DOE, 2003) has published “a national vision for electricity’s second 100 years”. In addition to many of the issues described above, the report emphasizes promising technologies like conductors made from composite materials, high temperature superconducting cables and advanced electric storage (superconducting flow batteries or flywheels). Superconducting materials will make it possible to transport electricity over longer distances and with less energy losses and voltage drop. Superconducting materials can also be used in generators, as storage, and in condensers and motors – all equipment that is widespread in the entire energy sector.

Part of the long term vision is described as: “Grid 2030 is a fully automated power delivery network that monitors and controls every customer and node, ensuring a two-way flow of electricity and information between the power plant and the appliance, and all points in between. Its distributed intelligence, coupled with broadband communications and automated control systems, enables real-time market transactions and seamless interfaces among people, buildings, industrial plants, generation facilities, and the electric network.”

A special technology called *the grid-friendly appliance controller* is described. Pacific Northwest Laboratory has developed a prototype of a chip that monitors line frequency and is able to disconnect appliances within fractions of a second if the frequency is too low. The device can be used in refrigerators, freezers, air-conditioners, water heaters and many other appliances that can be disconnected for minutes without disturbing the consumer comfort. This can be used as disturbances reserves and free power generation otherwise reserved for this purpose (see also gridwise.pnl.gov).

The analysis includes a road map for the development of new technologies. Examples of milestones are shown in table 4.2. Although our focus is on an even longer perspective (2050-2100) it can be interesting to see the evaluation of the time needed to deploy new technologies.

	Transmission	Distribution	Demand Side Management
2010	- 100 kilometres of superconducting cables deployed	- Distributed intelligence feasibility proven - Remote outage detection in place - Plug & play protocols for distributed generation and demand response - Architecture defined for intelligent automated systems	- Demand-side management programs more widely used - Smart appliance feasibility proven - Greater use of customer side DG/CHP
2020	- Half the power flows over smart grid - Long distance superconducting cables installed - Average grid losses reduced by 50%	- Real-time, two-way flow of information and power	- All appliances have smart capabilities
2030	- Superconducting backbone installed with fault limiters and transformers - 100% of power flows through smart grid	- Low-cost, small-scale storage - Superconducting cables and equipment deployed	- Low-cost, small-scale storage - Superconducting cables and equipment deployed

Table 4.2. Examples of milestones for the development of new technologies

4.7 Other

The World Energy Council outlines some scenarios for 2050[1]. There is global economic growth and energy is used more efficiently but global primary energy demand increases. In developing countries, primary energy supply becomes 3-5 times as large. Fossil fuel supply decreases but is still 50-75% of primary energy and the rest is mainly renewable energy and some nuclear power. In most cases, carbon emissions are larger than in 1990. Non-fossil technologies emerge at moderate cost and biomass and solar energy are expanding.

Karlsson et al (1995) studied Swedish power supply until 2020 at the request of the governmental energy commission. If nuclear power is phased-out, wind power and biomass-fired cogeneration should expand to keep CO_2 emissions low. Energy conservation reduces electricity demand in industries and service premises. Electric heating is switched to biofuel.

Elforsk (2006) has conducted a study that illustrates the development of electricity use for various societal sectors in the Nordic countries during the next ten years. The analysts conclude that restructuring has stabilized the level of industrial electricity use. The households’ electricity consumption will probably hardly increase because new appliances use less electricity and the total future electricity consumption for domestic space heating will decrease.

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[1] Global energy scenarios to 2050 and beyond, www.worldenergy.org 060321

In the Nordleden project, the development of Nordic energy supply was analysed by Swedish and Norwegian experts (Rydén, 2003). They found that wind power expands substantially, especially if it is promoted by governmental policy. Expansion of the natural gas grid in the Nordic countries can be beneficial if the gas price is low. The gas would be used for industrial processes and could increase the electricity generation through cogeneration in district heating systems.

Similar considerations can be found in:
- Electricity technology roadmap – Technology for the sustainable society, 2025 (KEMA, 2002). This report has emphasis on environmental issues.
- Towards Smart Power Networks (European Commission, 2005a)
- Electricity technology roadmap, powering progress (EPRI, 2001)
- Energy End-Use Technologies for the 21st Century (World Energy Council, 2004)

4.8 Concluding discussion

The reviewed studies consider various issues in the energy system. Some studies try to give a comprehensive view of energy supply and use, whereas other focus the improvements of technological components. Certain reports outline a development that is more or less business as usual without great leaps or changes in direction, but other studies describe a more different energy system, which in the extreme has undergone a revolution. Table 4.3 is an attempt to assign properties concerning perspective and development to the main reviewed studies. The more comprehensive studies do not necessarily have a wide geographic scope. The positions of the studies in the quadrants are our estimates.

Perspective: Development:	Components	System
Business as usual	Grid 2030	EU 2003 WEC 2050 Eon 2006 IVA 2003 IEA 2004
Revolution	EU 2006 EPRI 2003	IEA 2003 Azar & Lindgren 1998

Table 4.3. Features of reviewed studies

There are many differences among the system studies but also many similar viewpoints. IEA (2004) and Eon (2006) foresee substantially increased global energy demand. IEA (2003) predict higher energy prices, which may promote transformation of the energy system to more environmentally benign energy supply, such as CHP plants and solar cells. New electricity generation technologies should emerge also according to IVA (2003). Azar and Lindgren (1998) consider it possible that utilization of renewable energy sources largely can replace fossil fuels. Eon (2006) foresees a restrained Nordic electricity consumption and expansion of district heating. IEA (2003) and IVA (2003) emphasize more efficient energy use, such as waste heat utilization. Azar and Lindgren (1998) find that primary energy demand need not increase. These kinds of issues are discussed in the next chapter.

5 Important issues for the development of the Nordic energy system

The following issues are likely to influence energy supply and use in the Nordic countries significantly during the next 50 years. We consider it probable that the mentioned issues follow the outlined trends but this is naturally uncertain. The development of the energy system is shaped by a complex interplay among technologies, actors and institutions in a technical, economic and social context, which is impossible to foresee even with a shorter time horizon. Most mentioned trends concern the world and Europe as well as the Nordic countries but the tendencies can be weaker or stronger in various regions of the world.

5.1 Global energy demand increases

Three-fourths of global commercial primary energy supply now comes from fossil fuels but one-third of the world population has no access to commercial energy[2]. Global energy demand is likely to increase due to industrialisation and enhanced standard of living in currently less developed countries (IEA, 2004, Eon, 2006). As a minor example, the demand for indoor climatisation through cooling is increased due to higher comfort requirements. The demand increase makes prices for all energy-carriers increase (IEA, 2003), including coal and the limited biofuel supplies. More expensive energy carriers make new technologies, renewable energy utilisation and energy conservation more profitable (cf. IEA, 2003).

5.2 Fossil fuel use

Fossil fuels are finite resources but the reserves are huge (www.worldenergy.org). Especially, the reserves for coal are large. However, a considerable part of the oil reserves are situated in The Middle East, which is a region with several conflicts. The use of fossil fuel may decrease (e.g. for transportation), but if this happens it is likely because of economic, strategic or environmental issues (cf. Azar and Lindgren, 1998). The large Nordic renewable energy resources can speed up the process of phasing out fossil fuels here, whereas this process may take longer time in less favoured regions of the world. The costs for all fossil fuels may be higher due to increased scarcity and applied policy instruments. Harmful climate-change consequences may emphasise the use of policy instruments, such as taxes and emission allowances (Sect. 3).

Today, EU imports 50% of the needed energy. This may increase to 70% in 2030. The high share of imported energy is seen as a strategic challenge for the European countries (European Commission, 2003). Fossil-fuel prices are volatile and unpredictable (Sect. 4.2, 7) and the market is dominated by a few large companies.

A global issue concerning fossil fuel that is under debate is *peak oil*, the occasion when annual oil production reaches its highest level and after which oil production will decline. Peak oil may be reached before 2020 but it is very uncertain how large proven and probable oil reserves are and then they would be depleted at current extraction rate. Deceased oil production and decreasing supplies will probably raise oil prices drastically, which restrains oil demand (Hoffman, 2005).

Fossil fuels will be concentrated to applications where they are advantageous compared to other energy carriers, like in cars in the short run. Oil will, as an example, soon hardly be used at all for space heating in Sweden but natural gas may expand considerably and can, for example, replace electricity for heating and drying in industrial processes (Elforsk, 2006). A disputable issue is whether an expanded natural-gas network delays the evolution of a more sustainable energy system or if natural gas is an advantageous transition fuel (IEA, 2003) that, for example, enables combined heat and power (CHP) production with a high ratio of electricity output. Through carbon dioxide capture at power plants and storage in oceans or geological formations, fossil fuels could possibly be used without climate degradation (Sect. 6.2, IPCC, 2005).

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[2] World energy council, www.worldenergy.org

5.3 Utilisation of renewable energy sources increases

Utilisation of renewable energy sources increases, primarily in the forms of biofuel, wind power and solar energy, for which technologies already are more or less commercial (cf. Azar and Lindgren, 1998, IEA, 2003). Green certificates and feed-in tariffs (Sect. 3), which promote renewable electricity, may become more widespread as global warming turn out to be more severe. There may be competition concerning the use of fertile soil for production of food, biofuels, timber or raw material for paper manufacturing.

Various biofuels may be used in cars, e.g. biogas and ethanol. Biogas can be derived from various organic materials through different processes and may be fed into natural-gas grids. Waste incineration first increases but is then maintained because it is restrained by reduced waste quantities, enhanced recycling and increased use of other waste treatment methods. Waste is used more as fuel in CHP plants and less for separate heat production because it becomes more important to utilize district heating systems for electricity generation for economic as well as environmental reasons.

Hydrogen is often mentioned as a vital pat of a future energy system. It must be stressed that hydrogen is not an energy source but an energy carrier. Hydrogen can be derived through gasification of biomass or by electrolysis driven by renewable electricity. Hydrogen may be used as fuel for e.g. vehicles and where it is advantageous to electricity because it can be stored (cf. Azar and Lindgren, 1998, IVA, 2003)

To enhance security of energy supply, a diversity of local, domestic and imported energy carriers can be used in a variety of conversion and distribution technologies. Increased use of renewable energy sources, which mostly are local, often increases supply security. Security of supply includes many issues, such as foreign trade, international political relations, threatening terror attacks, as well as the management and technological functioning of gas and electricity grids. Whereas the security of energy supply previously was primarily a national issue, it now belongs to the policy areas that the European Union desires to encompass.

5.4 Connection of energy systems

Nordic electricity generation possibilities are primarily limited by available water supplies for hydroelectric power production, whereas electricity generation in continental Europe primarily is restricted by the installed capacity of power plants. There is interplay between the Nordic and the continental power systems. The electricity grids in northern Europe are increasingly being connected and transmission capacities and energy flows between the systems increase. The Nordic energy-dimensioned power system is joined with the continental capacity-dimensioned power system. The linkages between national power grids level out electricity prices among countries and raise Nordic electricity prices to levels that are similar to continental Europe, which dampens electricity consumption (cf. Eon, 2006), especially for purposes where other energy carriers are rather easily applicable.

Current electricity transmission capacity between Nordic countries and with continental Europe and Russia is shown in table 5.1. For some connections, the capacity may be lower during shorter or longer periods. The total import capacity to the Nordic countries is 4 400 MW, whereas maximum 3 200 MW can be exported. In Denmark, there is a western (W) and an eastern (E) power grid, which will become interconnected by a 600 MW HVDC cable. Another addition to present connections is a 350 MW cable between Finland and Estonia, which will start functioning this year. A 700 MW DC cable between Norway and The Netherlands will commence operation in late 2007. Another transmission line with about 700 MW capacity will be built between Sweden and Finland and should be finished in 2010 (Nordel, 2005). A new connection between mid-Sweden and mid-Norway is planned for 2009.

From To	Denmark W	Denmark E	Norway	Sweden	Finland	Germany	Poland	Russia
Denmark W	-		1000	670		950		
Denmark E		-		1400		600		
Norway	1000		-	3300	100			50
Sweden	630	1800	3600	-	1800	600	600	
Finland			100	2200	-			1600
Germany	1350	600		600		-		
Poland				600			-	
Russia			50		0			-

Table 5.1. Transmission capacity (MW) between Nordic and neighbouring countries (Nordel, 2005)

There is interplay between power generation and electricity use in countries that have connected power grids. There is continuous electricity trade among most Nordic countries and between the Nordic countries and continental Europe. Changes in electricity generation or consumption in one country mostly influence power production in other countries. In the general case, there is a close interplay among electricity systems. Changes in demand or production in one area will spread to neighbouring areas[3].

Electric power flows in the network according to the balance in different parts of the system. Today, the flows are controlled by dispatching power generation at appropriate places in the system (e.g. by the Nord Pool spot market or by the Transmission System Operator, TSO, by ordering regulation power). When a transmission line is running full, power production must be adjusted, e.g. by increasing the production on the importing side of the line. In the future, FACTS (flexible alternating current transmission system) elements can be used to direct the flow of power in the network, which can be a key to improved utilisation of the network. Without FACTS elements, the power flows according to the resistance in the network and the flow must be controlled by dispatching electricity production in relevant parts of the network.

The power production that is now primarily influenced by the electricity trade among countries is coal-fired condensing plants because they are normally the committed units with the highest operation cost in northern Europe. They have low efficiency and cause large CO_2 emissions per unit of generated electricity compared to CHP plants. Reduced electricity consumption and increased power generation in other plants mostly reduce operation and CO_2 emissions from coal-fired condensing plants. In the future, natural-gas-fired combined cycles without heat recovery will increasingly play the role as such marginal electricity suppliers (SEA, 2002).

There is now basically a common deregulated electricity market in the European Union. The increasing electricity trade between countries is likely to level out electricity prices among the states. Nordic electricity consumers will therefore probably experience a substantially higher electricity price than they have been used to, which should make them reduce electricity consumption (cf. Eon, 2006). Continental price levels and price fluctuation patterns will be introduced in northern Europe as well. Due to the higher electricity price in continental Europe, electricity is there primarily used for purposes where other energy carriers are not possible and such consumption is largely linked to human activities, which primarily take place during daytime. Therefore, continental electricity demand variations are in the first place diurnal and price fluctuations follow the same pattern. In Nordic countries, hydropower storage has levelled out price differences due to demand variations between night and day.

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[3] Only if transmission capacity to a country is fully utilised for import, increased electricity demand or reduced electricity production in the country does not influence other countries, as the deficit must be covered by local resources. Also, if the transmission capacity from a country is fully used for export, reduced electricity demand or increased power generation in the country does not influence other countries.

The difference between continental and Nordic price fluctuations may be seen by comparing Nordpool spot market prices for the Kontek DC-link between Zealand and Germany with, for example, Swedish prices (www.nordpool.com/marketinfo/elspot).

Nordic seasonal electricity demand variations are to a large extent caused by the use of electricity for space heating, which probably will be reduced. Thus, the increased interconnection of Nordic and continental electric systems increases price difference between day and night but reduce price difference between summer and winter.

In most Nordic countries, per capita electricity consumption is much higher than the EU average (SEA, 2005a). The EU commission seems to have overlooked this fact in its forecast of future electricity generation (Sect. 4.3, European commission, 2003). Electricity use for manufacturing is often larger than in continental Europe because electricity has been cheap (Dag, 2000, Nord-Ågren, 2002). The European electricity market should increase Nordic electricity prices. Nordic industry will no longer have the comparative advantage of a low electricity price.

Increased interconnection of the electricity systems in northern Europe may also enhance the pressure on hydropower as regulating resource (cf. European commission, 2006). Hydroelectric power generation will primarily take place during the daytime of weekdays when continental electricity prices are high. Diurnal control of the power production will be utilised as far as possible with respect to allowed water level fluctuations. Measures that enhance diurnal scheduling possibilities, such as increasing generation and storage capacities, may become desirable (Nilsson, 2005).

District heating can become common in all Nordic countries (cf. Eon, 2006). Many district-heating systems will also probably be integrated with other district heating networks and with industrial steam systems. Energy flows between the connected systems increase. This enables enhanced utilisation of the heat from large plants for waste incineration or CHP production or industrial waste heat (cf. IVA, 2003). Cogeneration of electricity, district heating and industrial steam may be advantageous, especially if process industries with long annual utilisation times are involved (Danestig and Henning, 2004).

5.5 Energy demand increase

The level of total energy use and electricity consumption in 50 years is very uncertain. The total energy demand is increased by a higher level of activity in the society and reduced by higher efficiency of energy utilisation. The balance between activity and efficiency can be influenced by policy intervention that promotes or discourages different activities (see sections 3, 5.6 and 7).

Economic growth is a driver for increased energy use. When industrial production is increased, more energy is often used. New production methods may increase electricity consumption – sometimes increasing the overall productivity or energy efficiency.

As the population gets richer, larger houses are acquired and more equipment is bought, such as larger TV sets. New energy-demanding equipment is constantly brought to the market, e.g. computers, entertainment devices, etc. Young people’s lifestyles and a lower number of persons per household also increase the electricity consumption in households (Elforsk, 2006). New products make new functions and activities possible.

Economic growth also makes it possible to acquire services that otherwise would be too expensive. The use of air-conditioning can be such an example. The demand for indoor climatisation through cooling is increased due to higher outdoor temperatures and higher comfort requirements (IVA, 2003) but it could be discussed how sensitive man should be to his ambient climate.

Electricity consumption in commercial premises, such as shops and offices, for lighting and cooling etc. may increase also due to larger areas and longer working hours. Energy conservation may be difficult because several actors, such as owners, operators and users, are often involved (Elforsk, 2006).

A break-through in battery technology could rapidly increase the amount of electricity used for transportation. The hybrid cars are gaining grounds these years and this could be a first step toward fully electric cars. This could break the trend of increasing CO_2 emissions from transport. A massive use of electricity for transportation could result in a 10-25% increase in the total Nordic electricity consumption.

5.6 Decrease in energy demand

Generally, the demand for energy services may increase but at the same time energy is used more efficiently (cf. IVA, 2003, Eon, 2006). Depending on the balance between these two movements, the primary energy demand for Nordic industry, buildings and electric appliances is reduced or will still increase (cf. Azar and Lindgren, 1998). Energy demand can be decreased by energy conservation measures, which reduce the required primary energy supply. For instance, more energy-efficient equipment may be introduced (IEA, 2003). Energy-carrier switching reduces the use of one energy carrier (e.g. electricity) but increases the consumption of another energy carrier, such as biofuel. These measures should not reduce the comfort, benefit or utility of energy use.

Energy demand should preferably be covered with energy forms of lowest possible quality, which should be reflected by the prices of energy carriers. The general energy price increase due to enhanced global demand reduces primary energy use. Power grid integration can speed up a process where electricity (a high-quality energy carrier) is less and less used for low-temperature heating, e.g. direct electric heating. Nordic electricity consumption for district-heating production is likely to be reduced by one-half to 2 TWh a year during the next ten years (Elforsk, 2006).

Low energy buildings will become more frequent (cf. IEA, 2003, IVA, 2003). Better isolation and heat recovery can reduce the energy for space heating from 100-200 kWh/m^2 to less than 25 kWh/m^2. Climate change reduces the energy needed for space heating and decreases the seasonal variations of space heating demand (Skaugen and Tveito, 2002). This impact is much larger than the extra energy needed for air-conditioning. More energy-lean electronics reduce the need for office cooling (IVA, 2003).

In Sweden, extensive installations of heat pumps are taking place. They primarily replace electric heating and oil-fired boilers, which have become expensive due to energy-carrier prices and Swedish taxes. Heat pump installations and switching from electric heating to wood pellets or district heating reduce the total future electricity consumption for domestic space heating (Elforsk, 2006).

The per-capita electricity consumption in households has not increased for years in Denmark, Sweden and, possibly, Norway. The households' electricity consumption will probably hardly increase because new appliances use ever less electricity. This concerns old types of equipment that are common, such as refrigerators, as well as new kinds of devices that are becoming more frequent, such as DVD players, and totals to maintained electricity consumption despite the increased number of apparatus (Elforsk, 2006, cf. IVA, 2003).

Electricity consumption in premises used for non-commercial purposes (e.g. schools) may be reduced because it may be relatively easy to implement energy conservation measures in such buildings, which are mostly owned by large users with a long-term time horizon, such as municipalities. For similar reasons, electricity use for ventilation, lifts etc. in multi-family buildings should not need to increase substantially (Elforsk, 2006). Simultaneous cooling and heating of premises, which now sometimes unintentionally takes place, should soon be out of fashion when appropriate control schemes have been elaborated.

Very little electricity will be used for heat production but there may be some heat pumps and electric heating can be preferable in sparsely situated low energy houses. Fuels, district heating or solar energy have sufficient quality for heating and are used instead. Energy-carrier switching from electricity to district heating increases the heat sink for CHP production. Thus, the switching influences the electricity situation twofold, by lowering demand and enabling extended generation.

The switching from electricity to other energy carriers for space heating reduces the seasonal variations of electricity consumption. If electricity is predominantly used for purposes where other energy carriers are not possible (such as lighting, machine operation), the differences in electricity consumption between day and night as well as between weekdays and weekend are increased because such use is mostly linked to human activities including professional operations, such as manufacturing and teaching. On the other hand, globalisation make 24-hour operations of ICT equipment in the service sector more common, which slightly reduces the difference in electricity demand between day and night.

5.7 Everyday improvements and structural changes in industry

Energy demand is changed due to restructuring of manufacturing industry, expanding service business and changing behavioural habits at home and in other places. Nordic industry is used to low electricity prices and uses a lot of electricity and is therefore sensitive to the electricity price level (Elforsk, 2006). Electricity consumption should decrease because of higher electricity prices. It has been shown that Swedish small and medium-sized industries can reduce electricity use substantially (e.g. Trygg and Karlsson, 2004, Henning, 2005, Henning and Palm, 2006). This is probably the case also for other Nordic countries where the electricity price traditionally has been low, because electricity use and electricity price are correlated (Dag, 2000). Industrial electricity consumption will become more similar to continental Europe, where less electricity normally is used by manufacturing (Nord-Ågren, 2002).

Advanced communication and control systems can ensure that no operation is running without purpose, for instance, idling machines during non-working hours. Heat can be recovered for repeated utilisation in industrial processes and for heating. Municipal bodies and energy suppliers can help companies pay attention to energy conservation possibilities (Henning and Palm, 2006). Higher energy-carrier prices make it essential to avoid unnecessary energy use.

Future structural changes may mean that unqualified assembly work become rare in the Nordic countries, while manufacturing requiring more elaborated professional skills still will be frequent. However, enhanced global average standard of living may hold back the outsourcing of industrial goods production from the now industrialized countries.

Economic growth will probably be much larger than an increase of industrial electricity use because of an expansion of lines of business with low electricity consumption (e.g. telecom, pharmaceutics), switching to processes that require less electricity and maintained or decreased electricity use in industries with high electricity consumption. Higher electricity prices may accelerate such a development. As an example, steel production with blast furnaces now increases at the expense of more electricity-demanding steel manufacturing processes (Elforsk, 2006).

A development with less heavy industry could slow down the growth in energy demand. Companies with very high electricity demand (e.g. newspaper pulp and paper mills, Sect. 6.6) have to be situated where the electricity price is low, if possible with respect to supply of raw material (Elforsk, 2006). Processing of local raw material, such as ores and wood, on a large scale preferably takes place close to the resources because transportation would be cumbersome and costly. These industries need large amounts of energy.

Electricity-intensive metal melting works may be closed if the owners consider electricity prices too high and find more favourable conditions elsewhere, which would reduce Nordic electricity demand by at least 20 TWh a year (Elforsk, 2006). But for processes that require much electricity, such as aluminium melting works, remote areas in Nordic countries with hydropower resources (such as Iceland) will remain among the most favourable locations in the world.

5.8 Power production is changed

Condensing power production will be reduced in Europe because its low efficiency makes the generated electricity too expensive when fuel prices increase and policy instruments affect fossil fuels. However, natural-gas-fired combined cycles without heat recovery first expand because they have a higher electric efficiency than steam cycle plants and the gas causes slightly less CO_2 emissions. In Norway, offshore natural-gas-driven electricity generation could be connected to the main grid and yield 5-10 TWh/year. In addition, gas-fired condensing power plants may be built on land (Elforsk, 2006). But as more sustainable power supply emerges, natural-gas-fired condensing power plants will be used less.

The higher Nordic electricity prices, which are caused by higher fuel prices, policy instruments and the integration with the continental power system, make many new electricity generation units profitable, such as CHP plants, wind power and, in a longer perspective, emerging technologies, e.g. solar cells, fuel cells (cf. IEA, 2003, IVA, 2003). Distributed electricity generation can become widespread.

Combined heat and power (CHP) production has a much higher efficiency than condensing plants and CHP production is increased for district heating (especially in Norway) and industrial steam production (cf. IVA, 2003, Eon, 2006). Most district-heating systems are utilized for CHP production in the Nordic countries. With current fuel prices and policy instruments, biomass-fired CHP plants, but not natural-gas-fired units, are profitable to build (Elforsk, 2006). Municipal waste may also be used as fuel in CHP plants.

Nuclear power capacity decreases slowly throughout the century because large capital costs hamper investments in new plants and concerns about nuclear waste treatment increase. Climate change influences hydroelectric power production and water supplies increase but installed generation capacity is maintained (cf. Azar and Lindgren, 1998, Eon, 2006). Wind power expands considerably (e.g. Rydén, 2003).

5.9 Wind power interacts with hydropower, electricity consumption and transmission capacities

Nuclear power plants and CHP units mainly have seasonal fluctuations (due to maintenance and heat demand, respectively), which are partly balanced by lower demand in summer but still need to be compensated by hydropower (e.g. Henning, 2005). Wind power capacity expands and can be substantially higher in the future. By increased installed wind power generation capacity, the whole surrounding power system is influenced. Hydropower can be used to balance fluctuating power production, such as wind power, which primarily has short-term variations and can change from hour to hour. Nuclear power output cannot be controlled to match short-term variations in the same manner.

In a power system with wind power, there must be other plants that produce electricity when wind is low. At high wind, fluctuations in wind power output must rapidly be balanced by other plants, such as thermal or hydropower plants that can decrease and increase production. In extreme situations with fast load increase and rapid wind decrease, gas turbines may need to be committed in certain power systems. Wind power contributes to the reliability of a power system because, with a certain probability, there is some wind power available in peak load situations (Söder, 2004).

In a power system with wind power, there should preferably be some storage that can *store* wind power from high to low wind occasions. Wind is used then available and the plant with storage of fuel or water is used at low wind (Söder, 2004). Adaptation of electricity consumption through demand response (Sect. 6.3) can also help absorb wind variations.

Figure 5.1. The Middelgrunden offshore wind power park near Copenhagen

In rivers that are used for hydroelectric power production, there are large reservoirs that can store water from spring flood to winter, which can also be used to store wind energy. When extensive wind power generation occurs, hydropower production can be reduced and the other way round. Hydro reservoir storage makes it possible to install more wind power. The storage capability is primarily decided by reservoir size but also by desired hydropower scheduling. The stored water should be utiliszed at the most beneficial later occasion. Several studies indicate that an electricity generation mixture of wind power and hydroelectric power production allows a more economic management of hydro reservoirs than if there is no wind power (Matevosyan, 2004).

Within a large area, simultaneous wind conditions are different at various places and the total wind power production fluctuates less than the output from an individual plant. An area with high wind-power penetration may export electricity to neighbouring areas at high wind but import at low wind. Thus, controllable power plants in the other area (e.g. another country) help balancing the wind power (Söder, 2004).

There are transmission lines between the wind power plants, supplementing plants and demand and their capacities may restrict desired power flows. If transmission congestion between regions occurs simultaneously as extensive wind power generation, it can often be balanced by hydropower production. Wind and hydroelectric power plants have to be situated where the energy resources are available, but it should be observed that transmission capacity may need to be reinforced at the sites of other kinds of new power plants, as well (Matevosyan, 2004, Söder, 2004).

Spillage (curtailment) of wind power should of course be avoided but it may not be economically feasible to exclude spillage, just like water sometimes is spilled at hydroelectric power stations. But hydro storage can reduce spillage substantially. Wind power storage in hydro reservoirs, or even spillage, may be more profitable than reinforcing transmission capacity. In a market with several producers, the trade-off between wind spillage and hydro storage depends on the current and expected future market prices of electricity. In a region with limited external transmission capacity, wind and hydropower operators can conclude a mutual agreement on generation control (Matevosyan, 2004).

Possible wind power capacity is primarily an economical trade-off that depends on the interplay between wind power and hydropower, transmission, electricity demand and generation in the same and neighbouring areas and, possibly, spillage. If wind power plants that produce about 20 TWh per year were installed in Sweden, it should be possible to manage like the current wind power in western Denmark (Söder, 2004).

6 Promising long term technologies

Energy efficiency has improved over the last century and will continue to do so. Technologies develop in all areas concerning energy supply and demand. Martin et al. (2000) have studied emerging energy-efficient industrial technologies. They point out 26 promising technologies that are expected to have very high potential for increasing the energy efficiency in industrial production. This includes membrane technology for food and wastewater, advanced sensors and control equipment, process integration (e.g. pinch analysis), micro turbines and several other technologies. Some of them are described in the following sections (Petersen and Larsen, 2005).

New technologies for energy extraction (utilisation), conversion, distribution and use emerge along with enhanced efficiency of existing technologies. Emerging technologies that are expected to become of substantial importance are outlined in this chapter.

6.1 Electricity from sun and sea

The solar inflow on earth is very much larger than human energy use. Solar cells can be used to transform sunlight directly into DC electricity. The photons in the light interact with electrons in a semiconductor material and produce a current. The now installed solar cells are primarily made of crystalline silicon but thin-film solar cells made of amorphous silicon or various compounds (primarily cadmium telluride, copper indium selenide) emerge. The efficiencies of solar cells are continuously increased. Monocrystalline silicon cells are most efficient, followed by polycrystalline ones. Copper-indium-selenide, cadmium-telluride and amorphous-silicon solar cells have slightly lower efficiencies. Some solar-cell materials, such as monocrystalline silicon, are rather costly. Sunlight can be concentrated to the cells by lenses or reflectors, which reduces the cell area required for a certain power production. The solar cells are normally gathered in a module that typically has a size of one square meter and that can produce 100 W. Elevated cell temperature reduces output but it can be alleviated through cooling and the obtained heat could be utilised for low-temperature heating purposes (Kåberger et al., 2003).

Global solar-cell production is continuously increasing considerably. The initial niche market for solar cells was for separate appliances on locations without power grid or there cabling was inconvenient, such as lighthouses. Solar cells have also been used in consumer electronics, e.g. pocket calculators. But now, most installations of solar cells are grid-connected, primarily due to economic support in Japan and Germany. To cover a Swedes present, rather high, electricity consumption would, as an example, require 150 m^2 of solar cells. Solar cells are now often integrated with materials covering walls and roofs, which reduces costs (Kåberger et al., 2003, Fidje, 2005). There are visions of large-scale installations in sun-rich but sparsely populated countries (e.g. Algeria), where the generated electricity can be used to derive hydrogen from water through electrolysis. The hydrogen fuel could then be transported through pipelines to consumers in more densely inhabited regions, such as Europe.

For electricity generation from the sea, the northern Atlantic Ocean between Norway, Iceland and southern Greenland has among the highest wave power resources in the world, except for the seas south of Cape Horn and Australia. There are several technologies under development and demonstration for electricity generation from wave energy. Waves can give rise to an oscillating water column that is enclosed in a caisson on the shoreline (a roof and a wall into the water, e.g. in a deep-water harbour) with air on the top, which is compressed and drives a turbine. This technology was tested in Norway already during the 1980s. There are also floating versions. In a *pivoting flap* device, waves make a plate oscillate. The plate compresses a hydraulic fluid, which transfers power. In a *tapered channel* device, waves bring water into a basin, which is evacuated to the sea through a turbine. Such a device has been tested in Denmark. For some devices, wave fronts may be concentrated by reflectors to capture more power.[4]

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[4] World Energy Council, www.worldenergy.org/wec-geis/publications/reports/ser/wave/wave.asp 060409

If waters at the coastline are shallow, most shoreline plants are not possible. Offshore, the energy from the up-and-down motions of a floating buoy may be derived through a piston that can generate power. This technology is now tested in Sweden. In a *hose pump* device, a buoy or pontoon heaves in the waves and compresses water in the hose which is transferred to an electricity-generating turbine. In the offshore oil and gas industry, there is established technology and experience on construction and maintenance of reliable equipment in the unforgiving marine environment, which may be transferred to wave power utilisation. Existing wave energy conversion technologies are competitive in isolated communities that are now supplied by diesel generators. Several issues have to be investigated for shoreline and offshore demonstration plants, such as wave forecasting, long term fatigue of lines and electricity-grid connections.[5]

6.2 Climate neutral utilisation of fossil fuels

Carbon dioxide capture and storage (CCS) means that carbon dioxide (CO_2) is separated and stored. (This section is based on IPCC, 2005.) Normally the CO_2 is compressed to high density to facilitate transport and storage. CCS is primarily applicable to power plants but also to plants producing hydrogen for, as an example, transportation. CCS should preferably be integrated by the building of a new plant. The concept aims in the first place at fossil fuel combustion but could be used for biofuel as well, which would create a carbon sink.

The carbon dioxide can be captured through pre-combustion, oxyfuel combustion or post-combustion. A pre-combustion system uses the primary fuel to produce hydrogen that is combusted. The fuel reacts with steam and air or oxygen to yield a mixture of hydrogen and CO_2 from which the gases can be separated. This concept produces CO_2 at high pressure and constitutes a natural part of an integrated gasification combined cycle (IGCC) power plant. By oxyfuel combustion, oxygen, which has been extracted from air, is used by the fuel combustion. The flue gas consists mainly of CO_2 and water vapour, which can be condensed. A post-combustion system separates the CO_2 from the flue gases normally using a liquid organic solvent. Pre and post combustion captures about 90% of the CO_2 and oxyfuel combustion captures nearly all CO_2.

The carbon dioxide may be stored in geological formations, the ocean or in mineral carbonates. The main geological storage option is to inject the CO_2 into onshore or offshore saline formations. The CO_2 may also be stored in depleted oil and gas reservoirs or used to enhance oil and gas extraction. By such geological storage, the CO_2 is trapped by a layer of shale and clay rock above the storage, but some CO_2 may migrate anyway. The CO_2 would usually become liquid and gradually dissolve in water already in place and finally react with rock minerals. The CO_2 can also be used to extract methane from unminable coal beds. It is unlikely that more than 1% of the CO_2 would leak from a geological storage but better understanding of leakage processes is required. Potential geological storage is likely to have sufficient capacity for this century but improved local estimates are needed.

Ocean storage could be done by injecting and dissolving carbon dioxide into the water below 1000 meters depth or depositing it onto the seafloor below 3000 m depth, where the CO_2 is expected to form a lake, which would delay CO_2 dissolution into the water. CO_2 is acid and the long-term effects of CO_2 injection on ocean ecosystems are unknown. Ocean mixing results in CO_2 reaching the surface and atmosphere (Fig. 6.1).

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[5] Ibid.

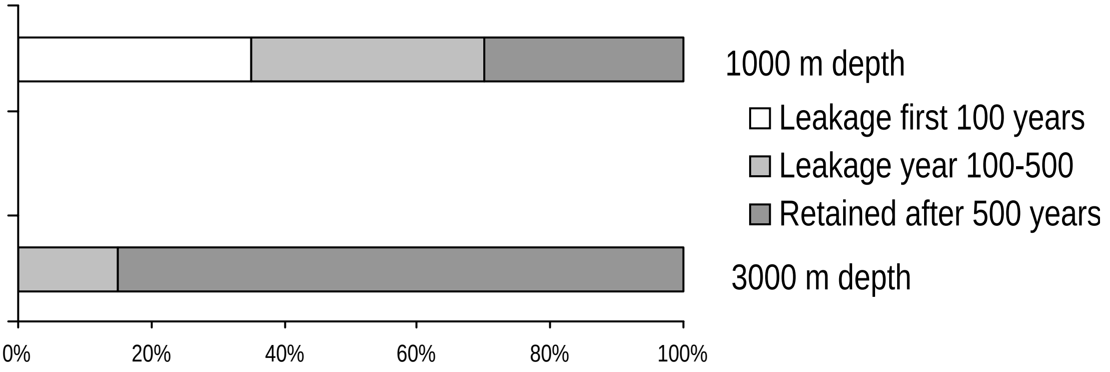

Figure 6.1. Release of CO_2 from ocean storage at two injection depths (based on IPCC, 2005, p 13)

By mineral carbonation, carbon dioxide would be helped to react with alkaline or alkaline-earth metal oxides in silicate minerals or industrial waste (e.g. steel slag) to yield stable solid inorganic carbonates (e.g. limestone), which could be disposed in silicate mines. The process would require very energy-demanding mining, crushing, milling and transport of ore.

The locations for carbon-dioxide generation and disposal are decisive. In general, many power plants are within 300 km from potential geological storage sites but regional assessments are required. Transport could take place in pipelines or as liquid CO_2 by ship, road or rail. Energy is required for the separation, compression, transport and storage of CO_2, which reduce the total efficiency of energy conversion. CO_2 capture systems increase the fuel consumption per unit of produced electricity with 10-20% for natural-gas-fired combined cycle (NGCC) plants and 15-25% for coal-fuelled IGCC plants. Separation and compression are most costly and ideas that may reduce costs need to be applied.

CCS is likely to increase throughout the century. Carbon-dioxide separation by pre or post combustion and most geological storage concepts are already used in some commercial applications but there is only a pilot plant for oxyfuel combustion, and ocean and carbonate storage is subject for research. Large amounts of CO_2 have been injected for decades in Texas to enhance oil recovery. There are commercial plants with CO_2 capture and geological storage in Norway, Canada and Algeria. However, the whole concept has hitherto not been applied to a large power plant (e.g. 500 MW). The Swedish energy company Vattenfall will start building a 30 MW pilot plant in Germany in 2006 (www.vattenfall.com).

6.3 Demand response

It has been recognized to be crucial for the liberalized electricity system that electricity demand reacts on prices. This is called demand response (or load management), and is voluntary adjustment to prices. It can be spot prices, real-time prices, or even demand used as reserves (e.g. regulating power).

It is not realistic that commercial companies will invest in “the last” generation capacity that will only be used for a limited number of hours per year. For the infrequent peak, it is expected that demand response can be made superior to investment in production. Also, demand response has a positive impact on competition. In situations with limited competition, demand response can reduce the possibility for producers to misuse market power (Nordel, 2004, DOE, 2006).

The current level of demand response is limited, but some experiences exit: In the dry winter of 2002/2003, spot prices were high for more than a month and the demand in Norway was between 1,000 and 1,500 MW lower than for normal years. Also, some reaction was found in Sweden, while the reaction was insignificant in Finland and Denmark. The reaction was in the order of 3% of peak demand. In a recent report, the US Department of Energy describes the current level of demand response in the US (1-3% of peak load) as low. California Public Utility Commission (PUC) has issued a goal of 5% demand response in the economic market to be reached in 2007 (in addition to existing demand response in the reserve market)[6].

In the future, a much larger share of the total electricity demand can be developed to be price sensitive. The current modest level is influenced by lack of communication systems (including advanced meters), lack of advanced markets and lack of tradition as well as a limited frequency of extreme price spikes. One can imagine that a threshold price can be associated with the majority of all electricity consumption. When the price exceeds this pre-set value, demand is reduced automatically.

Today only around 50% of the electricity demand is metered with interval meters, which measure the demand hour by hour. Many consumers are only measured each month, every second month or once a year. Without interval meters, only the average price signal reaches the user. Typically, capacity problems are related to the daily demand cycle with high demand during the day and lower demand during night. To react on such short-term capacity problems, an interval meter is needed. Large investments are under way in advanced meters, e.g. in Sweden. In 10 years time, all users probably have an interval meter with automated meter reading. This will make it possible for small users to react on prices.

Nord Pool is the successful Nordic electricity exchange. Each day around noon the price is set for each hour of the following day. When the price is determined, the planned level of demand and production in each price area is also determined. This is done on the basis of bids for buying and selling electricity. This will result in a balancing of production and demand at a certain price. Currently three alternative bid forms exist:

- The basis bid form is a curve describing the offered production and demand at varying prices. E.g., if the price is above 20 €/MWh, 1 000 MW can be offered, and an additional 500 MW may be offered if prices exceed 30 €/MWh. E.g. hydropower plants can use this form. With few start-stop costs, the time distribution of the won bids is less important. The same style of bid can be used for demand but with reduced demand with increasing price.
- Block bids where the bid covers not one hour, but four or more consecutive hours. The bidders are free to decide start and stop time for the block. This form of bid is targeted e.g. coal fired generation, which is costly to start and stop.
- A flexible hourly bid, which is only activated during the most expensive hour of the day. An industrial process that can be stopped for one hour – and only one hour – can use the bid form to react to high prices.

The existing three bid forms are only a fraction of all possible bid forms. Demand response resources could be used to a larger extent if additional types of bids did exist, e.g.:

- A generalised form of the flexible hour bid, where any number of the most expensive hours could be targeted (to avoid demand).
- Or an alternative where the cheapest hours could be targeted (to increase demand)
- Or a combination of the two, where demand could be moved from the most expensive hours to the cheapest hours.

In future, when communication and computation is not a problem, any kind of markets and bids can exist (Kok et al., 2005).

The same can be imagined concerning the delivery time. The spot market is a day-ahead market. This is supplemented by an hour-ahead market (Elbas) and regulating power (15 minutes warning) and reserves (with seconds to minutes warning). In the future, the number of markets can be very large. Computers can be negotiating, disregarding manmade design issues like bid form, warning time and bid size (Crisp, 2006).

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[6] See: http://www.cpuc.ca.gov/Published/News_release/26901.htm

6.4 Advanced markets with dynamic nodal pricing

The principle of marginal pricing is that the consumer must pay the cost the he or she causes. If the demand is reduced or increased, the reduced or extra costs will correspond to the change in cost at the most expensive plant. So the correct price signal is the marginal cost of the most expensive plant. This principle is followed at the Nord Pool spot market (Sect. 6.3). For each hour, the price is equal to the generation cost in the most expensive production unit.

However, the pure production costs are not the only costs related to electricity. The transmission and distribution network must be financed, losses must be paid for and a certain level of reserves must exist. These costs are covered by the Transmission System Operator (TSO) and the Distribution System Operator (DSO). Today TSO/DSO costs are often covered by simple tariffs, e.g. a fixed mark-up (x € per MWh). As computation and communication are getting more powerful and cheaper, more advanced tariffs can be used to collect the costs to the TSO/DSO. The ideal is “marginal costs, nodal pricing”. That is, tariffs that vary in time and in space (grid node).

For example, the extra losses introduced by an extra electricity demand are dependent on these two dimensions: Time and space. The marginal losses can even be negative. In some situations, the alternative to a local demand is to transform local production to a higher voltage, transport it to neighbouring areas and transform it back to low voltage. In this case, the losses would be much lower if the local demand was increased. In the future, tariffs can be calculated in real time and the price signal will be stronger that day, where simple tariffs are smoothing out cost differences.

A similar line of arguing can be done in relation to some types of reserves. In some cases, a reduced or increased demand can reduce the need for reserves, e.g. upward regulation reserves to balance prognosis errors. Such advanced pricing schemes would increase the incentive for demand response and would increase the utilisation of the capital of grids and power plants.

6.5 Power electronics, FACTS and WAMS

Electric networks are generally sized based on peak loads. Throughout the year, the load varies due to weather, time of day, season, and day of the week. This results in many lines that are 100% loaded less than 5% of the time. Electrical system behaviour is governed by Kirchoff’s Law. Power flow ultimately is determined by system resistance, power sources and sinks. Power flows through the grid following the path of least resistance. As a result, many lines are under-utilised by 10% to 30%, even during system peak periods.

Transmission assets can be better utilised by applying advanced power electronics technologies such as FACTS (Flexible AC Transmission System), or Dynamic Thermal Circuit Rating, Video Sagometer, and advanced energy storage technologies that enable optimisation of the use of existing assets (power plants and network) during peak periods (Gellings, 2003).

Electricity systems may become unstable, a situation that can happen especially when large volumes of electricity is transported over long distances. By using extremely accurate measurement (synchronised with GPS clocks) it is possible to calculate the difference in phase angle between different parts of a large network. A big difference in phase angle is a sign of instability. This feature cannot be measured locally and only high-speed communication system can warn about a potential unstable condition. Such systems are called WAMS for wide area monitoring systems and WAPS for wide area protection systems.

6.6 Electricity, heat and fuel from process industries, especially pulp and paper

Process industries produce pulp and paper, iron and steel and chemical products, such as automobile fuel, and use very much energy. Therefore, efficient energy utilisation in these lines of business is essential. Cogeneration of electricity and steam for production processes can be extended in several process industries where both energy carriers are needed for the manufacturing of goods.

Paper production largely concerns paper for newspapers in Norway and for offices in Finland, with Sweden having a mixture of both. The former paper is mostly produced with mechanical pulp that requires much more electricity manufacturing than the latter, which normally comes from chemical pulp. How the Nordic wood is utilised substantially influences electricity demand and supply. If wood, on the one extreme, is used for production of newspaper-paper, 1.8 MWh of electricity is *consumed* per tonne of wood but if the wood, on the other extreme, only is used for heat and power production it can *produce* 1.5 MWh of electricity. Intermediate electricity-balance impact have, in turn, manufacturing of mechanical pulp, office paper and chemical pulp (Elforsk, 2006).

Enhanced use of recycled paper by the manufacturing of paper for newspapers can reduce electricity consumption considerably. Switching from newspaper-paper to office-paper production would reduce electricity demand and enable additional cogeneration of electricity and steam in connection with the chemical pulp manufacturing for the latter paper quality. A new chemical pulp and paper mill can be self sufficient with electricity and even sell surplus electricity (Elforsk, 2006).

Black liquor arises in chemical pulp mill processes and is now normally combusted to produce steam, and possibly electricity, for production processes. Black liquor can be gasified to enable enhanced electricity generation in gas turbines or production of automobile fuel.

Heat recovery can be enhanced through process integration. Process integration methods help analysing how production processes can be integrated to a whole plant with efficient energy utilisation and low environmental impact. Possible energy savings may be up to 40% in a chemical industry and up to 50% in pulp mills, compared to current energy use (SEA, 2006). Through combinations of processes and plants, synergies can be exploited. Local industrial metabolisms may be established, which include, for instance, biofuel refineries. Pinch analysis can, for example, help show multiple utilisations of heat flows in a plant and reduce waste heat. As a last step, surplus heat can be used for hot tap water or space heating, possibly using heat pumps and district heating systems.

6.7 Other emerging technologies

Fuel cells exist today and can transform hydrogen or natural gas into electricity and heat. PEM fuel cells (Proton Exchange Membrane) operate at moderate temperatures (80-200^{o}C) with an electric efficiency about 40%. Heat can be recovered, adding to a total efficiency of 80%. Units of up till 250 kW are available. A Solid Oxide Fuel Cell (SOFC) operates at higher temperatures and can reach electric efficiencies up to 50% in combination with gas turbines. Fuel cells can be pollution free and can have a small-scale-benefit: The units can be combined into any size, so the technology can be used in cars or in individual houses. Future development is expected to reduce the cost and increase the lifetime and efficiency of fuel cells Danish Energy Agency et al., 2005).

Today, cogeneration of heat and electricity takes place in relation to district heating systems or industries. The size of such plants varies from large central combined heat and power (CHP) units (e.g. 600 $\text{MW}_{\text{electricity}}$) to smaller systems in town-size district heating (e.g. 5-50 MW). A new trend includes *micro generation* that is adapted to a single household, e.g. with a generation capacity of 1 $\text{kW}_{\text{electricity}}$ and 2 kW_{heat}. The technology can be a standard motor or Sterling engine. In the future, micro turbines or fuel cells can also be utilised. The perspective is that the benefit of combining heat and power production can be expanded to a larger market, because no district-heating grid is needed. Mass production can give investment costs per kW output comparable to traditional central power plants (Hatziargyriou et al, 2006, Ito et al., 2004).

Micro generation systems based on natural gas are sold in Great Britain today and the technology may develop fast. The installations have the size of a refrigerator and are in some cases controlled as a traditional heat boiler: When heat is needed the system is started and the produced electricity is used in the house, or exported to the grid in the case of surplus production. With advanced communication, it is possible to coordinate the electricity production in many such small units with the general need for generation, e.g. local spot prices.

A break-through of *high temperature super conducting materials* will have a major impact in the whole electricity sector. Loss-free materials can be used in cables allowing large volumes of energy to be transported over larger distances. The footprint of super conduction cables can be much smaller than traditional ground cables or overhead lines, which can ease the construction of such networks both in cities and in the open landscape. An existing cable path can carry two to five times more electricity with superconducting cables. Super conducting materials can also be used to increase the efficiency in generators and motors.

Figure 6.2. Superconducting cable. (www.supercable.com)

It is characteristic of today's electricity system that demand and production must be constantly balanced. With more wind power and other intermittent power, *electricity storage* becomes more and more needed. Only few possibilities for storage of electricity exist today. The cost and efficiency of the current storage possibilities limit their use.

Production from hydropower plants can easily be adjusted and the water in the hydro dams can be seen as energy storage. Also, pumped storage is used where water is pumped into a dam at night and used for electricity production in the daytime. One storage technology is compressed air energy storage (CAES), where compressed air is stored in an underground storage, e.g. a salt cavern. The technology is demonstrated in Germany and USA.

Other potential energy storage technologies include flywheels with superconducting magnets as bearings or hydrogen used as energy storage. Hydrogen can be produced with electrolysis and electricity can later be produced from hydrogen in fuel cells. Currently the over-all efficiency in this cycle is low (60%), but is expected to increase during the next 20-30 years (e.g. to 80%).

Today, the level of *security of power supply* is the same for most end users. A few critical users have back-up generation to increase their security of supply, e.g. hospital, airports and some commercial facilities (e.g. computer centres). In the future, the level of security may vary much more than today. Underprivileged households may select a low degree of security of supply because it is cheap. Each meter might in the future have a price tag: At what price level will it be disconnected?

At the other end of the security-of-supply scale, *microgrids* may accomplish an extreme security of supply to e.g. manufacturers of electronic chips or other high-value items. A microgrid may include a DC-network with local backup from energy storages, like batteries, flywheels or fuel cells. The purpose of microgrids can be to maintain a 99.9999999% security of supply. This level of security of supply is expensive and clearly not for everyone. Microgrids can operate in parallel with the national grid or independent of this if faults happen. The concept of microgrids is also used in connection with small low-voltage grids with the purpose of integrating decentralised production[7].

LED (*light emitting diodes*) lighting can today prove a significant efficiency gain compared to incandescent light, e.g. in traffic lights – where LED can produce the needed colour directly. A LED is based on semiconductor material, just like computer chips, and the development takes place with the same speed as for computers. LED lighting may reduce peak electricity demand in Europe with 40 GW (European Commission (2005b). Electricity used for lighting could be reduced by 30% in 2025 (Larsen and Petersen, 2005).

As for lighting, electricity demand for cooling can be reduced through new technology. By absorption cooling, heat or steam can be used instead of electricity to produce cooling, primarily for indoor climatisation but also for industrial processes. Cooling driven by heat from a CHP plant gives more cooling per unit of fuel input than using electricity from an efficient condensing power plant for cooling. *Heat-driven cooling* enables additional electricity generation instead of consuming electricity. A central plant for electricity, heat and cooling production can supply electricity, hot-water and cold-water networks. Alternatively, distributed chillers can use district heating for local cooling production (Rydstrand et al., 2004).

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[7] See: microgrids.power.ece.ntua.gr

7 Long term scenarios for the Nordic energy system

Here are presented some qualitative scenarios for the Nordic energy system within the time horizon 2050. Table 7.1 presents what various general features of society could look like in the three scenarios. These properties may primarily serve as a background, giving an impression of conditions, which we imagined could bring about the energy system fashions that are outlined in the following sections. We have not elaborated the scenarios based on every individual parameter in table 7.1. We consider scenario 1 as more probable as scenarios 2 and 3. The scenarios are not intended to reflect certain emission levels or particular extents of climate change, but the outlined energy systems may *cause* different emissions and climate impact. The three scenarios show three quite different societal development paths and the two latter scenarios may be classified as extremes. Therefore, we consider it likely that the scenarios comprise most plausible future situations within the spectrum of possibilities.

Scenario	1 Medium path	2 Free market	3 Green
Economic growth	Medium	High	Low
Material standard	Modest growth	Increasing	Maintained
European Union	Current structure	Centralised power	Fragmented
Market regulation	Medium	Little	High
Competition, influence of companies	Medium	Strong	Weaker
Decision makers' time horizon	Medium	Short	Long
Political control through regulations and fees	Medium	Weak	Strong
Primary energy demand	Medium	High	Low
Dominant owner of energy supply system	Mixture	Large private companies	Common management through municipalities and states
Climate policy	Medium	Weak, no post-Kyoto agreement	Firm control toward lower CO_2 emissions
Security of supply	Mixture	Global market	Local supply
Occupied environmental space[a]	Medium	We eat a too large slice of the global pie.	Globally justified share
Dominating human attitude	Mixture	Egotism / Individualism	Solidarity

Table 7.1. General possible features of societal development in the three presented scenarios

[a] A measure of resource use (e.g. Spangenberg, 2002)

The first scenario is to a high degree an extrapolation of current trends. Moderate growth, moderate environmental awareness and moderate liberalisation balanced by national interests. It is possibly very human to predict that the future will be an extension of current trends. However, rapid changes often happen and make forecasts look ridiculous. Danish forecasts made in 1970 noticed that electricity-consumption growth had been 7% p.a. for the last 10 years and predicted the same growth for the future. 7% is the same as a doubling every 10 years and a four times increase in 20 years. The history – after the first oil crisis - showed a very modest growth of 1-2% p.a.

The oil crisis in 1972 was a shock for most western countries. In Denmark, oil was the preferred energy source for electricity production and the increase in cost was frightening. As a consequence, cars were not allowed to drive on Sundays – this saved the expensive oil and secured that the crisis was not overseen. The current price level of 70 US $ per barrel of oil was not predicted by forecasters only two years ago.

Wars and other crises in The Middle East or Iran could make oil supply more vulnerable and lead to even higher oil prices than seen today. A coup in Saudi Arabia would have a similar effect. The energy demand in China is growing fast and could make energy prices increase even more rapidly. A new energy-price crisis may put a heavy burden on the Nordic heavy industry. It would have a dramatic impact on overall electricity consumption if heavy industry declined in the Nordic area.

The gas crisis in the winter 2005-2006 is another fine example of a wake-up call for Europe. When it became clear that the Russian gas supply could actually affect the European security of supply – energy soon came up high on the EU agenda.

Twenty years ago, the Chernobyl accident shocked the world and changed the prospects of nuclear power. A new accident would probably have similar impact on nuclear policy.

Crises happen as well as positive surprises. Few had, as an example, predicted the fall of the Berlin wall. We don't know the nature of the next paradigm-shifting crisis. It could be a currency crisis because of the trade deficit from US to China. A breakdown of the US dollar could disturb the world trade of energy and other items.

The current trend with focus on free trade and liberalisation of energy markets could quickly be reversed if energy or economical crises happen. The French and Dutch people's no-votes to the new EU constitution now delays or even stops further EU integration and centralisation.

One can say that the most probable future is an unexpected one. To increase our understanding of the future and to provoke discussion, we also sketch two very different energy scenarios: A free-market-scenario and an environmental scenario. These emphasize how different technologies can be employed.

7.1 Scenario 1: Medium path – a continuation of current trends

This scenario is based on important issues for the development of the Nordic energy system and promising long-term technologies, which are described in chapters 5 and 6, respectively. The society has intermediate properties concerning the general features that are indicated in Table 7.1, such as economic growth, market regulation and energy policy, and a balance between public and private control of energy supply.

Global energy demand will increase due to industrialisation and enhanced standard of living in currently less developed countries. The demand increase makes all energy-carriers more expensive, which in turn makes new technologies, renewable energy utilisation and energy conservation more profitable.

Fossil-fuel use decreases because of environmental concern and cost increase, which is caused by policy instruments and enhanced demand in combination with limited supplies. Instead, utilisation of renewable energy sources increases primarily biofuel, wind power and solar energy. Biomass supplies are increased by climate change because it stimulates wood growth.

The common deregulated electricity market in the European Union, and higher transmission capacities, and energy flows between the Nordic and continental power systems will level out electricity prices and raises Nordic electricity prices to levels that are similar to continental Europe. Electricity is primarily used for purposes where other energy carriers are not possible and such consumption is largely linked to human activities, which primarily take place during daytime. Therefore, electricity demand variations are diurnal, and price fluctuations follow the same pattern.

The demand for energy services increases but energy is used more efficiently and primary energy demand is reduced. The benefit of energy use remains unchanged. Energy demand is changed due to restructuring of manufacturing industry, expanding service business and changing behavioural habits at home and other places, among other things. Heat is recovered for repeated utilisation in industrial processes, for example in pulp and paper mills, and for heating. Electricity is almost only used for electricity-specific purposes and sparsely for heat production. Climate change reduces space-heating demand and decreases the seasonal variations of space heating demand. The demand for indoor climatisation through cooling is increased due to higher outdoor temperatures and higher comfort requirements and can to a certain extent be covered by absorption cooling. Switching from electricity to other energy carriers for space heating reduces the seasonal variations of electricity consumption.

A diversity of domestic and imported energy carriers (with priority to local resources) is used in a variety of conversion and distribution technologies. Condensing power is reduced but natural-gas-fired combined cycles without heat recovery first expand and then decrease. Combined heat and power (CHP) production is increased for district heating and industrial steam production. Many district heating systems are integrated with other district heating networks and with industrial steam systems. Nuclear power capacity decreases slowly throughout the period. Climate change increases precipitation, which enhances water supplies for hydroelectric power production. Distributed electricity generation increases, e. g. small-scale CHP. Less peak generation capacity is required due to load management.

Installed wind power capacity increases and the electricity production can increase because climate change causes more winds. Wind power plants interact with hydropower, electricity consumption and transmission capacities. Hydropower can be used to balance fluctuating power production, such as wind power, which primarily has short-term variations and can change from hour to hour. The increased interconnection of electricity systems in northern Europe also enhances the use of hydropower as a regulating resource.

Solar cells and some fuel cells, wave power plants and hydrogen systems emerge. Fossil-fuelled power plants with carbon dioxide capture and storage emerge slowly. Black liquor is gasified for electricity generation in gas turbines or production of automobile fuel.

7.2 Scenario 2: Free market

While the current trends (as included in scenario 1) include a balance between market and regulation, this scenario is only market. Negative impact of climate change is neglected. The Kyoto agreement is ended and the development of the energy system is left to the market. Subsidies for environmentally friendly energy supply are abolished and building codes are relaxed. National concerns about security of supply are transformed to EU internal market considerations. It is accepted that security is a quality that consumers (individuals and companies) have to pay for. Advanced communication systems can be used to buy and sell electricity in real time.

It is expected that this scenario show a high growth in energy demand due to rapid economic growth and little regulation. Changes in electricity demand due to climate change will be marginal in comparison to the high demand in this scenario. Nuclear power and large-scale hydropower capacity is expanded. Environmental protests are ignored. With little wind power and much hydro and nuclear power, the system is robust against many kinds of disturbances. Dry years are managed by extensive electricity import and use of fossil-fuelled power plants. The EU is still heavily relying on imported fuels.

7.3 Scenario 3: Green development

A quite different development would occur if environment was the first priority. In this scenario, private companies have less influence and public utilities dominate energy supply. The consequences of climate change are generally considered to be severe, which influences political decisions. A firm policy towards low CO_2 emissions includes subsidies to environmentally friendly electricity production, like wind and solar power. Energy storage (also e.g. flywheels with superconducting magnets as bearings) balances intermittent supply. All energy sources are taxed according to their CO_2 content. CO_2 emissions are reduced to 50% of the current level. When this development path was begun, it prevented further expansion of natural gas use and waste incineration but encouraged material recycling in the societal metabolism. The low electricity consumption makes the need for power system integration low and nuclear power is phased-out until 2040.

Due to the reduced energy use (less than today) the hydropower – although having the same capacity as now – has a more important role in the energy system because it supplies a larger fraction of the electricity. The larger water supplies due to climate change emphasize this situation. The extensive wind power production is *stored* in hydropower dams then required. Because renewable energy sources dominate energy supply, climate change impacts on these resources have a larger influence in this scenario.

Domestic energy carriers dominate, and distributed energy conversion is common, which promotes supply security. Fuel cells are appreciated for their small-scale advantages. There are DC microgrids in buildings, which can be fed from local electricity-generating units, such as solar cells, or the common electricity grid and which eliminate transformers (for computers etc.) that in practice served as electric heating.

The efficiency of energy utilisation is very high and energy demand is lower than today. New houses are all super low-energy houses. Indoor climatisation is demanded but air-conditioning equipment is solar-driven. All major electric appliances must meet minimum energy standards. Most of the requirements are stricter than the average buyer would demand, but are cost-efficient seen throughout the lifetime of the products. Heavy industry, like metal works, has largely moved to Iceland to benefit from the low-cost energy there.

8 Concluding remark

In this report, possible development of Nordic energy supply and use during the next 50-100 years is outlined. Climate change will increase precipitation, winds and biomass growth, which can enhance hydropower and wind power production and biofuel supplies. Higher temperatures reduce space-heating demand but increase electricity demand for air conditioning. But technical and economical progress seems to have larger impact on the Nordic energy system than climate change. The scenarios illustrate that the way forward is difficult to predict and can take many forms. Global energy demand should increase due to industrialisation, which raises energy prices. It promotes switching from fossil fuels to local renewable energy sources, which secure energy supply. Nordic primary energy supply may decrease without reducing the comfort, benefit or utility of energy use due to more efficient energy utilisation. Nordic power grids and electricity markets are integrated with continental Europe, which raises Nordic electricity prices and restrains electricity consumption, e.g. for heat production. Together with climate change, it reduces the seasonal electricity demand fluctuations. Condensing power production seems to be reduced, whereas distributed generation (e.g. solar and fuel cells) and combined heat and power (CHP) production expand. Hydropower storage balances fluctuating wind power output. Power electronics and super-conducting materials improve power system operation. Demand response and markets with dynamic pricing reduce peak generation.

However, many scenarios for the future are possible. It is most probable that events occur that we cannot even imagine today, such as shocks concerning international relations. Other development paths than those outlined in this report may show up. One issue is how energy demand changes due to restructuring of manufacturing industry, expanding service business and changing behavioural habits. Nordic energy use may decrease due to more efficient energy utilisation but will higher energy-carrier prices and, possibly, decreased standard of living due to global competition also reduce the benefit, comfort and utilities owing to energy use?

Electricity systems in different countries are now increasingly being technically and economically integrated but to which extent will national power grids be linked to each other, energy flows increased, electricity prices among countries levelled out, Nordic electricity prices increased and Nordic electricity consumption reduced? Condensing power is reduced but natural-gas-fired combined cycles without heat recovery may first expand and then decrease. Condensing power may continue to serve as the basis for European electricity generation and the role for natural gas may become more important in the Nordic countries due to grid expansion in Sweden and elsewhere. Nuclear power has not been discussed in detail in this report but it may develop in many ways: A relatively rapid phase-out, a maintained capacity through continuos reconstruction or an extensive expansion with several new reactors.

This report focuses technical issues concerning the progress of the energy system but the development is also deeply influenced by other societal factors that interplay with technology in the shaping of future energy supply and use. For example, many formerly public energy utilities have now been privatised and previously national energy companies are merged to international groups. But issues concerning how various actors, such as governments and companies, influence or dominate energy supply are just mentioned at some instances in this study.

The report shows that there are several problems to solve but also many possibilities that may be realised concerning energy extraction, conversion, distribution and utilisation.

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10 References

Andréasson J, Lindström G, Grahn G, Johansson B (2004) Runoff in Sweden-Mapping of climate change impacts on hydrology, XXIII Nordic Hydrological Conference, Tallinn, Estonia, 8-12 August, NHP report no. 48, pp. 661-669.

Azar C and Lindgren K (1998) *Energiläget år 2050*, Fysisk resursteori, Chalmers tekniska högskola, SE-411 96 Göteborg, Sweden.

Bergh, J., Michael, F., Sigurdsson, B., Kellomäki, S., Laitinen, K., Niinistö, S., Peltola, H., Linder, S. (2003) Modelling the short-term effects of climate change on the productivity of selected tree species in Nordic countries, *Forest Ecology and Management*, Vol. 183, pp. 327-340.

Carlson A. (2002) *Considering External Costs – Their Influence on Technical Measures in Energy Systems*, Dissertations No. 766, Linköping institute of technology, SE-581 83 Linköping, Sweden.

Clausen, N.-E., Barthelmie, R., Batchvarova, E., Gryning, S.-E., Pryor, S., Jacob, N., Tarp-Johansen, Holttinen, H., Ólafsson, H., Lundsager, P., Tammelin, B., Bergström, H. (2004) Impact from climate change on the wind energy potential in the Nordic region. European Wind Energy Conference, London, UK, Nov 22-25.

CRISP (2006) Distributed intelligence in critical infrastructure for sustainable power. EU-project ENK5-CT2002-00673.

Dag, S (2000) *Volvo Faces a Deregulated European Electricity Market*, Dissertation No. 663, Linköping institute of technology, Linköping, Sweden.

Danestig M. and Henning D. (2004) Increased system benefit from cogeneration due to cooperation between district heating utility and industry, 9th international symposium on district heating and cooling, Espoo, Finland, 30-31 August, ed. T. Savola, Helsinki university of technology, TKK-ENY-20, pp. 97-104.

Danish Energy Agency, Elkraft System, Eltra (2005) Technology data for electricity and heat generating plants.

Danish Energy Regulatory Authority (2006): Electricity prices. www.energitilsynet.dk

DOE (2003) Grid 2030. A national vision for electricity's second 100 years. United States Department of Energy. Office of Electricity Transmission and distribution.

DOE (2006) Benefits of demand response in electricity markets and recommendations for achieving them. U.S. Department of Energy.

Dybdal, A., Björn Rydell, Lars Byberg, Kaija Niskala, Mikael Togeby (2005): Monitoring Demand Response. Result for the Nordic countries. Nordel/Energinet.dk.

Economist (2004) Building the energy Internet. , 0013-0613, March 13, 2004, Vol. 370, Issue 8366

Elforsk (2006) *Elanvändningen i Norden om 10 år: Resultat från ett Elforskprojekt sammanfattat i 20 punkter*, Elforsk, Stockholm, Sweden.

E.On (2006) *Morgondagens energisystem, MOSES*, E.ON Nordic, SE-205 09 Malmö, Sweden. www.eon.se/upload/eon.se/dokument/om_e.on/nyfiken_pa_energi/energins_utveckling/moses.pdf

EPRI (2001) Electricity technology roadmap. Powering progress. Summary and synthesis.

EPRI (2003) Electricity sector framework for the future. EPRI, Palo Alto, USA (www.epri.com).

European Commission (2003) European energy and transport trends to 2030.

European Commission (2005a) Towards Smart Power Networks - Lessons learned from European research FP5 projects. EUR 21970.

European Commission (2005b) Doing more with less. — Green Paper on energy efficiency.

European Commission (2006) European SmartGrids Technology Platform. Vision and strategy for Europe's electricity networks of the future. EUR 22040.

Fidje (2005) Solar energy – an overview, http://www.os.is/cefiles/solar/ce_smhi20050526_fidje.pdf

Forsius, J., P. Kuivalainen, P. Mäkinen (1996) Effects of climate change on the production and consumption of electricity in Finland. In: Roos, J. (ed.), The Finnish research programme on climate change, Final report, Publications of the Academy of Finland, 1996, 4/96, pp. 484-491.

Gellings, C. W (2003) CEIDS and The Power Delivery System of the Future. Electric Power Research Institute.

Hatziargyriou, N., N. Jenkins, G. Strbac, J. A. Pecas Lopes, J. Ruela, A. Engler, J. Oyarzabal, G. Kariniotakis, A. Amorim (2006) Microgrids - Large Scale Integration of Microgeneration to Low Voltage Grids. CIGRE.

Henning D (2005) *El till vad och hur mycket i svensk industri: ett projekt i Energimyndighetens forskningsprogram Allmänna energisystemstudier, slutrapport,* IKP Energisystem LiTH / Optensys Energianalys, Linköping, Sweden (www.stem.se).

Henning D and Palm J (2006) *Energitillförsel och energihushållning i samverkan: Syntes av energianalyser inom programmet uthållig kommun,* ER2006:15, Swedish energy agency, Eskilstuna, Sweden.

Hoffman, J (2005) Global insights: Peak oil - Approaching a new world order?, *Chemical Market Reporter*, Vol. 267, No. 3, pp. 21-22.

IEA (2003) *Energy to 2050: Scenarios for a sustainable future*, International Energy Agency, Paris, France (www.iea.org/textbase/nppdf/free/2000/2050_2003.pdf).

IEA (2004) World Energy Outlook 2004. International Energy Agency, Paris.

IEA (2005) World Energy Outlook 2005. International Energy Agency, Paris.

IPCC (2001) *Summary for Policymakers - A Report of Working Group I of the Intergovernmental Panel on Climate Change*, IPCC, WMO, Geneva, Switzerland (www.ipcc.ch).

IPCC (2005) *Carbon dioxide Capture and Storage: Summary for Policymakers and Technical Summary,* IPCC, WMO, Geneva, Switzerland (www.ipcc.ch/activity/srccs/index.htm).

Ito, Y., Zhongqing, Y., Akagi, H. (2004) DC microgrid based distribution power generation system. Power Electronics and Motion Control Conference, 2004. IPEMC 2004. The 4th International.

IVA (2003) *Energi 2050 – närmare solen, Energiframsyn Sverige i Europa,* Kungl. Ingenjörsvetenskapsakademien, Box 5073, SE-102 42 Stockholm, Sweden. www.iva.se/templates/Page.aspx?id=277

Jóhannesson T, Adalgeirsdóttir G, Björnsson H, Pálsson F, Sigurdsson O (2004) Response of glaciers and glacier runoff in Iceland to climate changes, XXIII Nordic Hydrological Conference, Tallinn, Estonia, 8-12 August, NHP report no. 48, pp. 651-660.

Karlsson B G, Söderström M, Henning D (1995) *Simulering av kärnkraftsavvecklingen på uppdrag av Energikommissionen (Simulation of the Nuclear Phase-out at the Request of The Energy Commission),* LiTH-IKP-R-888, Linköping Institute of Technology, Linköping, Sweden.

KEMA (2002) Electricity technology roadmap: Technology for a sustainable society.

Kok, J. K., C. J. Warmer, I. G. Kampuis (2005) PowerMatcher: Multiagent control in electricity infrastructure. Energy research center of the Netherlands.

Kåberger T, Brogren M, Andersson B (2003) *El och värme från solen,* Kungl. Ingenjörsvetenskapsakademien, Box 5073, SE-102 42 Stockholm, Sweden.

Larsen, H. and L. S. Petersen (eds.) (2005) The Future Energy System – Distributed Production and Use. Risø Energy Report 4.

Ljungdahl K-G (1951) *Bränsle och kraft: orientering rörande Sveriges energiförsörjning,* Sveriges offentliga utredningar 1951:32, Handelsdepartementet, Stockholm, Sweden.

Martin, N., E. Worrell, M. Ruth, L. Price, R. N. Elliott, A. M. Shipley, J. Thorne (2000) Emerging energy-efficient industrial technologies. LBNL and ACEEE. LBNL 46990.

Matevosyan J (2004) *Wind Power in Areas with Limited Export Capability,* Licentiate thesis TRITA-ETS-2004-01, Royal institute of technology, Stockholm, Sweden.

Nilsson L R (2005) *Svensk vattenkraft ur ett europeiskt perspektiv – några exempel*, LiU-TEK-LIC-2005:13, Linköping institute of technology, Linköping, Sweden.

Nordel (2004) *Activating Price Elastic Demand at High Prices.* www.nordel.org/Content/Default.asp?PageID=129

Nordel (2005) Årsstatistik 2004. www.nordel.org

Nord-Ågren E (2002) *The Electricity Usage Pattern for Cooker Manufacturing in Three European Countries: A Benchmarking Study of Electrolux Factories*, LIU-TEK-LIC-2002:60, Linköping university, Linköping, Sweden.

Parkpoom, S., G. P. Harrison, J. W. Rialek (2004) Climate change impacts on electricity demand. Universities Power Engineering Conference, 2004. UPEC 2004. 39th International

Petersen, L. S. and H. Larsen (eds.) (2005) Technologies for Sustainable Energy Development in the Long Term. Proceedings, Risø International Energy Conference, 23 - 25 May.

Ringel M (2006) Fostering the use of renewable energies in the European Union: the race between feed-in tariffs and green certificates: *Renewable Energy* 31(1): 1–17.

Rummukainen M., Kjellström E., Ólafsson H., Hesselbjerg Christensen J., Bøssing Christensen O., Førland E., Jylhä K., Ruosteenoja K., Räisänen P. (2006) *Final report by the Climate Group*, Nordic project on climate and energy, www.os.is/ce

Rydén B (ed.) (2003) *Nordleden: Slutrapport för etapp 2*, Profu, Götaforsliden 13, SE-431 34 Mölndal, Sweden.

Rydstrand M, Martin V, Westermark M (2004) *Heat driven cooling*, FOU 2004:112, Swedish District Heating Association, Stockholm, Sweden.

Sailor, D. J. and A. A. Pavlova (2003) Air conditioning market saturation and long-term response of residential cooling energy demand to climate change. *Energy*, Vol. 28, pp. 941–951.

SEA (2002) *Marginal elproduktion och CO2-utsläpp i Sverige (Marginal Electricity Production and* CO_2 *Emissions in Sweden*, in Swedish), ER 14:2002, Swedish Energy Agency, Eskilstuna, Sweden.

SEA (2004) *Handel med utsläppsrätter*, ET 24:2004, Swedish Energy Agency, Eskilstuna, Sweden.

SEA (2005a) *Energy in Sweden 2005*, Swedish Energy Agency, Eskilstuna, Sweden.

SEA (2005b) *Prisutvecklingen på el och utsläppsrätter samt de internationella bränslemarknaderna*, ER 2005:35, Swedish Energy Agency, Eskilstuna, Sweden.

SEA (2005c) *Energimarknad – Tema: Stormen Gudrun*, ET 2005:21, Swedish Energy Agency, Eskilstuna, Sweden.

SEA (2006) Programbeskrivning för programmet processintegration, Swedish Energy Agency, Eskilstuna, Sweden.

Skaugen, T. E. and O. E. Tveito (2002) Heating degree days – Present conditions and scenario for the period 2021-2050. Norwegian Meteorological Institute. Report 01/02. Oslo, Norway, http://met.no/english/r_and_d_activities/publications/2002/index.html

Skaugen, T., M. Astrup, L. A. Roald, Torill Engen Skaugen (2002) Scenarios of extreme precipitation of duration 1 and 5 days for Norway caused by climate change. NVE.

Spangenberg J. H. (2002) Environmental space and the prism of sustainability: Frameworks for indicators measuring sustainable development, *Ecological Indicators*, Vol. 2, No. 3, pp. 295-309.

Söder L. (2004) On limits for wind power generation, *International Journal of Global Energy Issues*, Vol. 21, No. 3, pp. 243-254.

Trygg L, Karlsson B (2004) Industrial DSM in a European electricity market - a case study of 11 industries in Sweden, *Energy Policy*, Vol. 33, No. 11, pp. 1445-1459.

Venäläinen, A., Tammelin, B., Tuomenvirta H., Jylhä, K., Koskela, J., Turunen, M. A., Vehviläinen, B., Forsius, J., Järvinen, P. (2004) The influence of climate change on energy production & heating energy demand in Finland. *Energy & Environment* 15(1), 93-109.

Watson, R. T., H. Gitay, D. Griggs, J. Sathaye (2001) Climate Change: 2001. IPCC Synthesis Report. UNFCCC – 7th meeting of the Conference of the Parties., Marrakech, Morocco, 31 October.

Wired (2001) The energy web, Vol. 9.07, pp. 114-127.
World Energy Council (2004) Energy End-Use Technologies for the 21st Century.

11 Appendix: Impact on electricity demand

In a study by Nordel the relation between temperature and electricity demand is analysed. As shown in the table below electricity demand increases with between 5% and 17% of the average demand when the temperature decreases 10^{o}C.

	Temperature dependency			Increase in demand with a 10^{o}C decrease in temperature		Electricity used for heating
	Heating degree days (below 17 ^{o}C)	Cooling degree days (above 20 ^{o}C)	Average demand	% of the average national demand	% of the average Nordic demand	% of the total yearly demand
Denmark	22 MW/ ^{o}C	49 MW/ ^{o}C	4,019 MW	5.5%	0.5%	5%
Finland	86 MW/ ^{o}C	5 MW/ ^{o}C	9,669 MW	8.9%	1.9%	12%
Norway	220 MW/ ^{o}C	124 MW/ ^{o}C	13,129 MW	17%	5.0%	19%
Sweden	269 MW/ ^{o}C	89 MW/ ^{o}C	16,607 MW	16%	6.1%	17%
Total	597 MW/ ^{o}C	267 MW/ ^{o}C	43,424 MW	-	13.4%	15%

Nordel analysis of temperature dependence (Dybdal et al., 2005). Based on data for year 2000-2005. A model of the hourly demand has been used. The model includes a detailed description of the daily and yearly load curves. The last column is calculated by using the number of degree days (se below) and the temperature dependency.

Daily average	Minimum	Maximum	Mean	2 years winter	10 years winter
Denmark	-18.9 ^{o}C	26.5 ^{o}C	8.0 ^{o}C	-9.1 ^{o}C	-14.0 ^{o}C
Finland	-33.3 ^{o}C	24.7 ^{o}C	4.2 ^{o}C	-20.8 ^{o}C	-27.1 ^{o}C
Norway	-22.0 ^{o}C	26.2 ^{o}C	6.0 ^{o}C	-14.8 ^{o}C	-19.7 ^{o}C
Sweden	-24.2 ^{o}C	25.2 ^{o}C	6.8 ^{o}C	-11.9 ^{o}C	-18.6 ^{o}C

Temperatures in the Nordic countries 1960-2005. Data provided by Nordel. The 2 years winter indicate the lowest temperature that can be expected every second winter. The 10 years winter indicate the lowest temperature that can be expected every tenth winter. The 10 years winter is often used when calculating the critical demand.

From the same data as above the degree days for heating and cooling can be calculated. Heating degree-days has been designed as a proxy for the need for heating. It is calculated as the difference between a fixed value of 17^{o}C and the actual temperature. E.g. 1 day with -3^{o}C is equal to 20 degree days.

	Denmark	Sweden	Norway	Finland	Nordic
Heating degree days (basis 17^{o}C)	3,306	3,799	4,086	4,728	
Cooling degree days (basis 20^{o}C)	12	10	8	13	
Heating degree days (basis 13^{o}C)	2,172	2,602	2,863	3,479	
Cooling degree days (basis 16^{o}C)	105	106	86	108	
Change in heating degree days (basis 13 vs. 17^{o}C)	-1,134	-1,198	-1,222	-1,249	
Change in cooling degree days (basis 16 vs. 20^{o}C)	93	96	78	95	
Change in heating degree days (basis 13 vs. 17^{o}C)	-34%	-32%	-30%	-26%	
Change in cooling degree days (basis 16 vs. 20^{o}C)	904%	1,062%	1,086%	810%	
Reduced electricity demand (heating), GWh	-599	-7,728	-6,457	2,578	-17,362
Increased electricity demand (cooling), GWh	109	205	232	11	558
Reduced total electricity demand (due to less heating), %	-1.7	-5.3	-5.6	-3.0	-4.6
Increased total electricity demand (due to more cooling), %	0.3	0.1	0.2	0.0	0.1