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EDITOR: JES FENGER

Impacts of Climate Change on Renewable Energy Sources:

Their role in the Nordic energy system

A comprehensive report resulting from a Nordic Energy Research project

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Edited by J. Fenger

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Nordic Energy Research

was established as a Nordic institution in 1999. It operates under the Nordic Council of Ministers. Nordic Energy Research will contribute to knowledge-based prerequisites for the cost-effective reduction of energy consumption, and to the development of new renewable energy sources and environmentally friendly energy techniques. It will achieve this by increasing expertise at universities, high schools and other research institutions, and by creating first-class research networks between the Nordic countries, between research and industries, and with regional actors.

Nordic co-operation

Nordic cooperation is one of the world's most extensive forms of regional collaboration, involving Denmark, Finland, Iceland, Norway, Sweden, and three autonomous areas: the Faroe Islands, Greenland, and Åland.

Nordic cooperation has firm traditions in politics, the economy, and culture. It plays an important role in European and international collaboration, and aims at creating a strong Nordic community in a strong Europe.

Nordic cooperation seeks to safeguard Nordic and regional interests and principles in the global community. Common Nordic values help the region solidify its position as one of the world's most innovative and competitive.

Contents

Preface

One of the issues in Nordic Energy Research's action plan for 2003–2006 was 'The Consequences of Climate Change for the Energy Sector', later renamed 'Impacts of Climate Change on Renewable Energy Sources: Their role in the Nordic energy system'. This issue has been addressed in a series of interrelated projects on the individual energy sources of hydropower, wind power, solar power and biofuels. In addition to this, there have been projects on climate modelling and statistics. A concluding project on energy system analyses describes in a more qualitative way how the different energy sources may play together in the future.

Nordic Energy Research financed the projects with a total of NOK 11,800,000 for the Nordic activity and NOK 1,000,000 for Baltic involvement. There was also support from the national energy sectors and individual participants.

This comprehensive report presents studies of each source and project in a separate chapter. Two of the project groups, 'hydropower and hydrological models' and 'hydropower, snow and ice' are connected, so their results are described in a single chapter. Each chapter includes a list of the scientific reports and papers that were produced in the course of the work, together with other selected relevant references. Not all of these works are cited in the text.

By and large, each chapter has been written by the principal investigators, but also other authors have contributed. All authors and further contributors are listed in the appendix. The opinions expressed are those of the authors and do not necessarily represent the official attitude of their respective institutions.

Summary

It is generally accepted that human emissions of greenhouse gases upset the thermal balance of the earth-atmosphere system and ultimately lead to global climate changes. The extent of the changes will depend on future emissions of greenhouse gases and will vary between the Earth's different regions. But a central estimate for the Nordic Region is that, by 2100, the temperature will have increased by about 3 °C, average rainfall will be 10% higher and the sea level may have raised 40 cm.

Such changes will have an influence on the production of renewable energy, which plays an increasingly important role in the Nordic Countries. At the same time, the increase in temperature will have an effect on the amount of energy consumed, mainly in the form of a reduction of energy used for heating. A Nordic Energy Research project, with a series of sub-projects, was initiated to study these impacts.

Climate modelling

Two global emission scenarios – the Intergovernmental Panel on Climate Change (IPCC) scenarios A2 and B2 – were chosen. These scenarios have been used in global climate models that typically have a spatial resolution of a few hundred kilometres. This is not sufficient for detailed studies, however, because it does not adequately take into account the influence of topography, weather fronts, storms and various forms of extreme events. In this project, the climate group therefore provided regional climate scenarios ('production scenarios') to be applied by the groups investigating various forms of renewable energy. In principle, the downscaling was achieved by 'nesting' more detailed regional climate models within results from global models.

The resulting regional climate scenarios contain a large number of climate parameters. The basic results are in the form of gridded time series, but they are also available in the form of means or higher-order

statistics. Especially important are temperature, precipitation and wind data, but evapotranspiration, snow and solar radiation are also significant for the purposes of this project.

The regional climate scenarios cover, separately: (i) the Nordic mainland, north-western Russia and the Baltic States; (ii) Iceland; and (iii) Greenland, at 50 km resolution. In all cases, the scenarios target the 2071–2100 period. For (i), a smaller set of two scenarios is also available for the whole of the 21st century. The application of different models gave somewhat different results, which remind us that, other than anticipating a significantly different climate in the future, we cannot predict exactly how this will manifest. In dealing with climate change and its impact, it is necessary to study different scenarios, and climate research should focus on dealing with the uncertainties.

It is acknowledged that, during the course of this project, the IPCC (The Intergovernmental Panel on Climate Change) has prepared a new (fourth) assessment to be published in 2007. In view of the general uncertainty in the subsequent impact analyses, the IPCC's revised assessments are considered to be of minor importance for this project.

Statistical analyses

Climate change studies include scenario analyses and attempts to detect climate change signals in historical data. The statistical analyses group has focused on the latter. Historical streamflow data and climate records from the Nordic and Baltic regions show that trends in annual streamflow are governed by changes in precipitation, whereas trends in seasonal streamflow and extremes are influenced, to a larger extent, by changes in temperature. This was also reflected when a comparison was made between regional time series of temperature, precipitation and streamflow. The observed increase in temperature has therefore strongly affected the hydrological regimes in the Nordic countries. This means that, if the temperature increase is a result of human-induced climate change, the streamflow is changing for the same reason.

A qualitative comparison of the findings of the statistical analysis group and the available streamflow scenarios established by the hydrological models group for the Nordic region showed that the strongest trends are consistent with changes that would largely be expected as a result of a temperature increase in the scenario period (such as increased winter discharge and earlier snowmelt floods). However, some expected changes have not been reflected in the trends so far, such as anticipated increases in autumn discharge and autumn floods. These changes are mainly those caused by an expected increase in precipitation.

Preliminary research indicates that, in some areas, variations in wind energy and hydropower are positively linked because of their shared dependence on the synoptic and larger scale climate; therefore, they show a common source of variability.

Hydropower

Hydropower is currently the most important renewable source of electricity in the Nordic Region, and is the renewable energy most strongly affected by climate. Global warming will shorten the Nordic winter, make it less stable and lengthen the ablation season for glaciers and ice-caps. This will lead to a more evenly distributed river flow throughout the year, a profitable situation for the power industry. There is also potential for increased hydropower production, as the highest modelled increase in river flow is simulated in areas with extensive development of hydropower, such as the Scandinavian mountains and the Icelandic Highlands. This implies that the projected hydrological changes might have practical implications for the design and operation of many hydroelectric power plants, as well as for other uses of water, especially from glaciated highland areas.

The new annual rhythm in runoff indicated in the simulations will put more stress on the spillways, and this is a drawback. The spillways will probably have to be operated more often in winter, because the more variable winter climate will generate more frequent sudden inflows at a time when reservoirs may be full. This will also have an impact on the infrastructure, with more frequent flooding problems downstream of the reservoirs. These areas are currently adapted to the present-day climate, with its stable winters and lack of high flows between autumn and spring.

Global warming thus adds a new aspect to the dam safety issue. Today, this is already a matter of great concern, and a re-evaluation of design floods is being done in Norway, Finland and Sweden. Far-reaching decisions must be made in a climate of increasing uncertainty. This must not hinder the necessary upgrading of existing hydropower systems. In summary, the power industry must develop a new strategy that is characterised by flexibility. This includes the need for structures to be designed to enable them to be adapted as new scientific findings on the impact of global warming are made.

The climate scenarios produced by different models differ quantitatively, especially the scenarios for precipitation in areas that are most developed for hydropower in Norway and Sweden. Generally, however, in Iceland, Greenland, and some glaciated watersheds in Scandinavia, one of the most important consequences of climate change is that of changes in glacial runoff. This will have impact not only on the hydropower industry, but also on roads and other lines of communication.

By and large, the annual runoff from glaciers and icecaps may increase by between 50% and 100% until the middle of the 21st century. Then, as the volume of glacier ice diminishes, it may continually decrease. Present values may be passed around the year 2200.

Wind power

The impact of climate change on wind power is more modest than its impact on hydropower. Changes in average wind speeds influence production of energy, and changes in extreme wind speeds, sea-ice cover and the formation of ice on wind turbines influence the loads on wind turbines and, thus, their design and cost. A study of climate change in relation to the production of wind power is therefore mainly concerned with the prediction of average and extreme values of wind speeds.

The climate models and scenarios have provided input that has been implemented in the form of tools for wind resource assessment and design. A modest change is expected in the average wind speed and wind power potential in the Nordic countries. Of the two scenarios used in the Climate and Energy Project, one indicates an increase of 10–15% in wind power potential, while the other contains large areas with a decrease in wind power potential, in addition to areas where it is increased.

Overall, it was found that there would be limited impact on the design of wind turbines. At some offshore locations, however, an increase of extreme winds was found (in the 10–15% range), meaning that the design of some wind turbine parts is likely to be affected, to ensure they can handle extreme loads.

The results suggest there will be significantly less ice cover in the Baltic Sea, in terms of both duration and geographical coverage, and new areas might be available for development of off-shore wind energy.

Solar power

The sunniest places on Earth receive up to 2,500 kWh/m^2 solar power annually, measured on a horizontal surface. In the Nordic Region, the situation is less favourable. The annual energy density varies between 1,100 kWh/m^2 in the south of the region and 700 kWh/m^2 in the north. A sunny summer's day without clouds may give about 8 kWh/m^2, whereas a cloudy winter's day gives only 0.02 kWh/m^2. In the Nordic countries, therefore, solar energy has so far been restricted to thermal systems and off-grid application of solar cells. With a reduction in the cost of production of solar cells, this situation may change.

The influence of climate change on solar energy production is mainly due to changes in irradiation (*i.e.* cloud cover) and temperature. Extreme weather events may require stronger constructions, but this is considered of minor importance.

There are three principal types of thermal solar system: the accumulation of heat through windows; the conversion of heat in collectors; and the concentration of solar radiation by reflectors. In the Nordic countries, single-glazed windows lead to a net annual energy loss to the outside; double-air-insulating-glazing has a roughly neutral effect; and double-heat-mirror-glazing with argon insulating gas generally gives a net solar energy gain. Future developments might include inert-gas-filled triple-glass windows, but larger areas of these could provide too much heat in summer and require special systems to distribute or store heat. Various types of collector systems are used, for example, to produce hot water or heat swimming pools. The technological development is mainly centred on solar panels that can be integrated in the construction of buildings.

Climate-induced changes in the energy balance have been calculated for Oslo. These show a small net gain in October–December and a net reduction in February–April. More important is a significant increase in the summer months of July and August, which could increase the need for shading and/or cooling and thus lead to increased electricity use.

Whereas climate change increases output from thermal solar systems, it is the opposite case for photoelectric solar cells, where output decreases with temperature. A reduction in snow cover may also reduce the reflectance from the ground and thus the total irradiance. All in all, electricity output could be reduced by a few per cent in Copenhagen, and by about 14% to 23% (according to the scenario used) in Helsinki.

Biofuels

So far, there have been very few studies of the impact of climate change on bioenergy potentials. This sub-project addresses the question of how the projected climate change will influence: the potential for peat production; the production potential of biofuels in forestry; and the potential to produce agricultural residues and energy crops on agricultural land.

Here, 'biofuels' refers to the biomass produced in agriculture and forestry, and to peat excavated from mires and used to produce energy. By and large, it appears that the projected climate changes will increase the potential for production of biofuels.

The production of peat depends upon the number of possible harvesting cycles, which increases with temperature. The average increase in peat production potential is estimated to 12% in Finland, 16% in Sweden and 9% in the Baltic countries. The increase in annual production potential would be 2,400 GWh in Finland, 480 GWh in Sweden, 90 GWh in Estonia, 36 GWh in Latvia and 18 GWh in Lithuania.

Similarly, the productivity of the forest ecosystems increases, mostly in the middle boreal forests such as those in central Finland and Sweden. In the south of Scandinavia and the Baltic countries, however, more frequent periods of drought might reduce the growth increase that would otherwise be induced by the elevation of temperature and CO_2 concentration. In general, the biomass growth in the Nordic and Baltic countries overall could increase by an average of 10–20%.

The total primary agricultural production of potential energy crops in the Nordic and Baltic Regions is 82 million tons per year. Agricultural crops have an energy content of 13 to 22 MJ kg^{-1}, with a consequence that the total annual primary energy production is in the order of 1.3 EJ.

Energy system analyses

How these changes will interact in the total energy system is an important question. For the sake of simplification, the project focuses on electricity, and investigates what impact the calculated climate changes will have on the energy system of 2010. In this case, reasonable assumptions about demand, generation and transmission capacities can be made. Assumptions can also be made about fuel costs and exchange prices within continental Europe.

The analysis shows that total water inflow to the Nord Pool area will increase significantly because of climate change. This increase will take place during winter, and this in turn will reduce the seasonal inflow variations. The forecast temperature changes will result in warmer winters, and will therefore lead to a drop in winter energy demand and fewer seasonal variations in demand. Both of these factors will mean a reduction in the need to use reservoirs to move summer inflow to winter production. Because wind energy and hydro energy are both based on natural resources and are produced at almost zero marginal costs, other changes in the generation of electricity will be caused by changes in these two natural resources. The climate scenarios show only slight changes in wind energy production.

In the long run (between 50 and 100 years), we can assume there will be extensive technological innovation. One obvious possibility is that of local electronic systems that will monitor the net frequency, and shut off refrigerators and other equipment at times of overload. To a large extent, this would compensate for variations in energy production.

Three scenarios for the next 50 years are presented to demonstrate the development possibilities. In the *medium scenario*, many different sources are used to secure energy supply, which favour local – often renewable – resources. The adaptation of electricity consumption by responding to demand can help to absorb variations in wind energy. In the *high-growth scenario*, the 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 a European scale. Large-scale generation technologies dominate. In the *green scenario,* on the other hand, highly efficient technologies are developed and heavy industry is less dominant. There is extensive small-scale energy generation in low-energy buildings.

The scenarios are not worked through in detail, but in all three there are obvious adaptation possibilities, since a moderate increase in the production of hydropower and wind power, or a decrease in demand for heating and an increase in demand for air-conditioning will only have marginal consequences for the energy system. Higher energy costs could also reduce consumption.

General conclusion

In this project, it has not been possible to treat each different energy source in the same way, but the general conclusion is that the climate changes expected during the next hundred years will have significant impacts, especially on the production potential for hydropower in the Nordic Region. These impacts must be taken into account in future energy planning. *Most of the impacts are beneficial and none are catastrophic*. In all probability, however, technological developments in the fields of the production, distribution and consumption of energy will gain in importance and will generally enable adaptations to be made.

We cannot know in detail how the world will develop, so climate projections can only be tentative. Further, we are living in a world that is becoming increasingly interconnected, and this is also true for energy production, distribution and use. An isolated evaluation of the situation in the Nordic Region for a timescale of any more than a few decades is therefore of doubtful value; a continuous evaluation of the situation is called for.

What happens in the coming centuries is beyond the scope of this project, but climate change will probably not stop in the year 2100, and neither will the need to adapt to it.

1 Introduction

Jes Fenger

The increasing greenhouse effect and the overwhelming probability of human impact on the global climate are high on the environmental agenda. The main culprit is carbon dioxide from the use of fossil fuel for energy production, but methane and nitrous oxide (mainly from agriculture) and, for example, industrial CFC-gases also play a role. In addition to this are various minor, less well understood influences from aerosols, land use changes and the depletion of the ozone layer. Further, there is a growing awareness that this is a complex problem with a variety of consequences. One consequence that has so far received little attention is that of the reverse impact of climate change on energy production.

1.1 Climate, energy production and consumption

A mixture of fossil and renewable energy sources is used for global energy consumption, which depends not only on the general standard of living, but also on the climate. Demand for heating will therefore decrease as temperatures increase, but this will be counteracted by the use of more energy for air conditioning. All things being equal, the expected climate changes will by and large reduce energy consumption in the Nordic Countries, however. In other parts of the world, the reverse may be the case.

Climate projections typically extend some 100 years into the future. Throughout this period, technological developments (such as in the storing of energy and increased standards of living) could change all our current ideas of energy consumption. It is especially important to note that the energy market will be increasingly integrated. Demand for air conditioning in southern Europe can thus put pressure on the production of energy in northern Europe, even if local consumption is reduced.

The situation is that fossil fuels affect the climate, but renewable sources do not, to any significant extent. On the other hand, renewable sources are dependent on the climate (for example, wind power is dependent on wind) but fossil fuels are not. Climate change influences energy consumption, irrespective of where the energy comes from. Therefore, the two energy types can, by and large, substitute each other.

This is a problem that Nordic Energy Research became interested in some years ago. One of the issues addressed in its 2003–2006 action plan was therefore the consequences of climate change for the energy sector, taking into account the impact of climate change on both energy production and energy consumption. The plan of action was approved in Helsinki on 10 September 2001, when the issue of climate change was addressed as follows:

> The significance of climate change for future renewable energy production in the Nordic countries and the Baltic Region.
> A compilation of information in order to predict future changes in wind pattern and thus to optimise future energy production based on wind and wave power. There will be a need to optimise the future production of electricity based on hydropower under changed climatic conditions, including changed conditions of precipitation. Further, it is important to develop optimal forms of production of biomass under changed climatic conditions. The production of biomass in forestry in the Nordic countries is sensitive, *i.e.* in relation to temperature, precipitation and extreme wind conditions. A tool in the evaluation of the above can be the development / refinement of climate models at a regional scale, *i.e.* the Nordic countries and the Baltic Region.

1.2 The proposed project

The planning workshop

As a first step, Nordic Energy Research allocated NOK 300,000 for a workshop to map relevant current research activities and research needs related to the impacts of climate on the Nordic energy sector, as a basis for establishing a new research programme. The workshop was organised by representatives from the five Nordic countries:

- Jes Fenger, DMU, Denmark
- Kristin Aunan, CICERO, Norway
- Bengt Tammelin, FMI, Finland
- Arni Snorrason, Institute of Energy, Iceland
- Sten Bergström, SMHI, Sweden.

The workshop was held in Copenhagen on 8–9 November 2001, and gathered together about 30 participants. Because the eventual goal of the workshop was to be a proposal for a research programme, the focus was on the brainstorming sessions about the future. The following key questions were identified:

- How will the Nordic energy situation develop?
- How will the climate change?
- How does the climate impact on energy demand?
- What are the direct impacts of climate change on the methods of production?
- What impacts on the energy market and energy system can be anticipated?
- Can Nordic experiences and know-how be 'exported' and used internationally?

There is a classic work of environmental literature called 'Small is Beautiful', which advocates renewable energy. A major problem, however, is that renewable energy sources that could mitigate emissions and climate change are generally *not* small any more, and they are certainly not always beautiful. During the discussions, it was acknowledged that renewable energy sources could themselves have an impact on the environment.

Background and scope

It was agreed that the proposed project should be a comprehensive study, aimed at creating awareness of this complex problem among governments, power companies and decision-makers in general. By doing so, it would lay the foundations for far-sighted, flexible planning. It was therefore crucial that the energy sector should be involved, and that the results (and the flow of information in general) should be published. A reference group that included representatives from the energy sector was established to review the content and results of the project, and to plan and prioritise impact assessments. Another group was also established, to take responsibility for all information management and dissemination concerning the project.

Since the future climate depends on general global development, with the attendant wide margin of uncertainty, the studies were (as far as possible) to be conducted as sensitivity analyses on the basis of a range of climate scenarios. It was also noted that the timescale might be 25, 50 or even 100 years, and therefore, by the time the impact has set in, available technologies and the energy market might be significantly different from today.

After consultations with Per Øyvind Hjerpaasen, then director of Nordic Energy Research, a proposal was worked out by Jes Fenger and Árni Snorrason with the assistance of Kristin Aunan (Cicero, Norway). It was based on two previously submitted project proposals:

> 'Consequences of Climate Change in the Energy Sector'
> (Jes Fenger, National Environmental Research Institute, Denmark)

and the already established

> 'Climate, Water and Energy'
> (Árni Snorrason, Hydrological Service, National Energy Authority, Iceland).

Project organisation

The organisation of the project was based on an extension and generalisation of the organisational structure of Nordic Energy Research's Climate, Water and Energy (CWE) Project. Árni Snorrason (Iceland) took on the responsibility of project manager, and Jes Fenger (Denmark), Kristin Aunan (Norway), Björn Karlsson (Sweden) and Bengt Tammelin (Finland) formed a steering group to assist in the management of the project. The Baltic countries were involved in the project in various ways described in the text, but did not participate directly in the management.

A CWE reference group, consisting of representatives from the energy sector, was strengthened to include all aspects of the project. The reference group's role was considered essential for the planning and management of the project, and it reflected all the main stakeholders concerned with the climate/energy issue.

The reference group's task was to identify key problem areas for the energy sector, critically review the groups' action plans and final products, and advise on the application of climatic and hydrological scenarios for the energy sector.

The reference group would be funded by the energy sector. The direct application of the project groups' results to key areas of sensitivity in the energy sector (such as sensitivity to floods and droughts, changes in seasonal river flow etc) would also be funded by the energy sector.

NOK 11,400,000 were allocated from Nordic Energy Research for the Nordic activities, including NOK 1,600,000 for the Baltic involvement. The national energy sectors in Norway, Sweden and Iceland contributed a total of NOK 1,800,000 and the participants contributed with related programs and research projects.

1.3 The final project and report

The project

The final project treated different renewable energy sources in five working groups:

1. Hydropower, snow and ice
2. Hydropower, hydrological models
3. Biofuels
4. Solar energy
5. Wind power

In addition to this, the following crosscutting groups were established:

6. Climate scenarios
7. Statistical analysis
8. Energy system analyses
9. Information management.

The groups on climate scenarios, statistical analysis and information management were already established under CWE.

The working group on energy system analyses was particularly important, since its task was to plan and carry out the actual impact assessments on the energy sector under the various climatic scenarios. It was therefore important for this group to have strong representation from all participating countries, and for the other countries around the Baltic Sea to be consulted and take part as active participants.

In general, the project was based on established, ongoing studies, which were given longer timescales and expanded to include the climate change dimension. It asked the essential questions of *how* and *when* the climate will change. It was specifically *not* the intention to initiate new climate studies, but to use existing knowledge as much as possible. If necessary, attempts would be made to influence ongoing climate projects in order to supply a consistent set of climate data for all sub-projects at marginal cost. The information management group created a framework for the exchange of information within the project, and for the export of information to stakeholders and the public about progress and results. The project organisation is shown in Figure 1.1.

The European Conference on the Impact of Climate Change on Renewable Energy Sources held in Reykjavik on 5–9 June 2006 was essentially devoted to preliminary presentations of results from the project (Árnadóttir, 2006).

The report

This final report is a comprehensive presentation of all the project's individual investigations. It attempts to connect them, using general descriptions of energy systems and policy, while most of the scientific results have been or will be published in more detail in larger reports from the individual working groups. References are given in the relevant chapters.

The following questions have been addressed for each of the four renewable energy sources (although not all in the same detail):

- Production potential in various climate scenarios
- Critical climate parameters (precipitation, wind, cloud cover etc)
- Time pattern on different scales
- Sensitivity to extreme events
- Environmental impacts
- Possibilities for local and centralised energy storage and/or transfer (with the possible exception of biomass) crucial for all renewable energy sources
- Area requirements.

Ideally, the project would have used climate scenarios that had been fully worked out before it started investigating their impact on the dif-

Project Management: Árni Snorrason, Iceland

Steering Group
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Kristin Aunan, Norway
Björn Karlsson, Sweden
Bengt Tammelin, FInland

Reference Group from Energy Sector
Elías B. Elíasson, Ideland
Lars Hammar, Sweden
Tom Andeersen, Norway
Malene Hein Nybroe, Denmark

	Hydropower, Snow and Ice Tómas Jóhannesson Iceland	**Hydropower Hydrological Models** Sten Bergstöm Sweden	**Wind Power** Niels Erik Clausen Denmark	**Solar Energy** Audun Fidje Norway	**Bio Fuels** Seppo Kellomäki Finland
Climate Scenarios Markku Rummukainen Sweden					
Statistical Analysis Hege Hisdal Norway					
Energy Systems Analysis Birger Mo Norway					
Information Management Jóna Finndis Jónsdóttir Iceland					
Final Report Jes Fenger Denmark					

Figure 1.1 Organizations of the Climate and Energy Project (CE) 2003–2006.

ferent energy sources, but this was not possible in practice. The uncertainties this has introduced are of minor importance, however, compared to the general uncertainty of the evaluations. More important is that climate change takes place in a global society under rapid development, and we do not know how the world will look in 50 or 100 years' time.

Renewable energy sources are, to a large extent, connected to electricity production. Solar power is also used directly for heating, and biomass is used for heating and the production of fuel for vehicles. This gives a somewhat biased view of the situation in the different Nordic countries. Roughly half of energy consumption is used for heating, but in Norway a substantial part of heating is based on electricity, whereas in Denmark practically all heating is based on fossil fuels and, to a minor extent, bio-fuels.

1.4 Literature

Árnadóttir S (2006) *European Conference on Impacts of Climate Change on Renewable Energy Sources* (Abstract Volume). Nordic Energy Research. (228 pp).

2 The problem

Jes Fenger

2.1 The greenhouse effect and climate change

The atmospheric concentrations of what are known as 'greenhouse gases' – carbon dioxide (mainly from energy production), methane and nitrous oxide (mainly from agriculture) and various industrial gases – are increasing. This leads to a shift in the thermal equilibrium of the atmosphere and an upward trend in surface temperatures. This, in turn, leads to changes in precipitation, cloud cover and wind patterns. The warming further leads to a rise in sea levels, partly due to the melting of glaciers and partly due to the thermal expansion of seawater. Already, the global mean temperature has risen about 0.6°C during the last century, and there are indications of impacts on various ecosystems.

It is uncertain what will happen in the future, however, mainly because we don't know how the world will develop. The Intergovernmental Panel on Climate Change (IPCC) has described a series of emission scenarios for the next 100 years, covering 40 combinations of growth in global population (from 7 to 15 billion) and growth in GDP (by a factor of 11 to 26), and a variety of distributions of energy production from fossil and non-fossil sources (IPCC, 2000). The scenarios are divided into four families according to whether they emphasise the economy or the environment (scenarios A and B), and whether they emphasise global or regional solutions (scenarios 1 and 2). Scenario A1 is further divided in terms of its emphasis on fossil fuels (A1FI), non-fossil fuels (A1T) and a balanced mixture (A1B). For each family, a representative marker scenario is designated.

Scenario A1 imagines a world with rapid economic growth and the introduction of new, more effective, technologies. The increase in population culminates around 2050. Scenario A2 presents a more homogeneous world, with an increasing population and slower technological development. To some extent, the world in scenario B1 is similar to that in A1, but with more emphasis on service, an information-based economy and sustainable technologies. Finally, scenario B2 assumes continued growth in population – although slower than in A2 – and a slower and more diverse development of technology than in A1 and B1.

All of these scenarios imply increasing *emissions* during the next few decades. In some, the emissions peak and start to decline towards the end of the century, but none of the reductions lead to a reduction in atmospheric *concentrations*. In all cases, the global climate models therefore project a warming (of 1.4 to 5.8°C) during this century and a further rise in the next centuries. A global rise in sea level of between 9 cm and 88 cm is anticipated for this century, and the rise may continue for several centuries (IPCC, 2001).

There has been some criticism about the assumptions underlying the scenarios, such as relating to development in (so far) developing countries, but this does not influence the basic spread in the results.

In its fourth assessment report, the IPCC (2007) anticipates temperature rises ranging from 1.1°C to about 6.4°C in the year 2100 – not much different from the 2001 results. The sea level is assumed to rise by between 18 cm and 59 cm.

The spatial resolution of global climate models is seldom better than 200–300 km so they are not generally satisfactory for detailed studies of the impact of climate change. Regional models can be nested in global results, for example, the way the Danish Climate Centre did with the HIRHAM4 model, which compares the climate for northern Europe around 2075 with that around 1990. This shows a general warming, which is largest in the north, during winter and at night. Further, it shows a tendency towards a wetter climate with more frequent heavy showers and increased precipitation. See also chapter 4.

It should be noted that other simulations give different results, especially at the more detailed level. So far, what we can say about the north with reasonable certainty is that: qualitatively, it will become warmer; some seasonal and geographical patterns of change are fairly robust; precipitation will increase and more will fall in the form of rain instead of snow; and winds will possibly be stronger. Changes in received solar radiation are uncertain, but a reduction of this, due to increasing cloud cover, cannot be excluded.

Many aspects of the climate are expected to change. Of particular interest are possible changes in variability and possible non-linear changes in extremes. Within the Climate and Energy Project, the climate group was tasked to provide regional climate scenarios ('production scenarios') for the project to use in assessing the possible impact of climate change on regional hydropower, wind energy, biomass production, solar energy and energy system analyses. A secondary task was to describe how these regional climate scenarios relate to a more complete knowledge-base on climate change (setting the Climate and Energy Project production scenarios in perspective. cf. Chapter 4).

2.2 Impacts on renewable energy sources

Climate change will have an impact on practically all natural systems and human enterprises. Popular expositions of this have been given for the Nordic countries (*e.g.* Jørgensen *et al*, 2002; Bernes, 2003; Mikkelsen, 2005), but the production of energy from renewable sources has largely been ignored. In this investigation, hydropower, wind power, solar energy and biomass are considered. Impacts on other sources of renewable energy (such as wave power and geothermal energy) can be assumed to be unimportant.

Hydropower is by far the most important renewable energy source for electricity production in the Nordic countries. In general, increased precipitation results in higher production potential and, since production is flexible, it may partially be used for peak load. However, because of changes in temporal pattern (including probable smaller spring floods and bigger autumn floods, and possibly more extreme events), there is also a need to adjust dam safety and regulation instructions. This may have a negative impact on the recreational use of reservoirs and other parts of the watercourses. Finally, changes in electricity demand – both geographical and temporal – may require adjustment of the transmission lines, which could be burdened in a different way. In the long run (100 years or more), the melting of glaciers can reduce the output.

Wind power is rapidly becoming an important factor in electricity production. This is especially the case in Denmark, which (directly or indirectly) accounts for half the world's production of wind turbines. Wind turbines are growing bigger; over the last 20 years, the average output of a wind turbine has increased from less than 50 kW to nearly 1,000 kW and the diameter of rotors has increased from 15 m to up to 70 m. At the same time, the construction of more wind turbines has been met with increasing resistance. Increasingly, offshore wind parks are being constructed and, in the case of these, a rise in sea level must in principle be taken into account, although the lifetime of individual wind turbines is probably shorter than the timescale for significant sea level rise.

A major drawback of wind power is that it fluctuates constantly. This may be compensated to some extent by the linking of systems in different locations, and it is therefore more of an economic problem. A further possibility is the development of steering systems that fit the wind power into the general production scheme on the basis of wind forecasts. A full exploitation of wind power requires the establishment of energy storing systems that are based, for example, on hydropower or the production of hydrogen.

Solar energy, which uses solar radiation directly for energy production, can take a number of different forms. Passive heating of buildings (for example, in the form of windows) is an established technique, and one that should be exploited more, possibly in connection with new building styles in a changed climate. Solar collectors are also well known; these are normally economically feasible, but not always satisfactory from an architectural point of view. They should be included in the design of buildings from the beginning of the design process, and not simply added as an afterthought, as can often be seen at the moment. The production of electricity with various forms of photocells is a promising technical possibility, but is so far only economically competitive for special applications. Large-scale production (in, for example, the Sahara) might be an option in the future.

Biomass production is influenced not only by climate change but also by its chief cause – the rising concentration of CO_2, which is the key element in photosynthesis and thus acts as a fertiliser. In addition to this, biomass is an adjustable fuel that can be used either directly or in converted form, for example, for transport. The (not negligible) drawbacks are that it uses potential agricultural areas for food production and there is a risk of pollution from increased use of fertilisers and pesticides.

2.3 Change in demand and distribution

One important aspect of the impact of climate change on energy production is the resulting change in demand. In the Nordic countries, a large part of the total energy is used for heating. It has been estimated that a temperature rise of 4°C in Denmark could reduce the energy necessary for heating by 25%, although this benefit may be offset to some extent by the introduction of air-conditioning. Other savings (for example in defrosting) are also possible.

By and large, the anticipated climate changes might reduce Nordic energy requirements. On the other hand, climate projections normally cover a timescale of 100 years, during which time technological developments and changes in standards of living may offset any predictions about energy use (as was clearly demonstrated in the wide variation between the IPCC emission scenarios). In connection with this, it is also important to note that the energy markets are interrelated, and will probably be increasingly so. Rising demands for air conditioning in the south of Europe, for example, could thus influence the situation in the Nordic countries.

Stronger links between the various energy sources over longer distances can solve distribution problems. The varying output from windmills can thus be compensated by connecting mills from a larger area, or by storing surplus production in water reservoirs and adapting demand.

One problem with studying the impact of climate on the production of energy is that climate changes have different timescales, and can take place over decades or centuries, whereas industrial investment is not normally planned further than about 10 years ahead. Estimates of climatic impact may therefore, to some extent, be based on outdated models of technology and society.

2.4 Literature

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3 The Nordic energy situation

Jes Fenger

Globally, the primary energy supply is based on approximately 80% fossil fuels, 7% nuclear energy, 11% combustible renewable material and waste, 2% hydropower and less than 1% of all other energy types, including geothermal, solar and wind (IEA, 2005). Thus, on a global basis, the contribution of renewable energy sources is, so far, modest. In the EU, the contribution of renewable energy sources has increased from 4.3% in 1990 to 5.5% in 2002. In the Nordic countries, however, the situation is different, with renewable energy sources contributing up to 75%.

3.1 The individual countries

The following information is taken from *Key World Energy Statistics* (IEA, 2005) and *The European Environment* (EEA, 2005).

Denmark

Domestic energy production has increased from practically nothing in the 1970s to about 28 Mtoe/yr in 2002, mainly in the form of oil and gas production. Final consumption (16 Mtoe/yr) has been nearly constant in the same period, and may increase slightly in the coming years. There is practically no hydropower, with no possibility of this being developed; and nuclear power has been abandoned. Combined renewable sources and waste accounted for 10.5% of the total primary energy supply in 2002 (20 Mtoe/yr) and this percentage is planned to increase. Wind power accounts for another 2.6% and fossil fuels for the remaining 87%.

Annual electricity production is 39,000 GWh, of which 4% is with biomass and 16% with wind. Heat production is 122,000 TJ/yr, of which 9% is with biomass; this is planned to increase to 50% by 2050.

Finland

Domestic energy production has tripled since the 1970s to about 16 Mtoe in 2002, mainly due to the introduction of nuclear power. Renewable energy use has also increased, and it is planned to increase this further by 30% between 2001 and 2010. Final consumption has increased by more than 40% since 1970. In 2002 combined renewable energy sources and waste accounted for 20.5% of the total energy supply (36 Mtoe/yr), hydropower for another 3%, nuclear power for 17% and fossil fuels for the remaining 60%.

Annual electricity production is 70,000 GWh, of which 12% is with biomass and 18% with hydropower. Annual heat production is 125,000 TJ, of which 20% is with biomass.

Iceland

Domestic energy production has increased about fivefold since the 1970s and is now nearly 2.5 Mtoe/yr, mainly because of an increase in geothermal energy, but also due to the production of hydropower having more than doubled. Of the total primary energy supply (about 3 Mtoe/yr), 55% is provided by geothermal (including some solar and wind), 18% by hydropower and the remaining 27% by fossil fuels.

Geothermal energy is dominant for heating (86% of 9,000 TJ/yr), and hydropower is dominant for electricity production (84% of 7,200 GWh/yr).

Norway

Domestic energy production has increased enormously since the 1970s and is now about 230 Mtoe/yr. This is due to the development of oil production and, to a lesser extent, gas. Final consumption has increased in the same period by about 35% to 21 Mtoe/yr. Total energy supply (about 27 Mtoe/yr) is provided by hydropower (41%) and combined renewable energy sources and waste (5%). The remaining 54% is provided by fossil fuels.

Land-based energy production is dominated by hydropower, which accounts for almost all the 123,000 GWh/yr. There are controversial plans, however, for land-based gas-fired power plants to strengthen the security of supply. Heat production is to a large extent electrical, with just 2% of 7,600 TJ/yr provided by biomass.

Sweden

There was nearly a fourfold increase in total domestic energy production between the beginning of the 1970s and the end of the 1980s, almost exclusively because of the introduction of nuclear power. Since then, total production has been nearly constant at about 32 Mtoe/yr, with final consumption nearly constant at about 35 Mtoe/yr in the same period. The primary energy supply (about 50 Mtoe/yr) is provided by hydropower (11%), combined renewable energy sources, including waste (16%) and geothermal, solar and wind (1%). Fossil fuels (37%) and nuclear energy (35%) provide the remainder.

Sweden has a substantial share of hydropower and some wind power, but is still highly dependent on nuclear energy. Electricity production is 155,000 GWh/yr, of which 2% is with biomass and 45% with hydropower. Heat production is 168,000 TJ/yr, of which 42% is with biomass.

The Baltic countries

In Estonia, primary energy use stabilised after a reduction at the beginning of the 1990s, and now stands at about 200,000 TJ/yr. The target of 12% of total consumption to come from renewable energy by 2010 has been achieved already, due to the use of biomass for heating. In 2002, renewable energy contributed only 0.2% to electricity production. It is planned to increase this to 5.1% by 2010.

Latvia has undertaken to produce 49.3% of its domestic electricity consumption by renewable energy (hydropower).

In Lithuania, nearly 10% of total energy consumption is produced by renewable sources. It has a commitment to produce 7% share of its electricity from renewable sources by 2010.

3.2 General development to date – and beyond

Although the use of renewable energy is quite different in the various Nordic countries, it plays an important role overall. Hydropower accounts for more than 50% of electricity production, mostly in Norway, Iceland and Sweden. Biomass is responsible for 3% and wind power for 1% (almost all of which is in Denmark). Solar power has, so far, played an unimportant role. For heat production, 34% is accounted for by biomass, mainly in Sweden and Finland. Solar heating has been unimportant so far. For transport, renewable energy has so far played practically no role. Transport accounts for between 18% (Finland) and 31% (Denmark) of final energy consumption, and this explains why fossil fuels are still an important energy source overall. The situation might change if fuel production based on biomass is expanded.

In spite of the large differences between them, the Nordic countries share some similarities in terms of their energy situations. For all of them, demand for energy is expected to rise in the order of 0.5% per year unless special measures are taken; and in all countries, some types of renewable energy source play (or are planned to play) an increasing role. Further, the national electricity production systems of all the countries are closely linked, and an impact in one country may have consequences in another through the integrated Nordic energy market.

3.3 Literature

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4 Climate scenarios

Markku Rummukainen, Kimmo Ruosteenoja and Erik Kjellström

Climate scenarios are a prerequisite for many evaluations of climate impacts. Global climate models normally only give a resolution of a few hundred kilometres; therefore, as described here, various regional downscaling techniques are employed to provide climate scenarios for more detailed impact studies. More detailed descriptions, additional results and other work that has been conducted on selected knowledge gaps on climate processes are given by Kjellström *et al* (2005), Benestad *et al* (2005) and Ruosteenoja *et al* (2006, 2007).

Various abbreviations and acronyms are used to label the scenarios and models; full names are given in the appendix.

4.1 Material and methods

Global climate models and emission scenarios

The Climate and Energy Project (CE) production scenarios are based mainly on two global climate models (GCMs): the ECHAM4/OPYC3 (Roeckner *et al*,1999) and the HadAM3H (Gordon *et al*, 2000). In addition, some results from a total of six GCMs are used to set the production scenarios in perspective, in terms of seasonal temperature and precipitation (*i.e.* the CGCM2, CSIRO Mk2, ECHAM4/OPYC3, GFDL R30, HadCM3 and NCAR DOE PCM; see McAvaney *et al*, 2001). Selected results from an even larger number of GCMs are considered in empirical-statistical downscaling of climate scenarios to a number of Nordic locations (see Benestad *et al*, 2005).

Of the different SRES emission scenarios (IPCC, 2000), the CE production scenarios follow the A2 and B2 cases. The availability of climate change projections for the other emission scenarios is very limited. In setting the production scenarios in perspective, pattern-scaling is applied to extend available regional temperature and precipitation projections even to emission scenarios and climate models that have not been explicitly used.

Due to the nature of the climate system, global climate models are an absolute necessity, even when attention is focused on regional climate change. Global models do not, however, adequately account for the more detailed features in space and time, such as the influence of topography (regional water masses, orographic enhancement of precipitation, and rain shadow), weather fronts, storms and various extremes. Special regionalisation techniques are used to complement global climate scenarios with such detail. This especially facilitates quantitative climate impact assessments. In CE, the main regionalisation technique is regional climate modelling, also known as dynamical downscaling.

Regional climate modelling

The CE production scenarios are made with two regional climate models (RCMs), the Swedish RCA (Jones *et al*, 2004; Räisänen *et al*, 2003, 2004; Kjellström *et al*, 2005) and two versions of the HIRHAM, one in Denmark (Christensen *et al*, 1996; Kiilsholm *et al*, 2003) and the other in Norway (Haugen & Ødegaard, 2003; Haugen & Iversen, 2005). As in the earlier climate, water and energy (CWE) project (Rummukainen *et al*, 2003), the CE regional climate scenarios are adapted from other efforts in national and European projects, especially PRUDENCE (Christensen *et al*, 2007). This is cost-effective, but also compromises the comprehensiveness of the results to some degree.

In CWE, a common regional climate scenario was created from available regional climate scenarios. These were combined by means of pattern-scaling to a composite scenario for the 2050s. In CE, separate scenarios are provided for the Nordic mainland, Iceland and Greenland. In the case of Greenland and Iceland, HIRHAM-based scenarios are made available for the period 2071–2100. For the Nordic mainland, scenarios made with RCA are available throughout the 21st century. The regional modelling domains are shown in Figure 4.1.

The CE regional scenarios were made at 50 km resolution, with mostly six-hourly model output for a large number of climate variables including temperature, precipitation, wind and snow.

The following convention of identifying these simulations is adopted: 'RCM-GCM-emission scenario'. As mentioned above, the 'RCM' is one of the CE regional climate models (the RCA or the HIRHAM). In

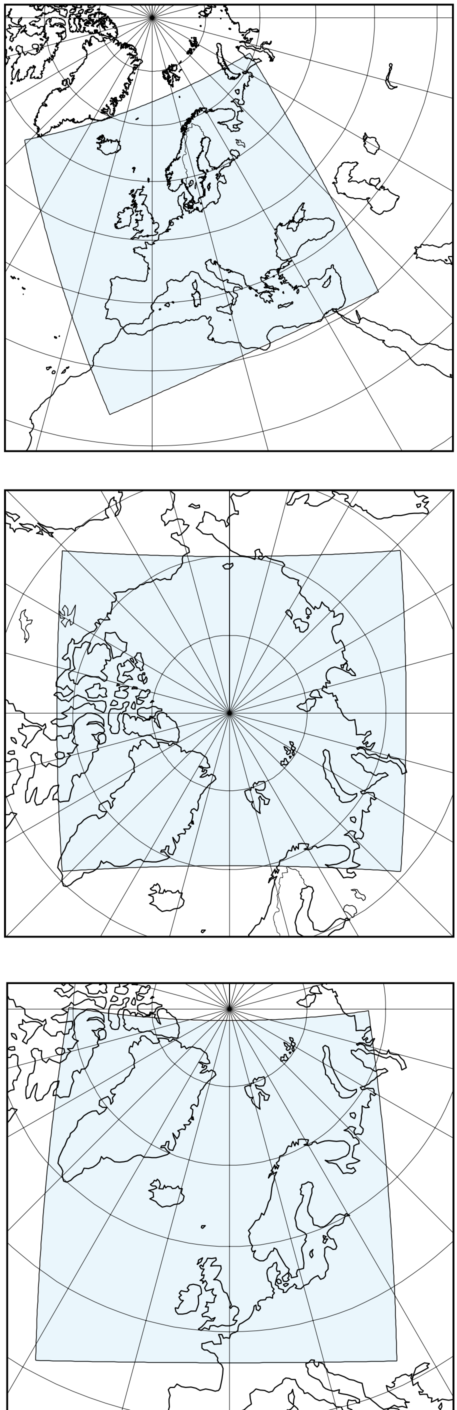

Figure 4.1. The CE regional model domains, from the top: RCA (Nordic mainland), HIRHAM (Greenland) and HIRHAM (Iceland). In each case, the domains are set up within other projects for regional climate modelling for larger European and Arctic regions. The actual modelling domain is enclosed by the shaded inner rectangles.

fact, two different versions of both of these models have been used. This distinction is made in the remainder of this report, if it has special significance. The 'GCM' is one of the two global climate models that have provided boundary conditions for the RCMs, either ECHAM4/OPYC3 (E) or HadAM3H(H). The 'emission scenario' is one of the SRES A2 and B2. In one instance, results from the ECMWF global reanalysis experiment ERA40 is used as boundary conditions instead of results from some GCM.

In addition to the RCM results used for the production scenarios, some results are also considered from the larger number of RCMs that contributed to the PRUDENCE project. Together with the GCM-analysis, this helps in setting the production scenarios in perspective.

Pattern-scaling

Whereas different emission scenarios reflect alternative plausible futures, with implications for the amount of climate forcing and subsequently climate change, different climate models can be taken as plausible alternatives of the sensitivity of the climate system. There is no perfect model, due to incomplete knowledge of various climate processes, lack of measurements or measurement precision, and limited computing resources. Even though methods are now emerging that enable us to place some measure of confidence on models, it is still necessary to consider as many emission scenarios and climate models as possible within the availability of model studies.

In order to compose climate scenarios for emission scenarios, periods and climate models that are not explicitly modelled, an approximation called pattern-scaling can be used to extend available scenarios to other emission scenarios and time periods (Christensen *et al*, 2001; Rummukainen *et al*, 2003; Ruosteenoja *et al*, 2007). This is done in CE, both to extend available GCM results to additional emission scenarios and to extend such RCM results that are available only for 2071–2100 to an earlier period. The scaling is based on simulated or emulated (Raper *et al*, 2001) global mean temperature change.

Pattern-scaling is an approximation and needs to be applied with care. In CE, pattern-scaling of RCM results is applied for seasonal mean temperature and precipitation over relatively large sub-regions (Figure 4.7). Some of the results are shown in Figures 4.8 and 4.9.

4.2 The CE production scenarios

CE scenarios for the Nordic mainland

For the Nordic mainland, two sets of regional climate scenarios were adopted. The first suite consisted of four RCAO runs for 2071–2100 (Räisänen *et al*, 2003, 2004) also employed in the PRUDENCE project (Christensen *et al*, 2007). These were based on two GCMs and two emission scenarios. The second suite consisted of two RCA3 regional climate model runs for 1961–2100 (Kjellström *et al*, 2005), with boundary conditions from one GCM and two emission scenarios. The availability of such long-range regional climate scenarios is a major advantage for climate impact analyses, as the transience of climate change (*i.e.* climate changes over time) can be taken into account and there are consistent scenarios for short, intermediate and longer timescales. These longer runs also facilitate an evaluation of pattern-scaling techniques.

Global climate simulations and subsequent regional climate simulations typically cover a period of the recent past (sometimes called a 'control simulation' or 'present-day simulation'), in addition to future projections. Due to any systematic biases that might exist in models, scenario results are often considered as changes from the present-day period to the chosen future period. A well-behaved model should, nevertheless, in present-day mode provide a decent match with the recent climate in terms of climate statistics. In regional climate modelling, there is an additional technique to evaluate the skill of the model. This can be done by applying global meteorological analyses as boundary conditions – such as the ECMWF 40-year re-analysis known as ERA-40 (Uppala *et al*, 2005) – instead of a GCM simulation. Below, some such results are considered for the regional climate model RCA3. This simulation is called RCA3-ERA40.

Before turning to the regional climate scenarios for the Nordic mainland, some relevant features of the RCA3-simulated 1961–90 conditions based on the ECHAM4/OPYC3 GCM are discussed in brief. (RCA3-E signifies this GCM-forced 1961–90 run. The corresponding scenario simulations discussed later are RCA3-E-B2 and RCA3-E-A2.) The seasonal cycle of the north-south pressure gradient between Portugal and Iceland in RCA3-ERA40 and RCA3-E is shown in Figure 4.2. This is a measure of the North Atlantic Oscillation (NAO) that is

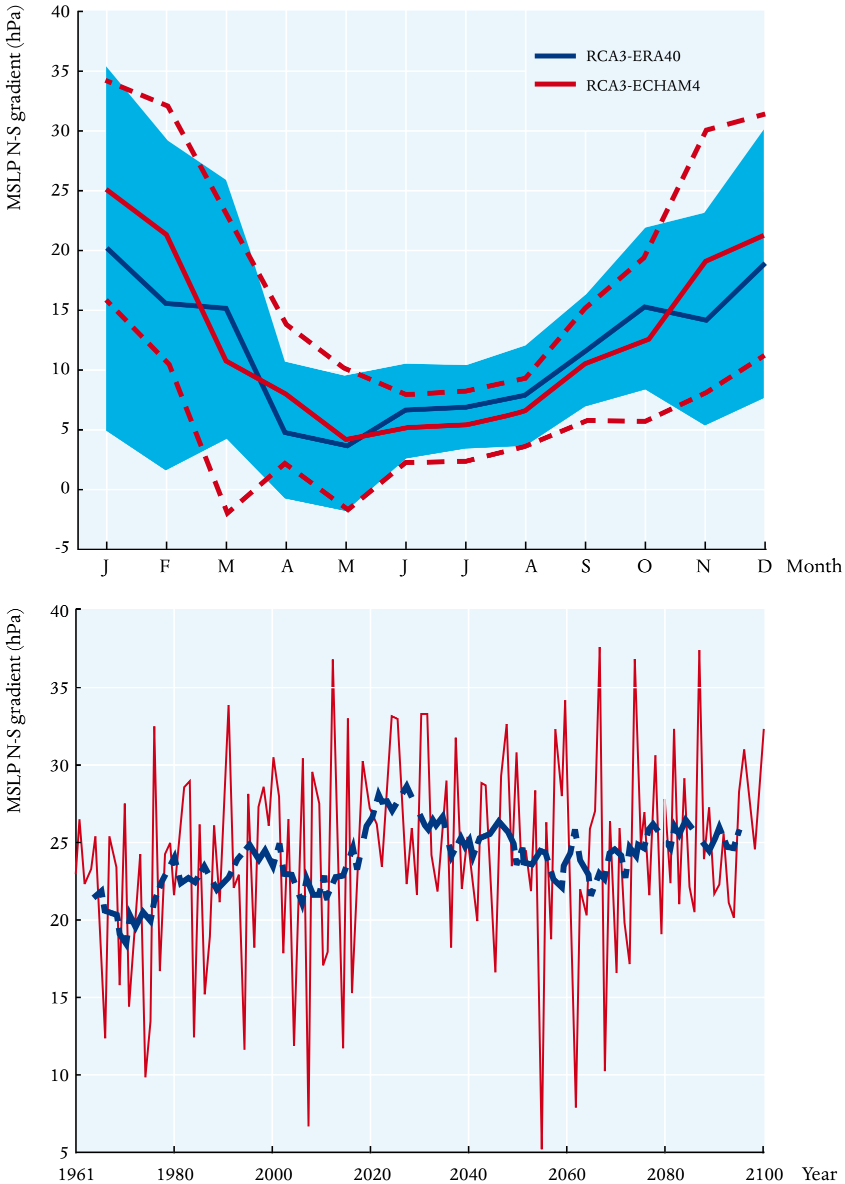

Figure 4.2. Simulated north-south MSLP gradients in RCA3.
Top: 30-year (1961–1990) monthly means (full lines), with a measure of the inter-annual variability (plus/minus one standard deviation) drawn with a shaded blue area for RCA3-ERA40 and with dashed lines for RCA3-E.
Bottom: The RCA3-E-B2 evolution of the gradient during an extended winter season (November-February, NDJF). The red line shows annual values. The blue line is a 30-year running mean.

of particular interest for regional climate variability, especially in winter. The seasonal cycle is captured, but at the same time is somewhat too strong in RCA3-E. In subsequent climate scenarios, there is a further enhancement of the impact of the NAO.

The NAO is such a large-scale feature that its behaviour is a characteristic of the driving GCM, rather than the RCM. There is a general tendency in GCMs towards more positive NAO conditions under global warming, although the exact response varies. This is exemplified by a comparison (Figure 4.3) of RCAO regional climate scenarios that were based on two different GCMs, the ECHAM4/OPYC and the HadAM3H. In the former, there is the same pronounced NAO-response as was discussed above. In the latter, the NAO does not change much. In both cases, the projected global mean warming is very similar. The same is true, to a large extent, for regional patterns of temperature and precipitation changes. These are, however, larger in magnitude in the case of ECHAM4/OPYC3 than for the HadAM3H. In particular, the projected near surface wind changes are distinctively different.

When the transient RCA3 regional climate scenarios RCA3-E-B2 and RCA3-E-A2 became available during CE, they received quite a lot of attention. Impact studies became more feasible for the whole of the 21st century. In Figure 4.4, regional climate changes in RCA3-E-A2 are depicted for temperature, precipitation and wind speed for successive 30-year periods until 2100. This illustrates the transient nature of regional climate change, the changes becoming successively more noticeable. It also appears that the patterns of change plant themselves very early on, which is indicative of the effect of climate change throughout the 21st century. In a subsequent application of these results, it is found that pattern-scaling techniques as applied in, for example, CWE, which are based on the global mean temperature increase, do not work well for all variables and seasons (Kjellström & Bärring, 2006).

The calculated warming is larger in winter than in summer in northern and eastern Europe, whereas the opposite is true for southern Europe. Precipitation especially increases in winter in northern Europe. In summer, the Mediterranean and central European region, all the way up to southern Scandinavia, experience reduced precipitation. Calculated regional changes in 10 m winds are largest in winter, with some tendency for the largest increases to occur over water bodies with reduced sea-ice cover.

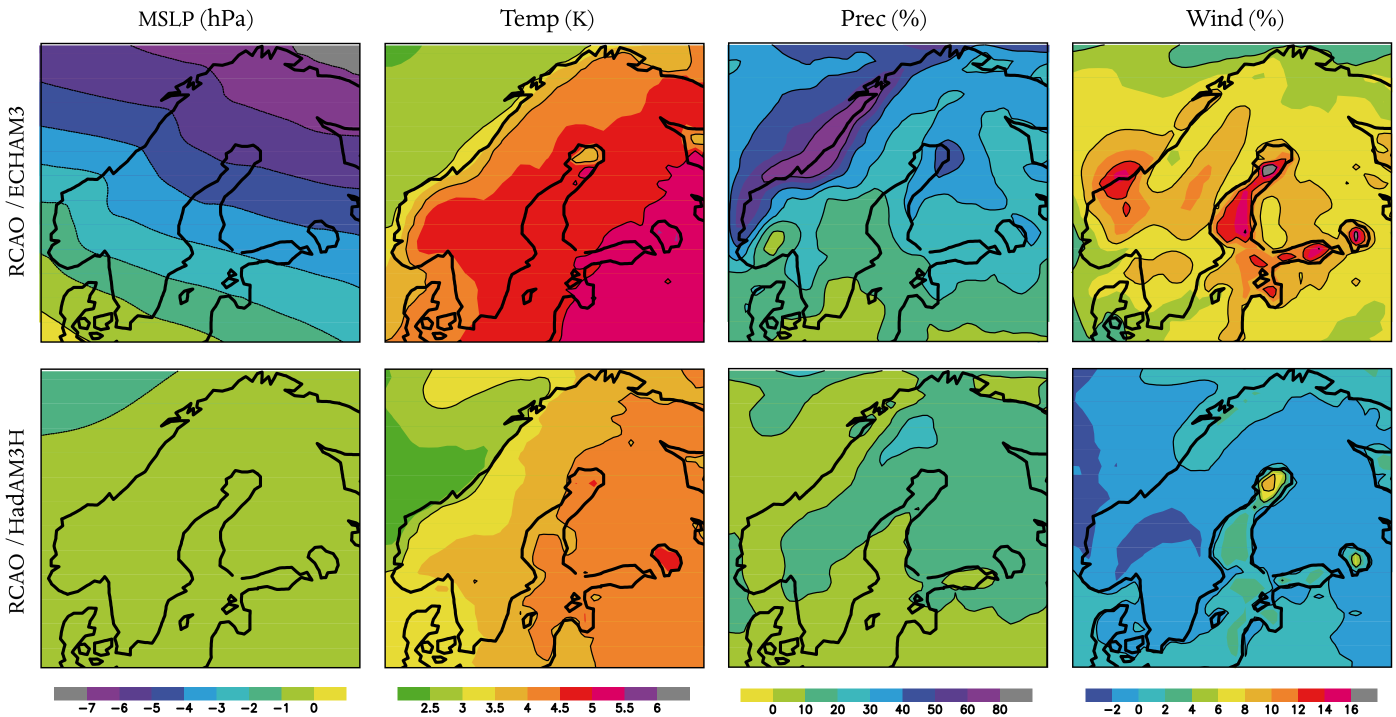

Figure 4.3. Two RCAO regional climate projections for 2071–2100, compared to 1961–90. In both cases, the scenarios are based on A2 emissions. The boundary conditions for RCAO are taken from two different GCMs. The panels from left to right show calculated annual mean changes in mean sea level pressure, air temperature at 2m height, precipitation and wind speed at 10m height (after Rummukainen *et al*, 2004).

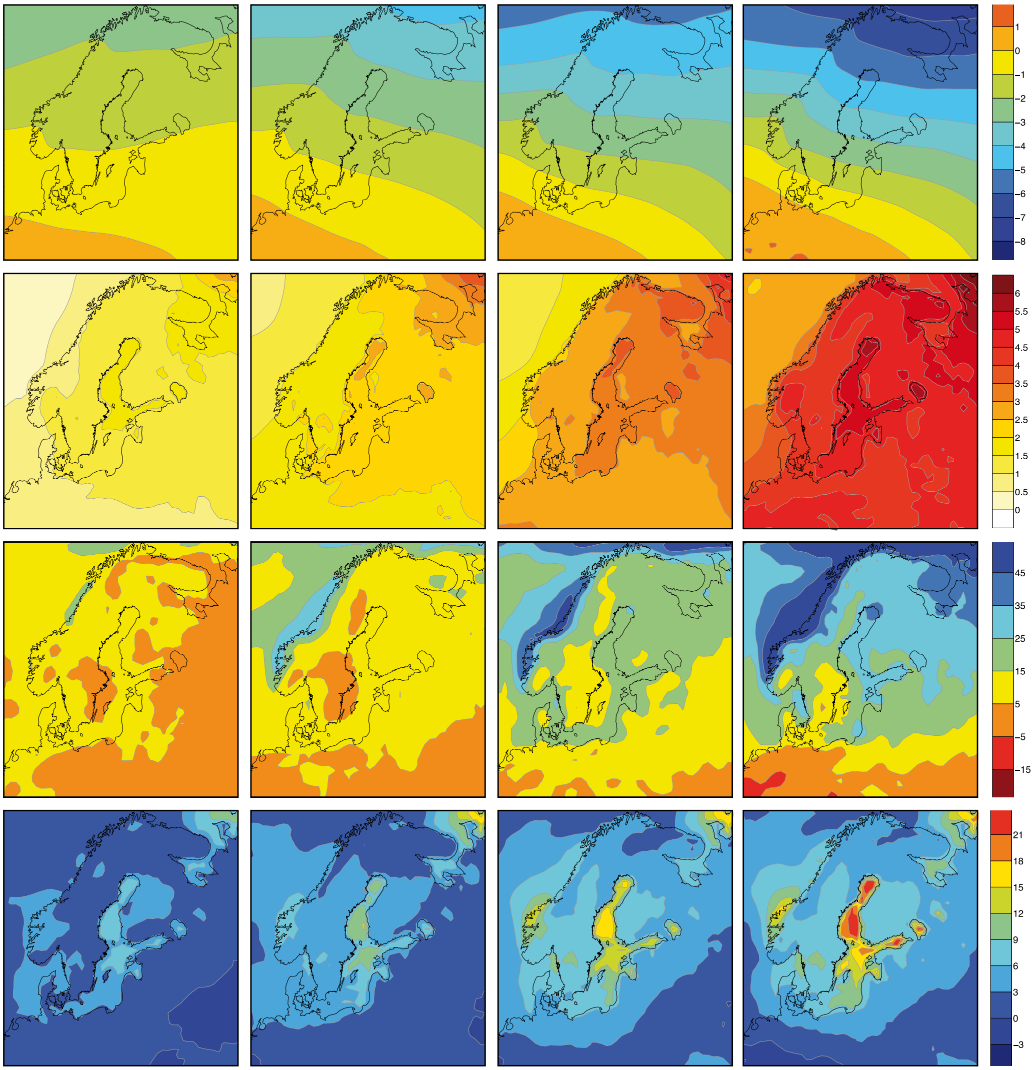

Figure 4.4. RCA3-E-A2 derived changes in, from top to bottom: i) annual mean sea level pressure (hPa); ii) annual mean 2m-temperature (K); iii) precipitation (%); and iv) 10 m wind speed (%). The changes are given for four successive 30-year periods (from left to right: 1981–2010; 2011–2040; 2041–2070; 2071–2100) compared to the period 1961–1990. The RCA3-E-B2 derived changes show similar patterns, but of smaller magnitude.

CE scenarios for Greenland

The CE regional climate scenarios for Greenland (Kiilsholm *et al*, 2003) are made with the HIRHAM regional climate model in Denmark (Christensen *et al*, 1996), with boundary conditions from the ECHAM4/OPYC3 GCM. The two scenarios that are provided correspond to A2 and B2 emissions. Both target the 2071–2100 period, compared to 1961–90. The emissions and the driving GCM are as for the RCA3 (and some of the RCAO) scenarios for the Nordic mainland. (Figure 4.5).

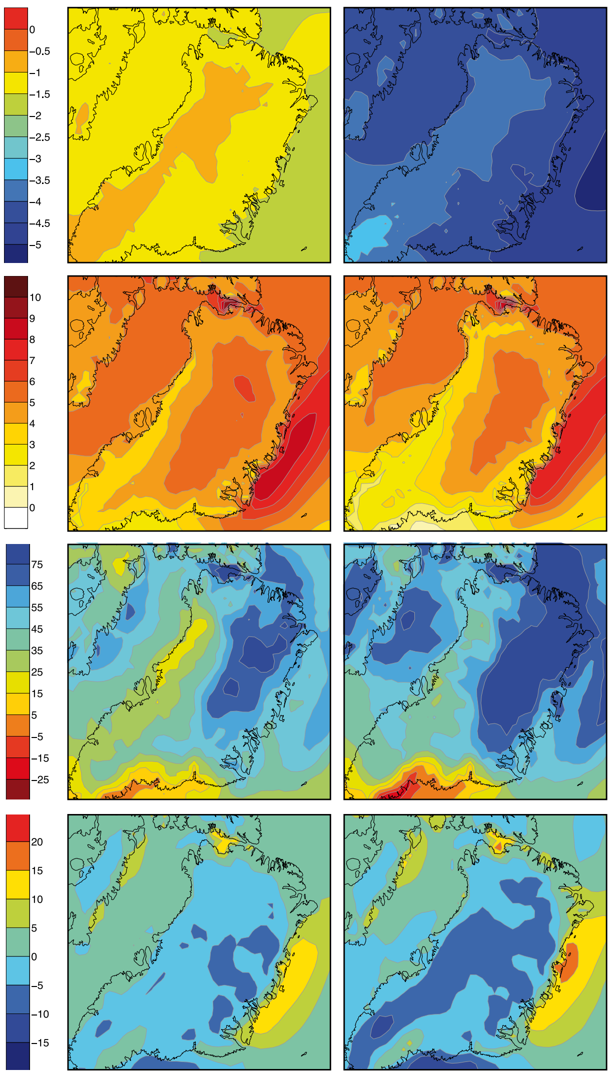

Figure 4.5. HIRHAM-E-B2 (left column) and -A2 (right column) derived changes in (from top to bottom) annual mean: i) mean sea level pressure (hPa); ii) 2 m-temperature (K); iii) precipitation (%); and iv) 10 m wind speed (%) by 2071–2100, compared to 1961–1990.

Taking the B2 case as an example, ECHAM4/OPYC3 projects a global mean temperature increase of 2.5 °C towards the end of the 21st century. For the Arctic Region, concurrent temperature increases are up to 5 °C in the annual mean and up to 9 °C in winter. Precipitation is projected to increase everywhere in the Arctic, from 5–10% in the south to 35% in the High Arctic. A substantial decrease of sea ice and snow-cover is also projected. The mean sea-ice extent shows a northward retreat. In the Davis Strait, the winter southern ice edge moves north towards the Disko Bay, as well as west towards the Canadian coast. On the east coast of Greenland, the southernmost ice edge is projected to draw back to about 200 km north of its present location. For the Greenland area, as simulated by the HIRHAM, there is an increase of near-surface air temperature ranging from 3 °C in the south to 5 °C in the north. Increased precipitation and melting cause an enhanced freshwater supply.

CE scenarios for Iceland

For Iceland, two regional climate model scenarios made with the HIRHAM regional climate model in Norway are adopted (Haugen & Iversen, 2005). Again, these concern projected changes for 2071–2100 compared to 1961–90, and for the emission scenarios A2 and B2. The boundary conditions are from the HadAM3H GCM.

The projected patterns of precipitation and temperature change are similar in these A2 and B2 cases studied (Figure 4.6), although their magnitude varies with the amount of emissions.

The projected warming is rather small in winter (possibly due to a reduction of the number of southerly windstorms) and in summer. A larger warming occurs in spring and autumn. There is also a substantial reduction in the intensity and frequency of cold spells in winter and spring, but some increase in the frequency and intensity of heatwaves in summer. A relatively large change occurs in the seasonal cycle of precipitation. Autumn becomes wetter, whereas spring becomes drier. (Note that the seasonality of Icelandic precipitation changes appears different in a larger number of GCMs and emission scenarios; see Figure 4.9.) In winter, there is some decrease of precipitation in south-west Iceland but increases in north-east Iceland. The mean topographic precipitation gradient also increases somewhat, and the annual mean precipitation changes little in the lowlands. Both the precipitation changes and changes in the mean wind (some decrease in the annual mean) seem associated with a reduction in the meridionality of storm tracks.

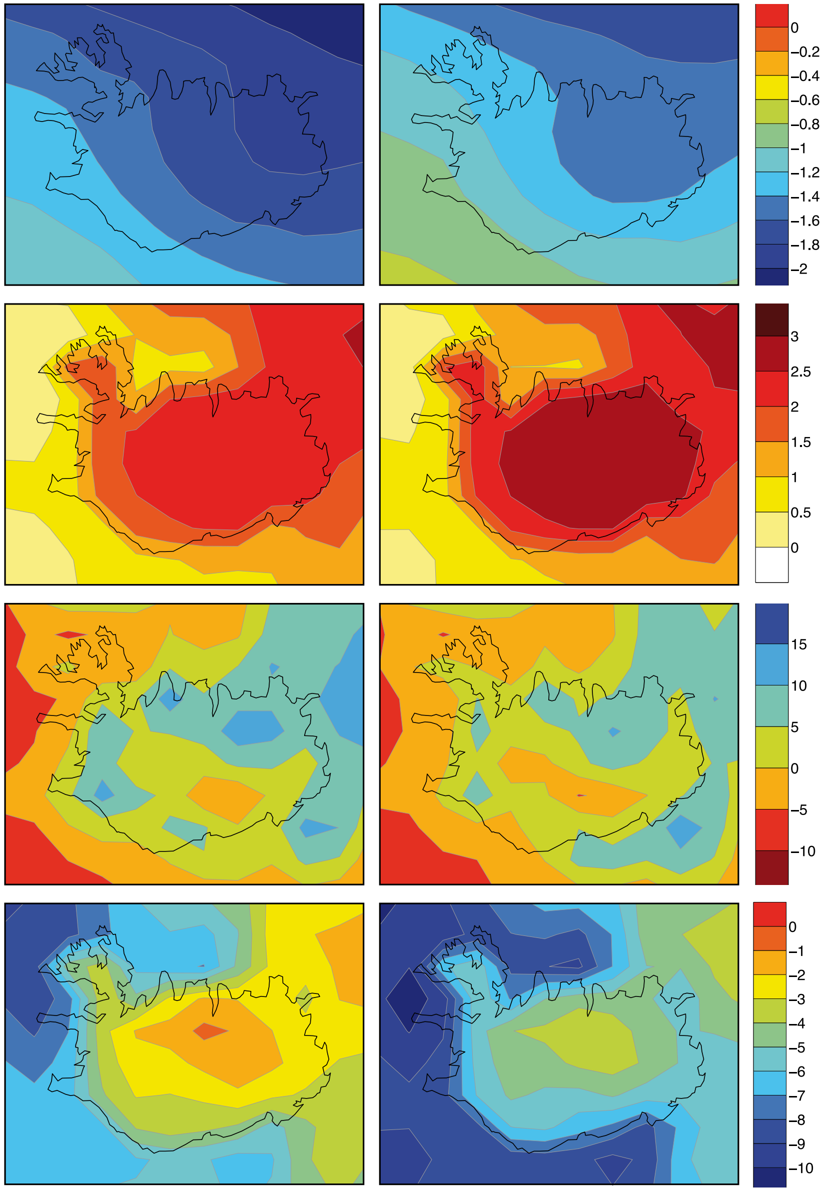

Figure 4.6. HIRHAM-H-B2 (left column) and -A2 (right column) derived changes in annual mean around Iceland (from top to bottom): i) mean sea level pressure (hPa); ii) 2 m-temperature (K); iii) precipitation (%); and iv) 10 m wind speed (%) by 2071–2100, compared to 1961–1990.

Comparison of RCA and HIRHAM

All climate models are based on the same physics. However, they differ in terms of resolution, numerical methods and such approximations of various climate processes that need to be invoked. In RCMs, the choice of the model domain and the import of boundary conditions can also lead to some difference between models. Some difference also arises from the simulated natural variability. Thus, even though many simulated changes are robust across different models, there are also differences between them. This is true for different GCMs that are run with the same emission scenario. It is also true for different RCMs, even when they are run with the same boundary conditions (*i.e.* GCM and emission scenario). Resulting seasonal and geographical means are, nevertheless, rather comparable across such RCMs, whereas spatial and temporal details, such as projected changes in extremes, can vary more.

As explained above, the CE production scenarios are based on three different RCM applications. The respective model domains overlap for the Nordic mainland, for which some comparison is provided in Table 4.1. A similar seasonal differentiation of the projected changes appears in all of these scenarios, as does a general enhancement of the calculated changes when going from the smaller B2 emissions to the larger A2 ones. There are also indications of a clear offset between the regional scenarios, depending on the GCM providing boundary conditions, with the choice of ECHAM4/OPYC3 leading to larger changes than HadAM3H. The largest changes always stem from the choice of ECHAM4/OPYC3 and A2. The smallest changes tend to correspond to choosing HadAM3H and B2. Of particular interest is the apparent difference in results for wind. Whereas scenarios based on ECHAM4/OPYC3 lead to some increases, especially in winter, in line with large-scale circulation changes in the North Atlantic sector, no particular wind changes show up in the scenarios based on HadAM3H.

Even when the same GCM and emission scenarios are used, there are differences between the regional scenarios. Some of these can be explained by simulated unforced variability, especially in the case of precipitation. Nevertheless, there is a tendency for HIRHAM to simulate larger temperature changes than RCA. The opposite is true for precipitation.

In summary, these regional climate scenarios convey a robust message about sizeable changes in temperature that are largest in winter and smallest in summer. There is also a clear tendency for increased precipitation in winter and, to some extent, in spring and autumn. The summer precipitation changes are very small. It should be noted, however, that some of the seasonal changes vary even within the region, such as a clearer decrease in summer precipitation in southern Scandinavia than elsewhere in the region.

	Temperature change (°C)				Precipitation change (%)			
	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
RCA-E-A2	6.0	4.8	3.3	4.7	52	39	−2	28
RCA-H-A2	4.3	3.8	3.0	4.3	26	17	−1	5
RCA-E-B2	4.8	3.8	2.5	3.6	39	27	2	24
RCA-H-B2	3.2	2.7	1.5	3.2	16	5	3	7
HIRHAM-E-A2	5.8	5.2	4.1	5.3	37	21	−8	24
HIRHAM-H-A2	4.6	3.8	2.8	4.6	25	6	1	-0
HIRHAM-E-B2	4.9	4.7	2.9	4.3	35	18	−2	16
HIRHAM-H-B2	4.0	3.2	2.1	4.0	18	+0	3	7

Table 4.1. Calculated Northern European Region (NEU, see Figure 4.7) seasonal temperature and precipitation changes by 2071–2100, compared to 1961–90, as modelled with the CE regional climate models. 'E' and 'H' refer to boundary conditions from ECHAM4/OPYC3 and HadAM3H, respectively. The HIRHAM-H-A2/B2 references are from met.no. The HIRHAM-E-A2/B2 results of DMI are from a different set of simulations than those used for the scenario for Greenland. The SMHI RCA results are from the RCAO runs. Corresponding results from the RCA3 runs are slightly, but not overly, different.

Data deliveries

Regional climate scenarios were delivered on request to the hydrological models group, the wind power group, the snow and ice group, the energy system analyses group, the biofuels group and the solar energy group. Many of the CE regional climate scenarios were also available for non-logged download from the PRUDENCE project.

Most of the data requests were on selected gridded precipitation and 2 m temperature results for appropriate geographical areas.

Depending on the application, time series and/or various kinds of temporal means were delivered. The hydrological models group also requested evaporation and soil temperature data and the wind group requested several variables of interest for wind and icing studies of wind turbines. The solar energy group requested data on 2 m temperature and humidity, as well as solar radiation at ground level for a few locations in the Nordic mainland (Copenhagen, Oslo, Trondheim, Tromsø and Helsinki).

4.3 Setting the CE production scenarios in perspective

Analysis of global and other regional projections

In addition to the small handful of CE production scenarios, some basic analysis of additional global and regional climate scenarios is useful, so as to better explore uncertainty ranges in projections of regional climate change, due to emissions scenarios, model choice and natural variability. This was performed for two periods, 2021–2050 and 2070–2099 (Ruosteenoja *et al*, 2006), relative to the baseline period 1961–1990 and for a number of Nordic sub-regions (see Figure 4.7). These analyses focus on area means of seasonal and annual near-surface (2 m) air temperature and precipitation.

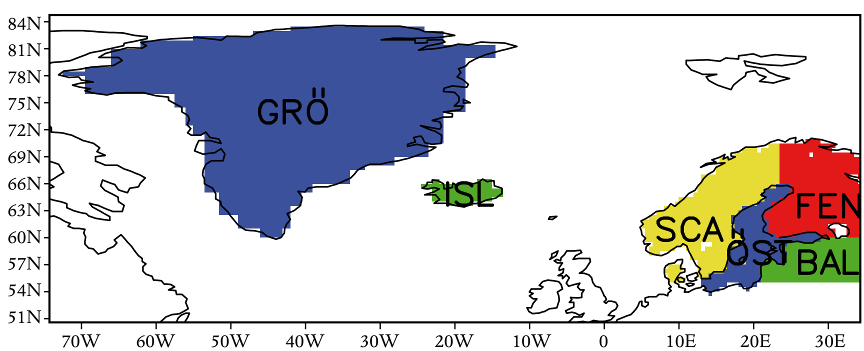

Figure 4.7. Regional subdivisions applied in the analyses of various GCM- and RCM-based climate projections. GRÖ = Greenland; ISL = Iceland; SCA = Scandinavia; FEN = Fennoscandia; ÖST = Baltic Sea; BAL = Baltic area. A larger northern Europe land region (NEU) is also considered, which comprises of SCA, FEN and BAL.

The analysis of GCMs and emission scenarios includes those that underlie the CE production scenarios. Results from four additional GCMs and two additional emissions scenarios are considered. Use is also made of 1,000-year control simulations to gain a measure of unforced natural variability. These runs are analysed into an expectation for the difference between two arbitrarily-chosen 30-year means of regional temperature and precipitation conditions in the absence of emissions. This facilitates the addressing of the significance of simulated climate changes.

The other part of these efforts is an analysis of an extended set of RCMs from the PRUDENCE project (Christensen & Christensen, 2007). The PRUDENCE RCM scenarios are available for 2071–2100, and are based on two GCMs. To some extent, these scenarios are expanded with pattern-scaling techniques as mentioned earlier. Additional analyses include estimates for extreme precipitation, frost and snow (Jylhä *et al*, 2007).

Probability intervals for regional climate scenarios projections

In addition to mean estimates based on sets of climate simulations, as discussed above, 95% probability intervals are also constructed (Ruosteenoja *et al*, 2006).

Individual model simulations do not offer a sufficiently representative estimate of projected climate change. One way to expand the simulations is by fitting them with a statistical distribution, such as the normal (Gaussian) distribution. This makes it feasible to obtain probability intervals for projected changes. In CE, this is done for temperature and precipitation, for both GCMs and RCMs. For the latter, one set is inferred from the PRUDENCE HadAM3-forced RCM runs. The other is based on a set of RCM runs that is synthetically expanded to emulate simulations corresponding to using boundary conditions from an additional two GCMs (Ruosteenoja *et al*, 2007).

Regional temperature and precipitation projections

Figures 4.8 and 4.9 illustrate the GCM-based 95% probability intervals of temperature and precipitation change towards the end of the century for northern Europe, Iceland and Greenland. The measure of natural variability expected for any two 30-year periods of unforced climate conditions is also shown. Responses larger than this measure can be considered statistically significant at the 5% level.

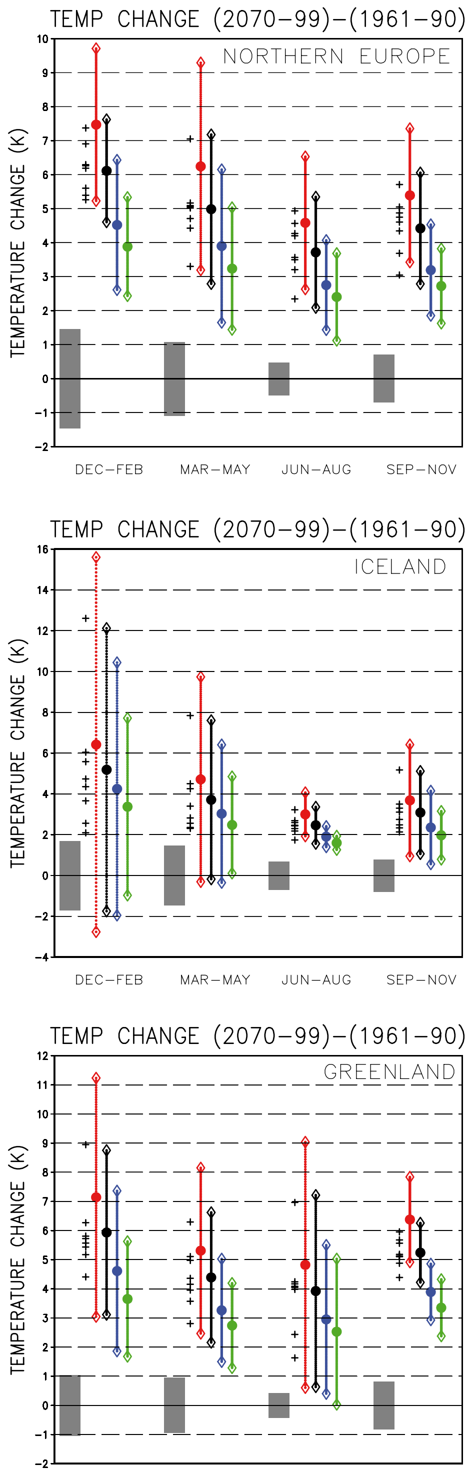

Figure 4.8. GCM-based temperature change projections for northern Europe, Iceland and Greenland. The coloured bars span 95% probability intervals corresponding to six GCMs and the A1FI (red), A2 (black), B2 (blue) and B1 (green) emission scenarios. The central dot in each bar denotes the median value. Individual GCM runs are shown for the A2 case with plus signs. The short grey bars show a measure of internal variability.

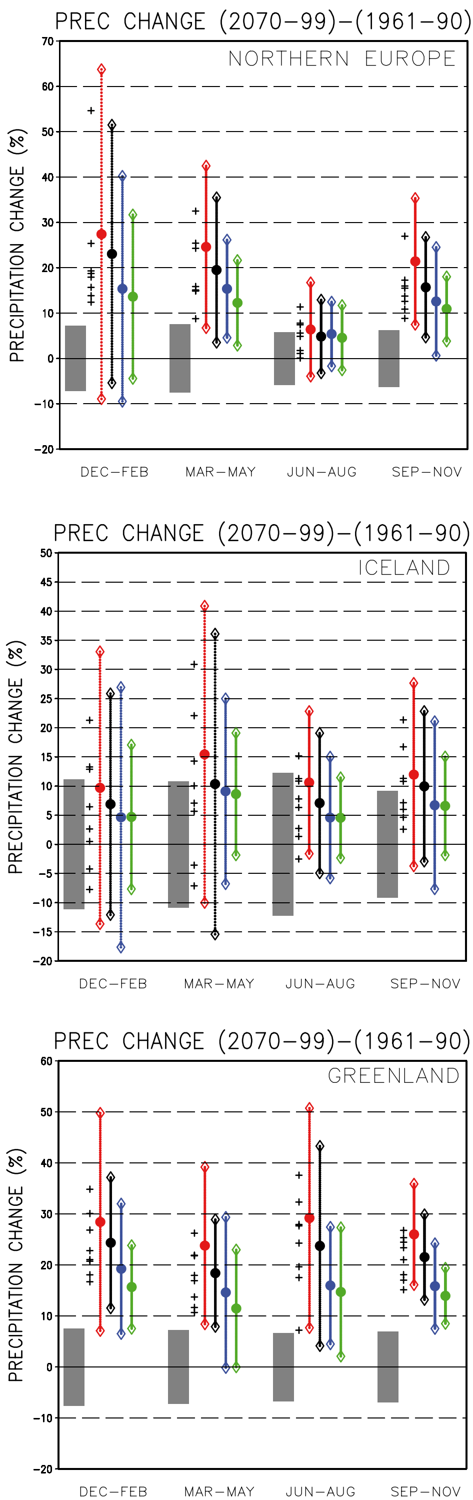

Figure 4.9. As Figure 4.8, but for precipitation.

There is a wealth of information in Figures 4.8 and 4.9. The general result is an increase of both temperature and precipitation for all seasons and regions. Projected mean warming is larger for winter than for summer and it increases with the accumulated emissions (A1FI > A2 > B2 > B1). In northern Europe, the strongest precipitation increase is projected for winter; in Iceland, it is for autumn. In Greenland, both winter and summer show larger precipitation increases than the intermediate seasons. The statistical significance of precipitation changes is distinctively lower than that of temperature changes.

The probability intervals are quite broad and they also overlap for the different emission scenarios. The calculation of these intervals is based on the assumption that the distribution of climate model responses is close to normal. This should ordinarily hold. However, some climate models yield results that deviate markedly from the rest. In such cases, normal distribution cannot be a good assumption. An example is the Icelandic temperature response in winter and spring, for which the probability interval is extended at both ends, due to one of the climate models used. Indeed, the lower end of the interval becomes negative, despite the fact that all projections show distinct warming. Another example is the projected winter precipitation change in northern Europe, where one model simulates a much larger relative increase than the rest.

Median temperature projections are almost invariably statistically significant. The exceptions are the RCM-based projections for the Scandinavian region in winter and the GCM-based projections for Iceland in spring in the earlier of the two considered periods, *i.e.* 2021–50 (not shown). For the majority of the regions, seasons and periods, both ends of the probability interval of temperature change are also positive. Median projections for precipitation are, in several cases, not significant. This is especially obvious in summer. The 95% probability intervals of precipitation change intersect the zero line in many cases.

4.4 Main results

The CE regional climate scenarios are based on RCA and HIRHAM regional climate model applications, with boundary conditions from two global climate models, the ECHAM4/OPYC3 and HadAM3H GCMs, and from two emission scenarios, the SRES A2 and B2. The use of regional climate models provides physically-based and internally consistent climate scenarios at a scale that is more applicable to impact modelling than anything available from global climate models. The resulting regional climate scenarios contain a large number of meteorological parameters. The basic results are in the form of gridded time series, but are also available in terms of averages or higher-order statistics. The regional climate scenarios were made available to the overall CE project, to be applied in the climate impact studies. Particular use is made of temperature, precipitation and wind data, but data for evapotranspiration, snow and solar radiation are also used.

The CE regional climate scenarios cover, separately: (i) the Nordic mainland, north-western Russia and the Baltic States; (ii) Iceland; and (iii) Greenland, at 50 km resolution. In all cases, the scenarios target the 2071–2100 period. For (i), a smaller set of two scenarios is also available for the whole 21st century.

The use of separate scenarios for different parts of the Nordic Region is not optimal; this is due to practical constraints. Comparison of the respective modelling set-ups is possible for the Nordic mainland. Some indications of systematic differences among them are also found, attributable to the choice of the driving global climate model and the downscaling regional climate model. There is, however, a general agreement among them as to the signs, magnitude, sensitivity to accumulated emissions and seasonality of simulated regional changes in temperature and precipitation.

An enlargement of the analysis of the specific regional climate scenarios to additional global climate models, regional climate models and emission scenarios, brings up both similarities and differences in regional climate scenarios for different parts of the Nordic Region. Some of the robust features already mentioned for the Nordic mainland are again found, such as the increase in climate change with accumulated emissions, and the apparent significance of temperature changes compared to precipitation changes. The calculated probability intervals remind us that, other than anticipating a significantly different climate in the future, we cannot predict it exactly. When dealing with climate change and its impacts, an appreciation of different scenarios is necessary, while climate research should focus on dealing with the uncertainties.

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5 Statistical analysis

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The projected climate change in the Nordic Region is expected to cause a warmer, wetter climate and thus an intensification of the hydrologic cycle. Studies of such changes include attempts to detect climate change signals in historical data. The focus of the statistical analysis group has been to look for trends, and to establish knowledge about the natural variability in climate and hydrology and the link between hydro-climatological variables.

Instrumental climatic (precipitation and temperature) and hydrologic records from the Nordic and Baltic Regions extend for more than 100 years. These records are long enough to document changes at inter-annual timescales. This enables regional studies of changes in long time series to be made. It is important to be aware that, even if annual averages remain unchanged, a change in seasonal or extreme values might be present. Changes in climate and hydrology may also vary considerably between regions. An overview of recent studies of long time series of precipitation, temperature, streamflow and other hydrological variables in the Nordic countries can be found in Hisdal *et al* (2003).

The main objective of the statistical analysis group has been to study spatiotemporal changes in historical data. This includes studies of: (i) trends in historical streamflow and climate records from the Nordic and Baltic Regions (*e.g.* Hisdal *et al*, 2007; Reihan *et al*, 2006; Jónsdóttir *et al*, 2006); (ii) links between hydro-climatological variables (*e.g.* Lindström *et al*, 2006); (iii) the link between atmospheric circulation, wind and streamflow (*e.g.* Jónsdóttir & Uvo, 2007; Pryor *et al*, 2006b); and (iv) similarities and differences in historical changes compared to changes expected in the future (*e.g.* Hisdal *et al*, 2006; 2007). This last topic includes a comparison with results from the CE project's climate scenarios group and hydrological models group.

The next section gives an overview of the data that were collected and analysed. The different studies made by the statistical analysis group are summarised in the sections that follow this, before some concluding remarks are given.

5.1 Data

The Nordic and Baltic countries have a good spatial coverage of long streamflow records that have undergone quality control to avoid stations that are significantly affected by human activity. In particular, a unique selection of basins with a minimum of man-made environmental changes (such as urbanisation, deforestation and changes in storage capacity) is available for studies of extremes. The record length enables documentation of changes at inter-annual timescales and testing for trends in common time intervals. The use of these data gives a unique opportunity to investigate changes in climate and streamflow in the Nordic and Baltic Regions.

A total of 162 streamflow records (with an average length of 83 years) of daily data from Denmark, Finland, Iceland, Norway and Sweden was collected. The data are stored in a common database, a Nordic version of the European Water Archive (EWA) of the Flow Regimes from International Experimental and Network Data (FRIEND) Project (Roald *et al* ,1993; Rees & Demuth, 2000). The data were selected to cover the whole Nordic Region, with a common time period that included 2002. The criteria for selecting series were that, as far as possible, the records should be unaffected by human-induced changes in the basin, and that the records should be as long as possible. Even if most catchments in the Nordic Region are only subject to minor land use changes and a minimum of water abstractions for irrigation, industry and public water supply, long pristine series are hard to find. The longest series will often be affected by human activities in the basin, causing various inhomogeneities. The series were therefore classified into three categories: series only suitable for analysis of annual values; series also suitable for analysis of monthly values; and series also suitable for analysis on a daily level. These data were mainly used to study trends and variability in annual, seasonal and extreme streamflow, and frequencies of flood and drought (*e.g.* Hisdal *et al*, 2006; 2007).

From Estonia, Latvia and Lithuania, a total of 70 streamflow stations with an average of 84 years of daily data, covering roughly the same time periods as the Nordic data set, were analysed. For the Baltic countries, the number of drought data series is small, due to impact on the baseflow caused by human activity in the form of melioration and water regulation by dams since the 1960s. An additional 93 temperature and precipitation records were also studied and, for Latvia, 32 series of maximum snow water equivalent and 22 series of the number of days with snow cover and the date of disappearance of a stable snow cover were analysed. Homogeneity tests were performed for annual, seasonal and extreme values. For the hydrological data in Latvia and Lithuania, the double-mass plot technique and the pair correlation analysis were used. For the Estonian hydrological data, the Standard Normal Homogeneity Test (SNHT) was applied (Alexandersson & Moberg, 1997). The SNHT test was also used for the Baltic meteorological data, single shift, using ratios for the precipitation data and differences for the temperature data. Each station was compared to four to nine references stations. Metadata catalogues of the hydrological and meteorological data from the Baltic countries were compiled. The Baltic data were mainly used to study trends (*e.g.* Reihan *et al*, 2006). In this chapter, only the streamflow trend results are presented.

An additional set of monthly regional index series of temperature, precipitation and runoff were compiled for eight Nordic regions. This dataset was used to compare the recent wet and mild years with long historical records, link the variability in streamflow to changes in precipitation and temperature, and compare historical data with the scenarios (Lindström *et al*, 2006).

In addition, wind data and atmospheric circulation data (*e.g.* the NAO index) were used to study links between hydro-climatological variables and larger scale atmospheric circulation (*e.g.* Jónsdóttir & Uvo, 2007; Pryor *et al*, 2006b). In comparison with streamflow / runoff records, long homogeneous wind speed time series are limited in both number and availability. Accordingly, for studies including wind, data are taken from:

- Two re-analysis data sets – the NCEP-NCAR re-analysis data (Kistler *et al*, 2001) and the ECMWF (ERA-40) data (Uppala *et al*, 2005)

- One global climate model (GCM) – Had CM3 (Pope *et al*, 2000)
- Observational records drawn for the period 1982–2000 from the International Surface Weather Observations and Integrated Surface Hourly Observations, supplemented by data from national inventories (Alexandersson, 2006; Cappelen & Jørgensen, 1999; Drebs *et al*, 2002; Norwegian Wind Atlas, 2003).

5.2 Trends in streamflow

Because the time period selected will affect the trend, it is important that a common time period is studied when comparing trends in different regions. At the same time, it is important to use time series that are as long as possible, to study long-term variability. A best possible Nordic coverage required a relatively short period to be selected (1961–2000). This period encompasses the total Nordic data set (162 stations). Two additional sets of stations, 1941–2003 (139 stations) and 1920–2003 (87 stations), were chosen to investigate longer-term trends. Analyses of trends in seasonal streamflow and extremes further reduce the number of stations. A minimum number of stations (46) are found for the analysis on a daily level for the period 1920–2003. The spatial coverage of data is not uniform, as a larger number of long-term records from pristine basins is available in Norway and Denmark than in Sweden, Finland and Iceland. This must be considered when the results are discussed. However, the dataset comprises a good quality, long-term set of homogeneous series of adequate spatial resolution with a minimum of human influence, to detect trends caused by climate changes, whether natural or human induced.

For the Baltic Region, the year 2003 was included, as this did not reduce the number of stations available for analysis. However, the longest period starts in 1922. The three time periods analysed for trends, 1922–2003 (22 stations); 1941–2003 (31 stations); and 1961–2003 (70 stations), are therefore slightly different than for the Nordic Region. For the temperature and precipitation data, the following periods were studied: 1925–2003 (26 temperature and 32 precipitation series); 1945–2003 (43 temperature and 67 precipitation series); and 1961–2003 (49 temperature and 93 precipitation series). The snow data were studied for the period 1950–2003.

The results of the trend studies presented were performed for the following hydrological variables: annual streamflow (calendar years); seasonal values (winter = December-February; spring = March-May; summer = June-August; autumn = September–November); timing (date of flood peak) and magnitude of floods, and summer drought duration and deficit volume (Nordic Region); and 30-day minimum flow (Baltic Region). For the Nordic countries, a rough differentiation of the flood generation mechanism was done by looking at spring and autumn floods separately. The spring flood period was defined as 1 March to 15 July, and the autumn flood period as 16 July to 11 November. Timing was defined as the date of the flood peak. For the Baltic countries, only spring floods defined as floods occurring between 1 December and 30 June were studied. A more detailed description of the findings can be found in Hisdal *et al* (2007) for the Nordic countries and Reihan *et al* (2006) for the Baltic countries.

In the present study, the Mann-Kendall test (two-sided), with a 5% significance level, which is frequently applied to detect trends in hydro-climatological time series, is applied. This test is non-parametric and searches for a trend in a time series without specifying whether the trend is linear or non-linear. A 5% significance level implies that there is a 5% probability of incorrectly rejecting the hypothesis of no change and detecting a trend, when in fact no trend is present.

Annual streamflow

Even if the majority of streamflow series do not show any changes, clear regional patterns are seen, depending on the time period analysed. For a large part of the Nordic Region, the annual streamflow shows an increase for the periods 1941–2002 and 1961–2000; but, because of some wet but cold years at the beginning of the 1920s, the trend towards increased annual streamflow disappears for the period 1920–2002. Unlike the 1990s and beginning of 2000, the 1920s were not only wet, but also cold.

For the Baltic Region, a negative trend in annual streamflow was found in the transitional and continental regions for the period 1922–2003. At the same time, in the marine regions of Latvia and Estonia, a weak positive trend was found. For the period 1941–2003, a positive trend also appears in some parts of the continental regions, but the whole of Estonia has a significant positive trend. The shortest period, 1961–2003, is characterised by a positive trend over the Baltic States except southern Lithuania, where, in most cases, no trend was found. It is plausible that the prevailing groundwater feeding and sandy soils cause these differences in trend over the region. These results are in agreement with previous Nordic studies summarised by Hisdal *et al* (2003).

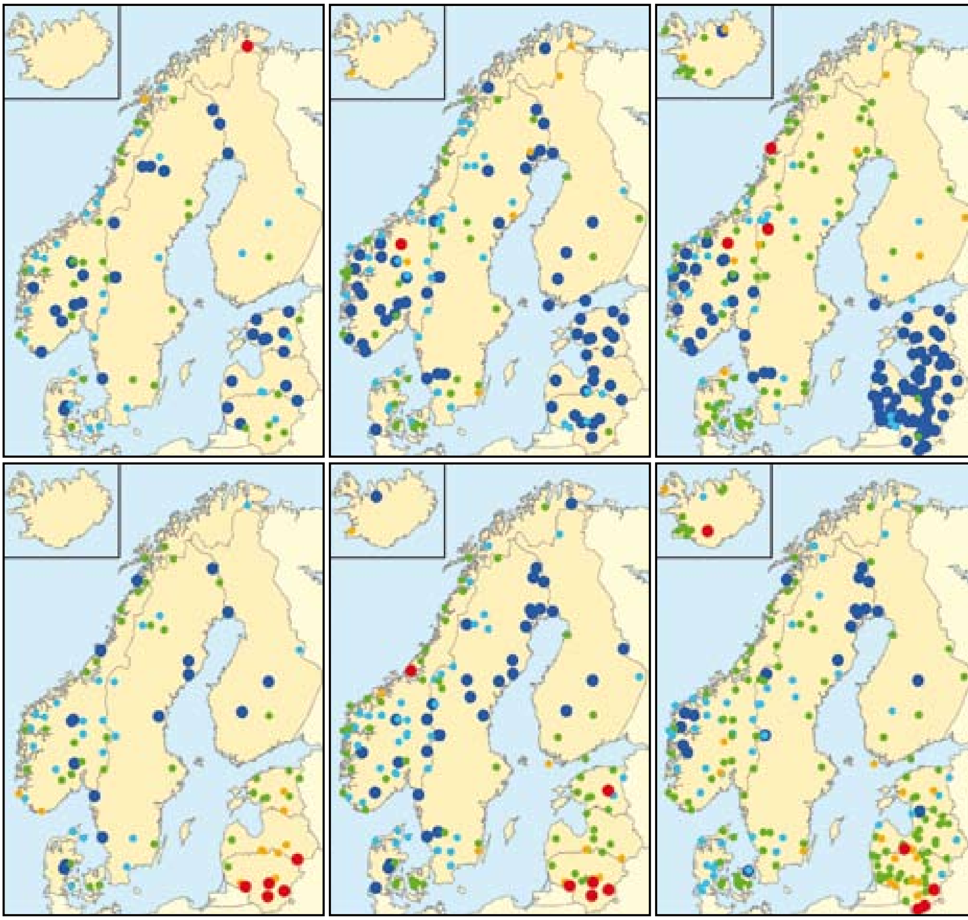
Seasonal streamflow

For the Nordic and Baltic countries, winter discharge in general shows a significant increase, regardless of the period studied (Figure 5.1, top). Trends with a 5% significance level are indicated with large blue circles (significant positive trend) and large red circles (significant negative trend). These are here called *significant trends*. Trends that are only significant at a 30% level are indicated with smaller circles (light blue for a positive trend, orange for a negative trend) and are here called *trends*. Green circles indicate that no trend was found.

The increase is mainly a result of increased temperature causing more precipitation as rain during the winter. In addition, a significant increase in precipitation was found for the Baltic countries. For the longest time period, south Lithuania has the weakest positive trend, which is related to the groundwater-dominated feeding.

For the spring season, a general positive trend for the Nordic countries can be observed, which is not seen in the Baltic Region (Figure 5.1, bottom). In general, for the periods 1922–2003 and 1941–2003, there is no trend in the spring streamflow in the marine regions or in Estonia. The coastal and transitional regions of Latvia and Lithuania have both negative trends and negative significant trends. For the period 1961-2003, a positive trend appears in the regions with lake regulations only. The other regions of the Baltic countries have either no trend or a negative trend. A probable explanation for the contrast between the Nordic and Baltic Regions is the generally warmer climate of the Baltic countries compared to the Nordic countries. Whereas increased temperatures in the Nordic countries lead to a shift in streamflow from summer to spring and winter, the shift in the Baltic Region is more from spring to winter.

Trends in summer flow were highly dependent on the period analysed, whereas, in general, no trend was found for the autumn season. Hence, there was no consistent pattern over larger regions or between the time periods studied. All changes in summer and autumn streamflow (no changes, positive and negative trends) reflect the tendencies in the precipitation series.



Significant negativ trend
Negativ trend
No trend
Positiv trend
Significant positiv trend

Figure 5.1. Trends in winter (top) and spring (bottom) streamflow for the periods 1920–2002 / 1922–2003 (left), 1941–2002 / 2003 (middle) and 1961–2000 / 2003 (right).

Flood and drought

The increased temperature has also caused a trend towards earlier spring floods in many of the catchments, and earlier snowmelt floods can be observed over the entire region (Figure 5.2). Only in Iceland can a tendency towards later spring floods be observed, which is caused by a trend towards lower spring temperatures. It should also be noted that the floods occur earlier in regions where spring floods are caused by rain only. An explanation for this will require further studies of extreme rainfall events during the spring.

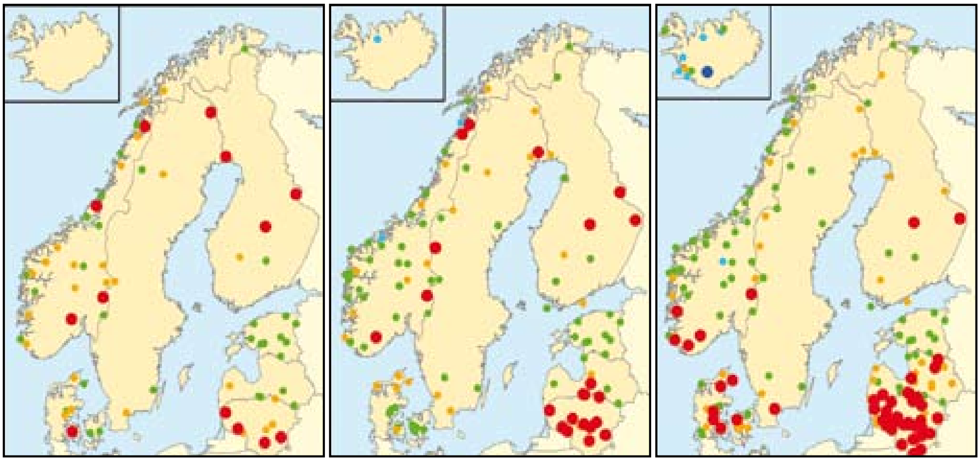


Figure 5.2. Trends in timing of spring flood for the periods 1920–2002 / 1922–2003 (left), 1941–2002 / 2003 (middle) and 1961–2000 / 2003 (right).

No clear regional patterns were found for spring or autumn flood peak values for the Nordic countries. However, a systematic negative trend in the spring flood peaks in the continental regions of the Baltic countries was found for all periods. The negative trends in spring floods are a result of increased temperatures and decreased snow cover. For the Baltic countries, a significant increase in spring temperature, and a decrease in the snow water equivalent, number of days with snow cover and length of the period with a stable snow cover was found.

A trend towards more severe summer droughts was found in the southern part of Norway. For the rest of the Nordic and Baltic Regions, no systematic pattern in trends was found.

5.3 Variability in flood and drought

In a separate study (Hisdal *et al*, 2006), 46 daily streamflow records from Denmark, Finland, Norway and Sweden covering the period 1920–2002 were analysed to study the natural variability in trends and estimated return levels of flood and drought. It was seen that detected trends and return levels strongly depend on the time period studied, because the natural variability in the extremes is large. The deviation (in percentages) from the average estimated 50-year annual maximum flood and summer drought based on different 30-year periods of observation is illustrated in Figure 5.3. The 50-year event is calculated based on 53 successive 30-year periods, *i.e.* 53 values of the 50-year event are obtained. The percentage deviation is calculated based on the difference between the maximum and minimum estimate relative to the average of the 53 estimates.

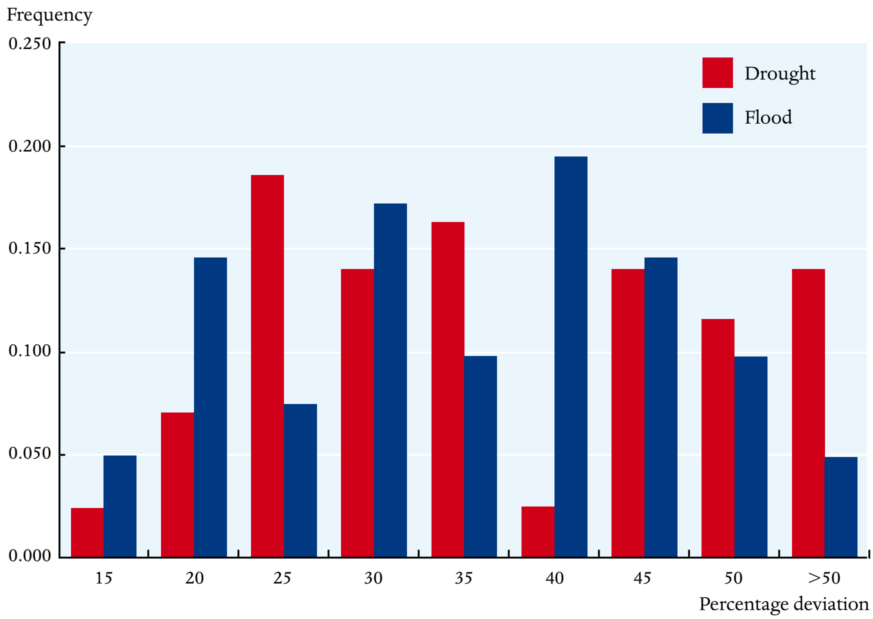


Figure 5.3. Deviation (in %) from the mean estimated 50-year event and the difference between the maximum and minimum estimated 50-year flood and drought.

In addition, for a subset of series, return level estimates based on historical records were compared to extreme estimates for a control period, 1961–1990, and a scenario period, 2071–2100. The scenarios indicated reduced annual floods in eastern Norway, increased annual floods in the western part and varying results for the basins in central and northern Norway. Droughts in general tended to become more severe in the scenarios. The differences between the control and scenario periods were larger than the maximum differences found due to natural variability in different 30-year periods for only one AOGCM-Regional climate model combination.

5.4 Comparison of trends and expected changes – regional series

Long-term regional series of temperature, precipitation and runoff were compiled for the Nordic countries. The series represented a total of 24 regions for precipitation and runoff, and 17 for temperature. Based on these data, a consistent set of index series for eight larger regions was developed on monthly, seasonal and annual bases. All series were normalised with reference to the period 1961–1990. Precipitation and runoff were normalised by division by the mean values, whereas temperature was normalised by subtraction with the mean and division by the standard deviation.

The regional data makes it possible to put recent years into perspective and compare both recent years and climate change scenarios with long-term historical observations. Compared to the reference period, the years after 1990 have been mild and wet, both in terms of precipitation and runoff. Annual temperatures were about 0.5–1 standard deviations above the reference level. All regions and seasons were warmer than in the reference period. In most regions, precipitation increased more than runoff. This could be caused by increased evapotranspiration, or be due to data uncertainties. The runoff in 1991–2000 was higher than in the reference period in almost all Nordic regions (Figure 5.4, left). The relative increases in runoff were highest in winter and spring. The largest increases occurred in northern Scandinavia.

In summary, the decade 1991–2000 differed from the reference period 1961–90 in the direction of change suggested by the scenarios produced in this project (Figure 5.4, right). However, the natural variability is considerable, and temperatures and runoff values similar to those in 1991–2000 have, in most regions, been experienced earlier, although not simultaneously.

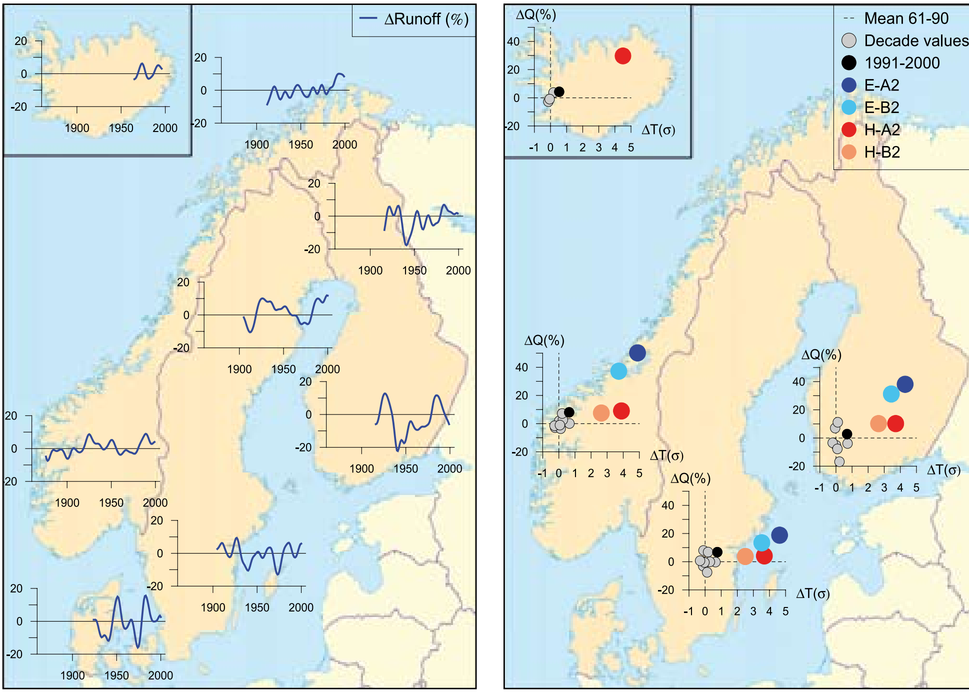


Figure 5.4. Left: Estimated regional runoff for eight regions relative to the reference period 1961–90 (in %), Gauss-filtered with a standard deviation of three years. Right: Estimated national averages of observed runoff (%) versus temperature (in standard deviations) for decades 1861–2000 (grey dots), mean 1961–90 (lines) and 1991–2000 (black dots). Scenarios for 2071–2100 are shown as larger coloured dots.

5.5 Wind

Analyses of re-analysis and GCM output

In the context of wind energy applications, where wind farms have typical lifetimes in the order of 30 years, the question that is often asked is, 'What is a *normal wind year*?' or, in other words, 'Over the lifetime of a wind farm, what is the average expected energy production?' Another common question is, 'Will non-stationarities in the global climate system cause the definition or magnitude of a *normal wind year* to evolve on timescales of relevance to wind energy developments?'

Analyses of the re-analysis data and historical output from HadCM3 indicate significantly increased wind speeds over the Baltic over the second half of the 20th century, with the majority of the increase being focused on the upper quartile of the wind speed distribution and in the south-west of the region. In addition to the high inter-annual variability, these analyses also indicate low frequency variability, and that wind energy densities over Denmark were approximately 10% higher during 1987–1998 than over the long-term mean from 1958–2001 (Pryor *et al*, 2005). Further analyses indicate that there is a high degree of co-variance of wind indices (normalised annual wind energy) in northern European countries that may limit the buffering of inter-annual variability by wind energy-derived electricity across the Nordic countries; but that there is an axis about which the correlations of wind indices over Europe integrated over altitude change sign; and that there is evidence for compensating trends in wind energy indices north and south of approximately 45°N. This highlights potential benefits for larger-scale integration of the electricity grid with respect to balancing wind energy production (Pryor *et al*, 2006a).

Linking historical variability of wind energy and hydropower

As noted by Pryor *et al* (2003), up to 70% of the variance of winter wind speeds over the Baltic can be attributed to the North Atlantic Oscillation (NAO), indicating strong links between wind speed variability and the synoptic and larger-scale climate. Relationships between precipitation and reservoir level in Norway were linked to inter-annual variability and decadal trends in the NAO, which explains up to 55% of the variance in streamflow and up to 30% of the variance in the hydropower (Cherry *et al*, 2005). As also reported by Ova (2003), the relationships between precipitation and the NAO are strongest in areas subject to zonal flow from the Atlantic (Norwegian coast, northern Sweden and southern Finland).

To assess the co-variability of wind climates (and hence wind energy density and runoff, and hence hydro-power availability), runoff records in Norway and wind speed records from across the Nordic countries were related to variability in regional scale pressure gradients, as characterised by principal component scores (PCS) derived based on analysis of sea level pressure. Runoff was most strongly linked to zonal flow components during the autumn and winter in southern and coastal areas of Norway (Tveito & Roald, 2005). A high degree of the variance of autumn and winter wind speeds in these regions was explained by the same PCS (Pryor *et al*, 2006b) (Figure 5.5). This preliminary research thus indicates that variations in wind energy and hydropower are positively coupled in some areas via their dependence on the synoptic and larger scale climate, and hence that they show a common source of variability and may exhibit the same sign of variability under given atmospheric circulation conditions.

5.6 Conclusions

The main objective of the statistical analysis group has been to study spatiotemporal changes in historical data. The trends in historical streamflow and climate records from the Nordic and Baltic Regions show that trends in annual streamflow are governed by changes in precipitation, whereas trends in seasonal streamflow and extremes are influenced to a larger extent by changes in temperature. This is also reflected when comparing the regional time series of temperature, precipitation and streamflow. Hence, the observed increase in temperature strongly affects the hydrological regimes in the Nordic countries. This means that, if the temperature increase is a result of human-induced climate change, the streamflow is changing for the same reason.

A qualitative comparison of the findings of the statistical analysis group to available streamflow scenarios established by the hydrological models group for the Nordic Region, showed that the strongest trends found are coherent with changes expected mainly due to a temperature increase in the scenario period – for example, increased winter discharge and earlier snowmelt floods. However, there are also expected changes that are not reflected in the trends, such as the expected increase in autumn discharge and autumn floods. These are changes caused mainly by an expected increase in precipitation.

The studies linking atmospheric circulation, wind and streamflow show interesting results. Further studies should be carried out, as understanding these links will help in predicting changes in climate and hydrology, and how they will influence the exploitation of renewable energy in the future.

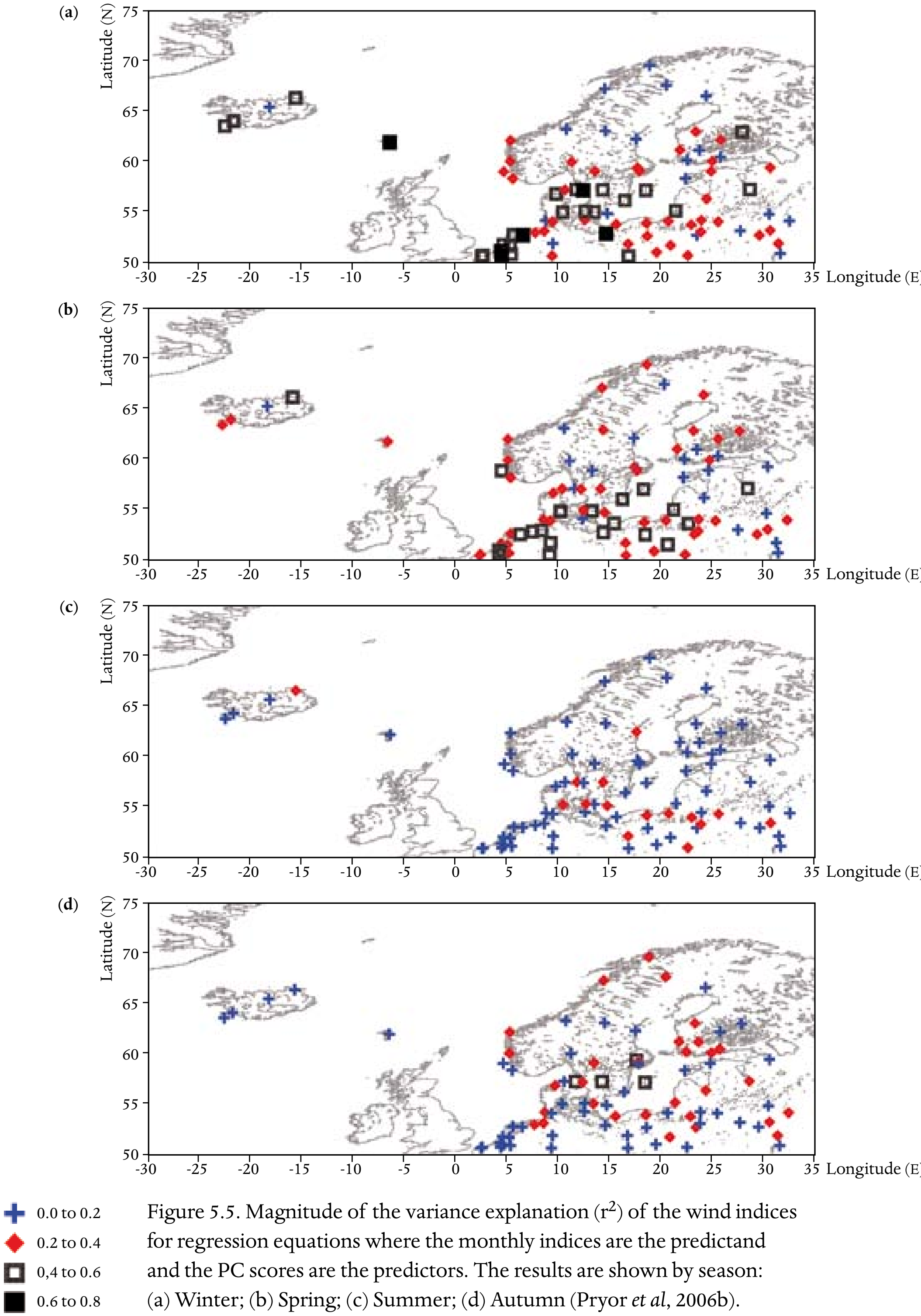


Figure 5.5. Magnitude of the variance explanation (r^2) of the wind indices for regression equations where the monthly indices are the predictand and the PC scores are the predictors. The results are shown by season: (a) Winter; (b) Spring; (c) Summer; (d) Autumn (Pryor *et al*, 2006b).

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6 Hydropower

Sten Bergström, Tómas Jóhannesson, Guðfinna Aðalgeirsdóttir, Liss M. Andreassen, Stein Beldring, Regine Hock, Jóna Finndís Jónsdóttir, Svetlana Rogozova and Noora Veijalainen

More than 50% of Nordic electricity is produced by hydropower, one of the basic pillars of the wealth of the Nordic countries. In the near future, the share of hydropower in the total production of electricity is expected to decrease, mainly due to the fact that a large percentage of economically feasible and environmentally viable options have been harnessed. Due to hydropower's excellent adjustability to demand and the liberalisation of the Nordic and European electricity market, its value has changed, however, and its role is now perceived more as the supplier and manager of peak power in the Nordic Region.

The main hydro-meteorological variables of importance for hydropower are *precipitation* and *temperature*, and the main hydrological systems of importance are *glaciers, snow pack and snow cover, lakes and rivers, soil moisture* and *ground water.*

Some of these systems (*e.g.* glaciers, snow cover, and ice on rivers and lakes) are very sensitive to climate. They are also governed by a number of processes that are likewise affected by climatic change. Some of these processes (*e.g.* evapotranspiration and snow cover) have a strong feedback to the atmospheric processes, whereas some (*e.g.* glaciers and ice on rivers and lakes) will change systematically with climate change.

The impacts on the hydropower industry are also many and varied, and many of these are directly linked to the hydrological changes. We can classify the problems in the following categories: changes in the mean and extreme values of the temporal and spatial distribution of runoff; changes in the river processes (*e.g.* erosion and sediment transport); ice formation; ice cover formation and break-up; and changes in the design practices and operational management of hydropower.

Future changes in climate increase the uncertainty, and thereby the risk, in the development and production of hydropower. It should be noted here that traditional practice regarding design and operation within the hydropower sector is based on extensive simulations of the energy system based on historical time series of river flow and other hydrological variables. This approach is based on the assumption that the stochastic hydrological systems are *ergodic*, *i.e.* that their underlying statistical characteristics do not change with time. This is called *stationarity*. The critical impact of climate change on the hydropower industry is the disruption of hydrological systems that have been assumed to be stationary, or at least approximately so. This affects both the mean and extreme values of the temporal and spatial characteristics of the hydrology of the Nordic countries.

The analysis of interaction between climate and hydrology is done through hydrological models. In Sweden, the HBV model has been applied to the entire drainage basin of the Baltic Sea, and harmonisation with the meteorological RCA model is in progress. In Norway, the Norwegian Water Resources and Energy Directorate, in cooperation with the Norwegian Meteorological Institute, has carried out a pilot project on climate change impacts on temperature and precipitation in relation to runoff. Work is in progress on a gridded model, and research on hydrological regionalisation is being done. This development is overcoming fundamental differences in the approaches of meteorological and hydrological models, and at the same time the scales of both schemes are merging towards a grid in the order of 1 to 10 km.

The two most important questions the hydropower industry asks about global warming are: 'What are its effects on future production?' and 'What are its effects on dam safety?' Within the CE project, a set of common maps of future water resources has been produced, based on climate scenarios and hydrological modelling techniques. This may serve as a foundation for assessments of the future production potential of hydropower in the Nordic area. The CE project also addresses dam safety issues in a future changing climate.

Change in glacial runoff is one of the most important consequences of future climate change in Iceland, Greenland and some glaciated watersheds in Scandinavia. Such changes will have a strong impact on the hydropower industry as flow volumes, seasonalities and extreme values change. The rapid retreat of glaciers also has other implications; for example, changes in fluvial erosion from currently glaciated areas, changes in the courses of glacial rivers, which may affect roads and other communication lines, and changes that affect travellers in highland areas and the tourist industry.

The studies within the CE project by the hydrological models group and the snow and ice group were carried out in Iceland, Finland, Greenland, Latvia, Norway and Sweden, in cooperation with national research programmes. A more complete account of the research can be found in Bergström *et al.* (2007).

6.1 Hydrological methods

Studies of the impacts of climate change on water resources were carried out based on the combined use of global climate models, regional climate models and a hydrological runoff model. Central to most studies was the use of the Rossby Centre Regional Atmosphere-Ocean Model (RCAO). Results from two different global General Circulation Models (GCMs) were used as boundary conditions for the regional model. The RCAO simulations were thus based on GCM results from HadAM3H from the Hadley Centre in UK, and additional simulations from ECHAM4/OPYC3 from the Max Planck Institute for Meteorology in Germany (Räisänen *et al*, 2003). These two global models were run under future conditions, with assumptions about emissions according to the A2 and B2 emission scenarios defined within the suite of SRES scenarios.

As shown by Rummukainen *et al* (2004), the global climate scenarios from the HadAM3H and the ECHAM4/OPYC3 models differ substantially. This is particularly pronounced for precipitation in the areas most developed for hydropower in Norway and Sweden. The use of these two models and two different emission scenarios helps towards understanding more of the uncertainties involved in the modelling of future climate and its impacts.

Hydrological climate change impact simulations for catchments representing different runoff regimes in Norway were carried out based on the four possible combinations of the two GCMs and the two emission scenarios mentioned above. Results from the GCM simulations were used as boundary conditions for two regional climate models: the RCAO model, and the HIRHAM model applied in the Regional Climate Development Under Global Warming (RegClim) project (Bjørge *et al*, 2000). HIRHAM is based on the physics of ECHAM4 and the dynamics of the weather forecast model HIRLAM (High Resolution Limited Area Model), which is used operationally at the Norwegian Meteorological Institute. HIRHAM produces climate variables with approximately 55 km x 55 km spatial resolution every six hours.

The Icelandic simulations were based on a HIRHAM (Haugen & Iversen, 2005) model, run with boundary conditions from the Hadley Centre (HadAM3H). The HIRHAM simulations were provided by the met.no in the context of the PRUDENCE project. From the scenario, monthly delta change values were evaluated for temperature and precipitation. For temperature, an average was estimated for the whole country, while, for precipitation, four different sets of values were estimated for different parts of the country. Little difference was observed in monthly averages between the A2 and B2 forced climate simulations for Iceland; an average of the two scenarios was therefore applied to the hydrological models.

In the Finnish dam safety studies, the design precipitation was based on scenarios obtained from the Finnish Meteorological Institute (Tuomenvirta *et al*, 2000), which use the HadCM2 model with IS92 emission scenario for 2070–2099. The baseline temperature and precipitation were changed according to five different scenarios, including the four scenarios from the RCAO model described above and the Had CM2 IS92a scenario used for the design precipitation.

All the hydrological simulations used the time-slice approach, whereby model simulations representing a slice of time in the present climate (control) and in a future climate (scenarios) were performed. The time slice for the control climate was 1961-90 and for the future climate 2071–2100.

For the hydrological modelling, the conceptual hydrological HBV model (cf. Lindström *et al*, 1997) was used in all countries except Iceland, where the WaSiM-ETH model was used (Schulla & Jasper, 2001). The HBV model is a conceptual semi-distributed runoff model originally developed for operational runoff forecasting. The model is usually run on a daily time step, and includes routines for snow accumulation and melt, soil moisture accounting, groundwater response and river routing. It exists in different versions in each of the Nordic countries. For practical reasons, the national version of the HBV model was used by each country in the CE project.

The hydrological impact studies were done with off-line simulations with the HBV and WaSiM-ETH models, using an observed database as a control climate. Changes in meteorological variables between the control and the scenario simulations from the regional climate model were processed in a model interface before being transferred to the observed climate database. This can be referred to as the 'delta change approach' (*e.g.* Hay *et al*, 2000) and is a common method of transferring the signal of climate change from climate models to hydrological models (*e.g.* Andréasson *et al*, 2004).

Within the hydrological models group, the HBV model was also applied to the Tasiilaq basin on Ammassalik Island, East Greenland (Einarsson, 2006). Re-analysed climate data from ECMWF were used as an input for the model. The model was calibrated on three water years (1985–88) and run for one reference period from 1961–1990 and two climate change scenarios for 2071–2100. The climate change profile for the scenarios was made by using two climate scenario runs based on IPCC SRES A2 and PCC SREA B2 emission scenarios. The driving data were from ECHAM4/OPYC3, a T42 data set. Sea-surface temperature fields/sea-ice extent were taken directly from the coupled model. Downscaling was done with HIRHAM in 50 km resolution. An increase of about 64% in mean annual discharge was observed for both scenarios. A great increase in the magnitude of discharge spikes in winter was also observed.

6.2 Nordic hydrological maps

Maps of hydrological state variables and fluxes for the Nordic Region under present (1961–1990) and future (2071–2100) conditions have been produced using the hydrological models HBV and WaSiM-ETH (Beldring *et al*, 2006). The maps were assembled from simulations done in Finland, Iceland, Latvia, Norway and Sweden using operational models from the national hydrological institutes of each country. Although model structure and model parameterisation, input data and spatial resolution vary, the maps present a relatively consistent view of hydrological conditions in the Nordic Region. Present conditions were assembled from a control run using observed meteorological data, with the exception of Iceland, where observed meteorological data were replaced by results from the atmospheric model MM5. The results were then integrated into a common format by staff at the Norwegian Water Resources and Energy Directorate.

The maps are based on the four different regional climate scenarios (excluding Iceland) described above, which in turn are based on two global models, each of them with two emission scenarios. Figure

6.1 shows a set of maps representing changes in average runoff (available water resources) for the whole area. More detailed maps of changes in seasonality of runoff, annual maximum snow water equivalent, number of days per year with snow-covered ground, annual maximum soil moisture deficit and evaporation changes are available in a separate report (Beldring *et al*, 2006).

Even though the runoff maps differ between the different scenarios, it is obvious that Nordic water resources (and thus hydropower production) are quite sensitive to climate variability and global warming. A common feature seems to be that the potential for production of electricity will increase during the 21st century, as the increase in runoff is often greatest in areas with the most developed hydropower.

Overall, there seems to be an increase in water resources, but in some areas drier conditions are indicated. The latter may be due to decreased precipitation or an increase in evaporation that overrides an increase in precipitation. A closer look at the seasonal maps shows that water shortage may become a problem in some locations.

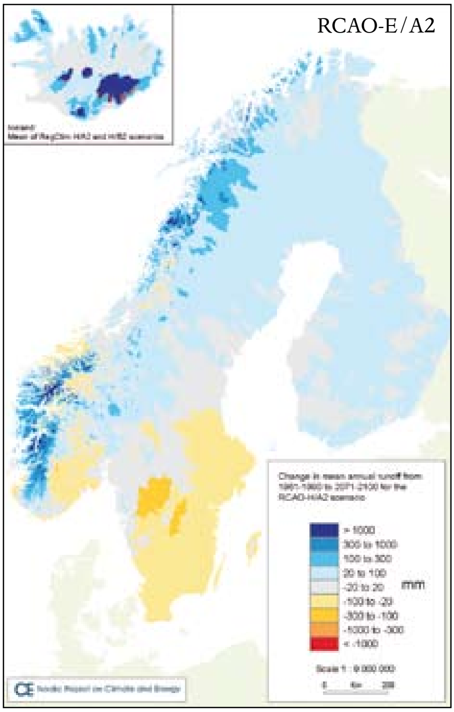
6.3 Climate impacts

River flow

The most immediate effect of a warmer climate in the Nordic area is a change in the seasonality of river flow, as the timing and amount of snow accumulation and melt will change. But precipitation and evaporation changes will also contribute. The end result will be runoff regimes that are quite different to those to which society (including the hydropower industry) is adapted under present-day conditions. In particular, the winters will be less stable, which will lead to more winter runoff and earlier onset of snowmelt in most areas.

National hydrographs were produced within the CE project. They represent average runoff conditions over a 30-year period of, more or less, the entire runoff volumes from the territory of each of the participating countries. The climate scenarios have been used to simulate how these hydrographs may change due to global warming, as shown in Figure 6.2.

More detailed studies from specific rivers were carried out by the CE hydrological models group (Bergström *et al*, 2007).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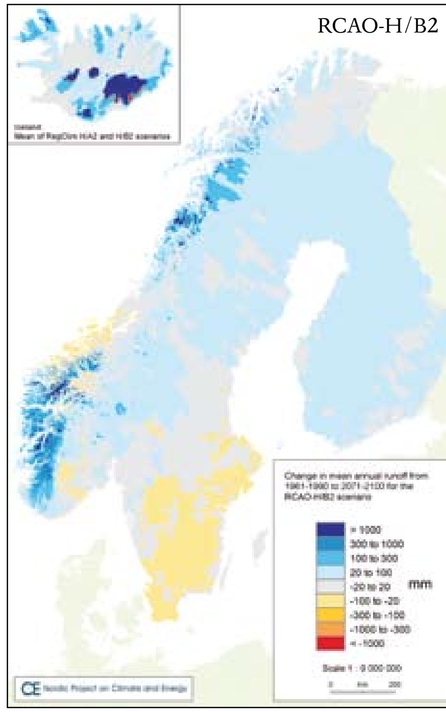
RCAO-H/B2
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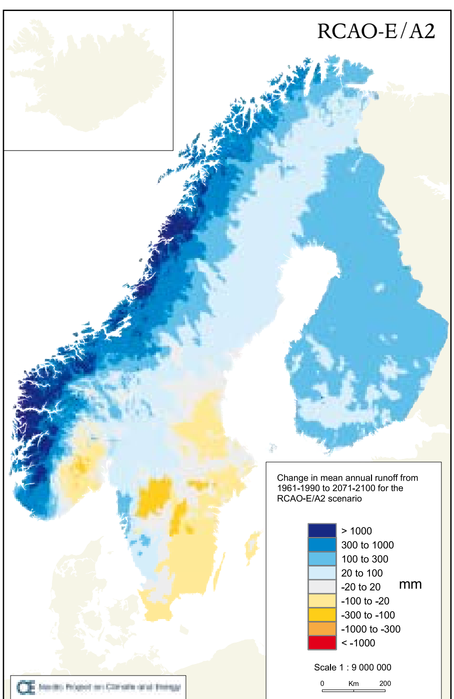
RCAO-E/A2
Change in mean annual runoff from 1961-1990 to 2071-2100 for the RCAO-E/A2 scenario
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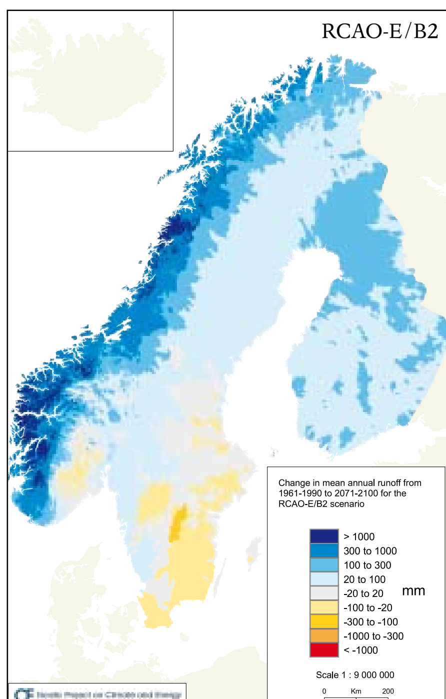
RCAO-E/B2
Change in mean annual runoff from 1961-1990 to 2071-2100 for the RCAO-E/B2 scenario
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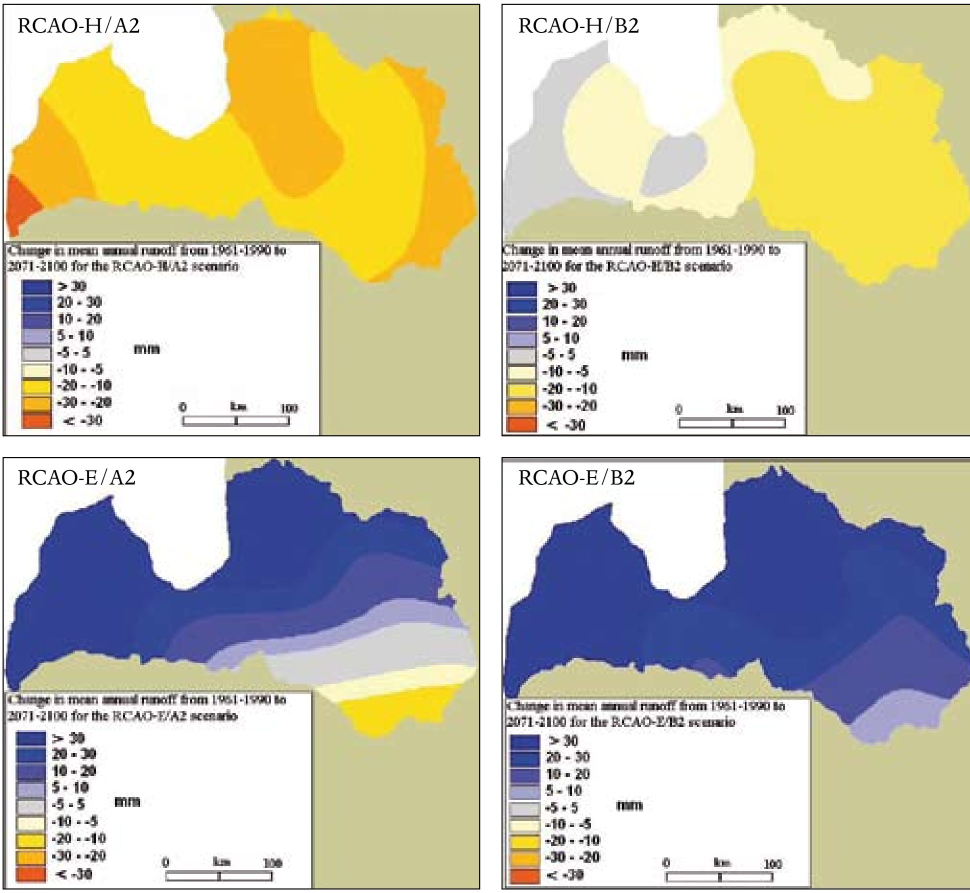
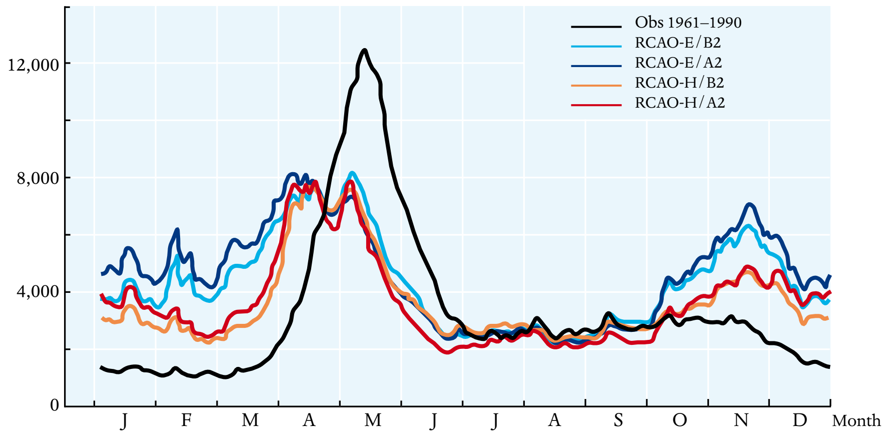
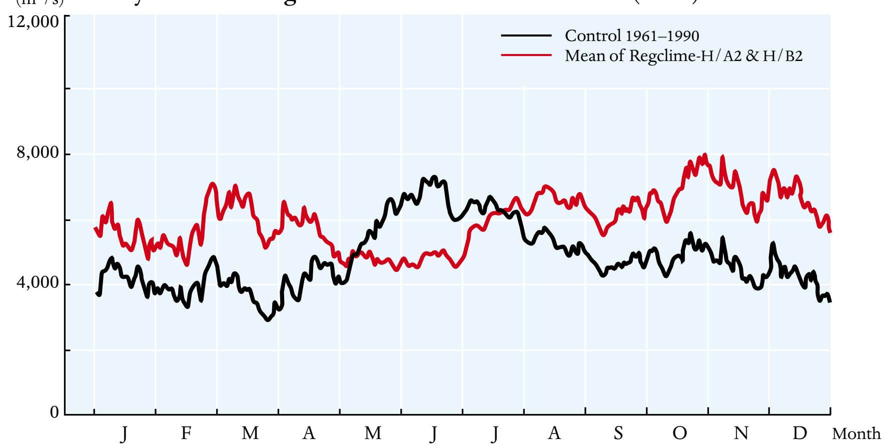


Figure 6.1. Changes in average runoff in the Nordic area including Latvia, according to climate scenarios and hydrological modelling carried out within the CE project. The two global climate models are HadAM3H and ECHAM4/OPYC3 run with the A2 and B2 emission scenarios. The results are processed by regional downscaling and hydrological models (from Beldring *et al*, 2006).

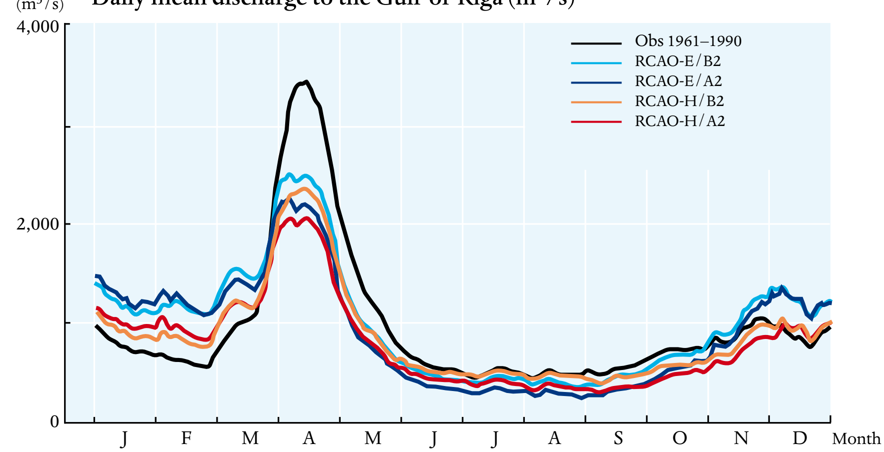
(m³/s) Daily mean discharge from the landsurface of Finland (m³/s)

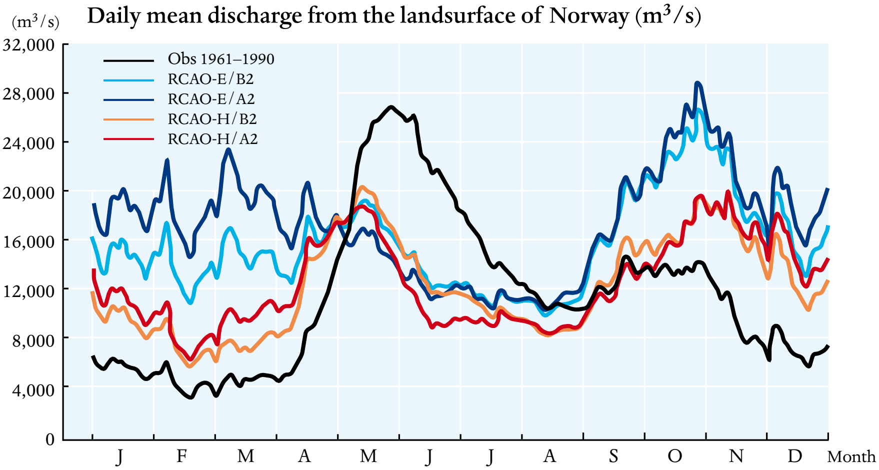


(m³/s) Daily mean discharge from the landsurface of Iceland (m³/s)



(m³/s) Daily mean discharge to the Gulf of Riga (m³/s)





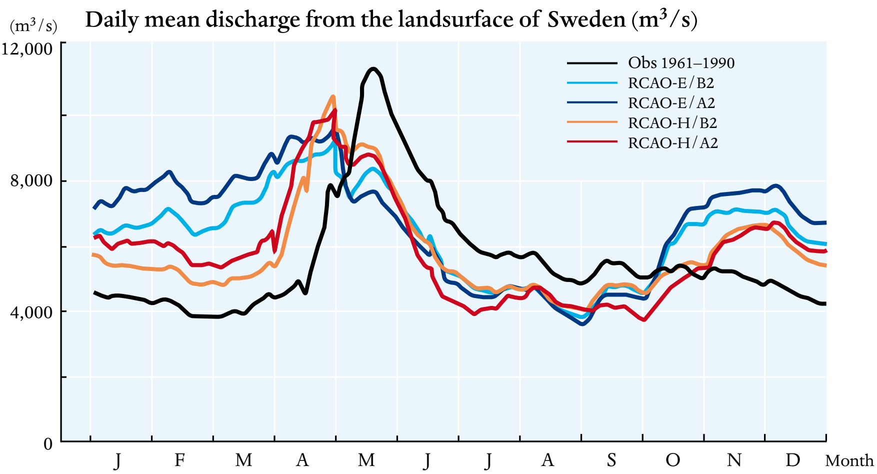


Figure 6.2. Changes in the seasonality and volume of runoff from each country for a 30-year period, as simulated by the climate scenarios and hydrological modelling within the CE project (from Beldring *et al*, 2006).

Hydropower production

It is obvious that the strong effects of global climate change on runoff regimes and runoff volumes (as illustrated in Figures 6.1 and 6.2) will have a strong impact on hydropower production in the Nordic Region. The more precise effect has been analysed by the CE's energy system analyses group, which has also considered the changing demands due to decreased heating requirements. This shows that the increase in production potential is lower than the increase in runoff due to increased spillage in the new climate. This may change, if the systems are upgraded to meet the new hydrological conditions caused by climate change.

Effects on extremes and dam safety

For the hydropower sector, changes in floods and extreme river flow that are induced by climate change are key issues. Because dams are designed according to strict national guidelines, which have been developed under the assumption that the climate is stable, the prospect of a changing climate is, of course, a matter of concern. The impacts of global warming on the national guidelines for dam design have been studied, particularly in Finland (Veijalainen & Vehviläinen, 2006) and Sweden (Andréasson *et al*, 2006), within national research projects and with support from CE. In both countries, this work is based on modifications of the original Swedish guidelines for high hazard dams as formulated by the Swedish committee on design flood estimation in 1990 (Flödeskommittén, 1990).The Finnish experience (taken from a comprehensive national analysis covering almost all major dams) is summarised in Figure 6.3. The Swedish studies were carried out in a smaller selection of rivers, and the results of these are summarised in Figure 6.4.

A general conclusion from the studies on design criteria for dams from a global warming perspective is that this is an issue that has to be taken seriously. The large difference between results from different climate scenarios implies that there is great uncertainty around this, and it is not obvious what the impact might be. The most important factor is whether the most extreme floods are generated by rain or snowmelt. A careful investigation for each specific site is therefore justified.

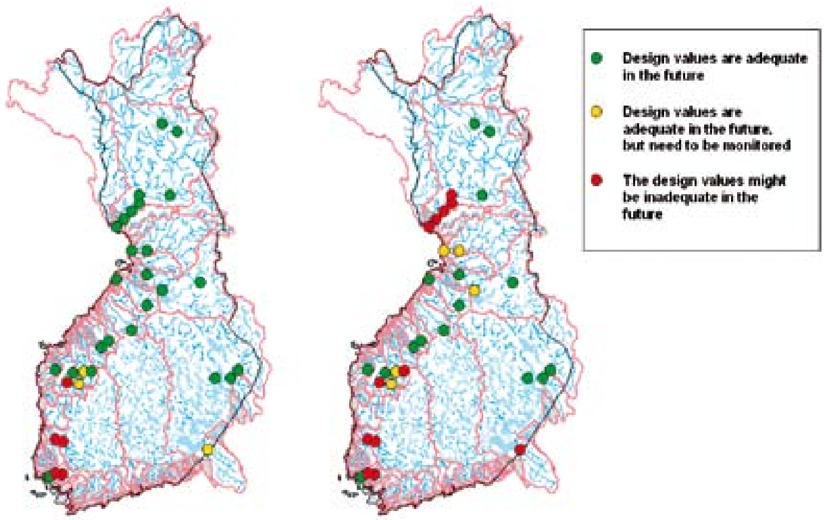


Figure 6.3. Synthesis of the Finnish group's work on climate change impacts on dam safety (from Veijalainen & Vehviläinen, 2006). Left: scenarios giving the smallest floods. Right: scenarios giving the largest floods.

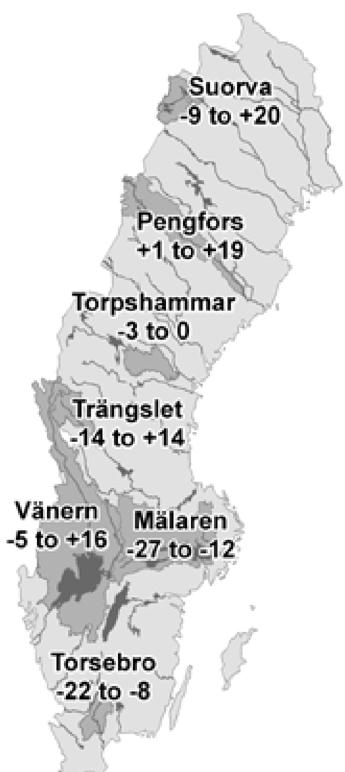


Figure 6.4. Synthesis of the Swedish group's work on climate-change impacts on dam safety (from Andréasson *et al*, 2006). The numbers shown are the span of change in the design flood, according to the four regional climate scenarios RCAO-H/A2 and B2 and RCAO-E/A2 and B2.

Other hydrological variables

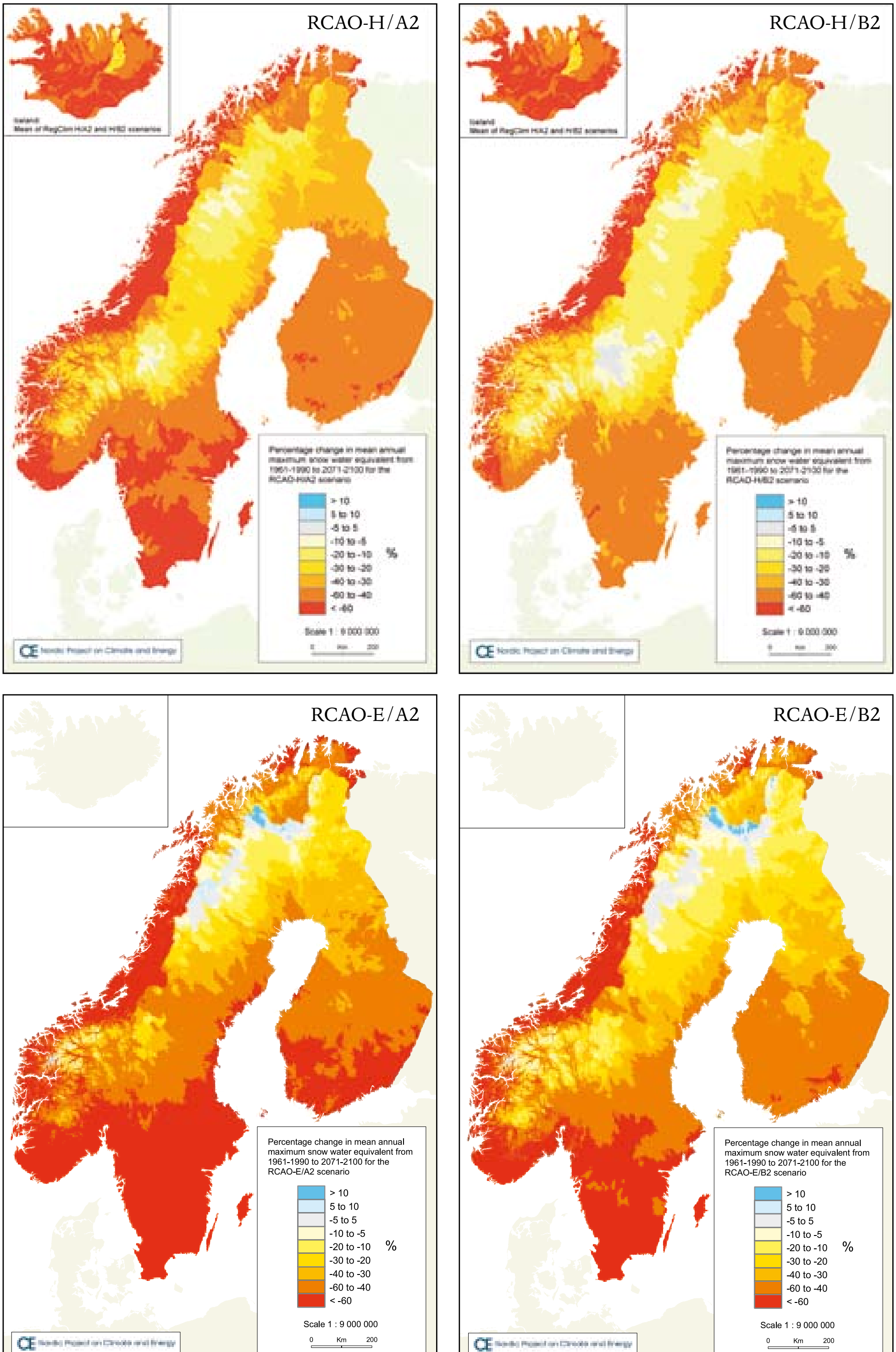
The hydrological simulations carried out within the CE project have generated a wealth of data on hydrological variables other than runoff. Some of these results are presented as maps by Beldring *et al* (2006) and some are by-products of the simulations for specific rivers in the different countries. Most dramatic is probably the change in snow cover, as illustrated in Figure 6.5. This effect is accounted for in the runoff maps (Figure 6.1), of course, but the change in snow cover will also affect sectors other than the power industry, such as tourism.

A study of changes in the frazil ice production and the likelihood of ice jams in the Þjórsá river in southern Iceland was conducted, based on the CE climate scenario for Iceland (Gröndal, 2006). It found that substantially fewer and less severe cold events with frazil ice production are expected in the future, leading to an about 30% reduction in the accumulated ice production in 2071–2100 compared with 1961–1990.

6.4 Glaciers and glacial hydrology

Glaciers cover about 11% of the total area of Iceland and receive about 20% of the precipitation that falls on the country. They store, in the form of ice, the equivalent of 15–20 years of annual average precipitation over the whole country. Substantial changes in the volume of glacier ice may, therefore, lead to large changes in the hydrology of g lacial rivers, with important implications for the hydropower industry and other water users. Glacial runoff affects most of the larger watersheds in Greenland, and it constitutes a relatively large component in

Figure 6.5. Changes in yearly average maximum snow cover in the Nordic Region according to four climate scenarios and hydrological modelling carried out within the CE project. The two global climate models are HadAM3H and ECHAM4/OPYC3, run with the A2 and B2 emission scenarios. The results are processed by regional downscaling and hydrological models (from Beldring *et al*, 2006).


RCAO-H/A2
Percentage change in mean annual maximum snow water equivalent from 1961-1990 to 2071-2100 for the RCAO-H/A2 scenario
> 10
5 to 10
-5 to 5
-10 to -5
-20 to -10
-30 to -20
-40 to -30
-60 to -40
< -60
%
Scale 1 : 9 000 000
RCAO-H/B2
Percentage change in mean annual maximum snow water equivalent from 1961-1990 to 2071-2100 for the RCAO-H/B2 scenario
> 10
5 to 10
-5 to 5
-10 to -5
-20 to -10
-30 to -20
-40 to -30
-60 to -40
< -60
%
Scale 1 : 9 000 000
RCAO-E/A2
Percentage change in mean annual maximum snow water equivalent from 1961-1990 to 2071-2100 for the RCAO-E/A2 scenario
> 10
5 to 10
-5 to 5
-10 to -5
-20 to -10
-30 to -20
-40 to -30
-60 to -40
< -60
%
Scale 1 : 9 000 000
0 Km 200
RCAO-E/B2
Percentage change in mean annual maximum snow water equivalent from 1961-1990 to 2071-2100 for the RCAO-E/B2 scenario
> 10
5 to 10
-5 to 5
-10 to -5
-20 to -10
-30 to -20
-40 to -30
-60 to -40
< -60
%
Scale 1 : 9 000 000
0 Km 200

the water budget of several hydropower plants in Norway. As an example, the Svartisen ice-cap and the smaller ice-caps and glaciers in the same watershed cover about 50% of the drainage area used by the Svartisen hydropower plant in northern Norway.

The effect of climate warming on glacial runoff includes an initial increase in total glacial runoff and peak flows, and a considerable amplification in the diurnal runoff oscillation, followed by significantly reduced runoff totals and diurnal amplitudes as the glaciers retreat (Hock *et al*, 2005).

During historical times, glaciers and ice-caps in the Nordic countries have retreated and advanced in response to climate changes that are believed to have been much smaller than the greenhouse-induced climate changes expected during the next 100–200 years. In many cases, these changes have left clear marks on the landscape in the glaciers' locality, as shown in Figure 6.6.

It has been estimated that the melting of all glaciers and ice-caps on Earth, excluding the large ice sheets of Greenland and Antarctica, would raise sea level by about 0.5 m, although there is still considerable uncertainty about the sea level rise equivalent of the ice stored in these glaciers. The rate of retreat of glaciers and the contribution of this to sea level rise have been monitored and modelled, and found to have increased in the latter part of the 20th century (Radic, 2006). Increased melt water flux from glaciers into the world's oceans may also have other far-reaching effects, including changes in salinity and vertical stratification of the upper layers of the Arctic Ocean and nearby oceanic areas, with possible consequences for thermohaline circulation in the Atlantic Ocean. Several ice-caps and glaciers were studied within the CE project (see Figure 6.7).

The main topics of study were:

- Mass balance modelling, including studies of precipitation and snowfall on the glaciers
- Dynamic glacier modelling where ice flow models were coupled with mass balance models
- Adaptation of climate scenarios for glacier modelling
- Runoff modelling with an emphasis on changes in total runoff, runoff seasonality and diurnal runoff variation.

Figure 6.6. The forefields of Brikdalsbreen in western Norway (photo, top: Kurt Erik Nesje, 2005) and an outlet glacier on the south side of the Langjökull ice-cap in western Iceland (photo, bottom: Oddur Sigurðsson, 2003) show clear signs of past changes in the position of the glacier margin. The linear feature clearly visible in the mountainside in front of Brikdalsbreen illustrates the extent of the glacier after an advance that took place in the 1990s. A similar feature in the mountainside to the side of the Icelandic glacier and the terminus moraine that extends across the lake in front of it bear witness to the advanced position of the glacier at the end of the Little Ice Age in the late 19th century.

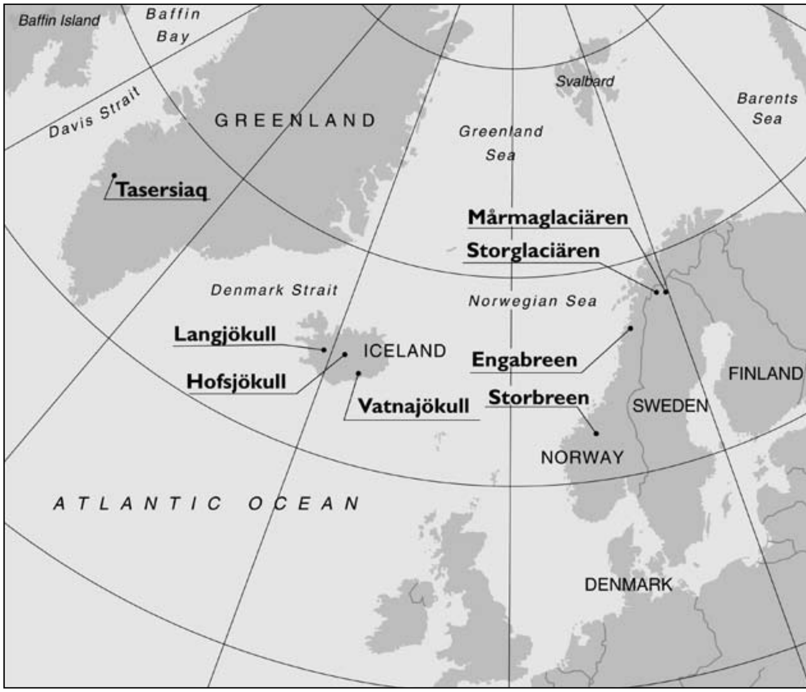


Figure 6.7. Location of the glaciers and ice-caps studied in the CE project.

ICELAND

- Vatnajökull, an ice-cap in south-eastern Iceland
- Hofsjökull, an ice-cap in central Iceland
- Langjökull, an ice-cap in western Iceland

NORWAY

- The Svartisen ice-caps in northern Norway, including the outlet glacier Engabreen from Vestre Svartisen
- Storbreen, a valley glacier in central southern Norway

SWEDEN

- Storglaciären
- Mårmaglaciären

DENMARK / GREENLAND

- Tasersiaq basin, a partly glaciated basin at the margin of the Greenland ice sheet where hydropower potential is being studied

In all cases, the models were calibrated with available observations of the mass balance and geometry of the glaciers. The models are able to reproduce the main characteristics of the mass balance turnover and ice flow, and may be expected to yield realistic estimates of the response of the glaciers to assumed climate changes. The main source of uncertainty in the results is due to future climate development, which, for temperature, spans a range between very little warming in the North Atlantic area to a warming similar to other oceanic areas on Earth. The precipitation is also very uncertain, with regard to both absolute changes and seasonal and spatial distribution.

6.5 Glacier modelling

Several types of climate change scenario, based on the general CE scenarios, were used for the glacier modelling (see Chapter 4). The projected increase in temperature between 1961–1990 and 2071–2100 is in the 2.5–3 °C range for Glomfjord (near Engabreen), Storbreen and Hveravellir, and about 3.5 °C for Storglaciären. The projected precipitation change varies by a factor of five between the three locations, from 5% for Hveravellir in Iceland to 28% for Glomfjord in Norway. It is unclear to what degree this difference in the projected precipitation change is due to 'natural' fluctuations in the climate simulations on which the scenarios are based, or whether it reflects a true deterministic signal due to imposed greenhouse forcing. The comparatively large change in precipitation projected by the CE scenario for this part of Norway is a consequence of very large precipitation changes due to enhanced westerlies in the ECHAM/AOGCM and subsequently in some of the RCMS of CE.

Glacier mass balance depends not only on mean annual climate but also on the seasonality of the climate. Therefore, future changes in the seasonality of temperature and precipitation need to be specified by the glacier modelling scenarios. As an example, Figure 6.8 shows the scenario for changes in monthly temperature and precipitation in the Icelandic Highlands that was used in mass balance and dynamic modelling of the Langjökull, Hofsjökull and Vatnajökull ice-caps. The figure shows that the highest warming is projected in the spring and, in particular, autumn, with lower warming during the summer and the lowest warming during winter. This variation is different from the scenario for Iceland, which was used in the previous CWE project (see

Jóhannesson *et al*, 2004), where the specified warming was highest in mid-winter and lowest in mid-summer, with a sinusoidal variation in between. The seasonal variation in the projected temperature changes shown in Figure 6.8 may be attributed to a shortening of the season with snow cover, and to the relatively small variation in temperature in Iceland during winter, caused by the proximity of the ocean. The projected precipitation increase is largest during autumn. As for most other aspects of the projected changes in precipitation, it is unclear to what degree these are due to 'natural' fluctuations in the climate simulations or a true deterministic signal due to greenhouse warming.

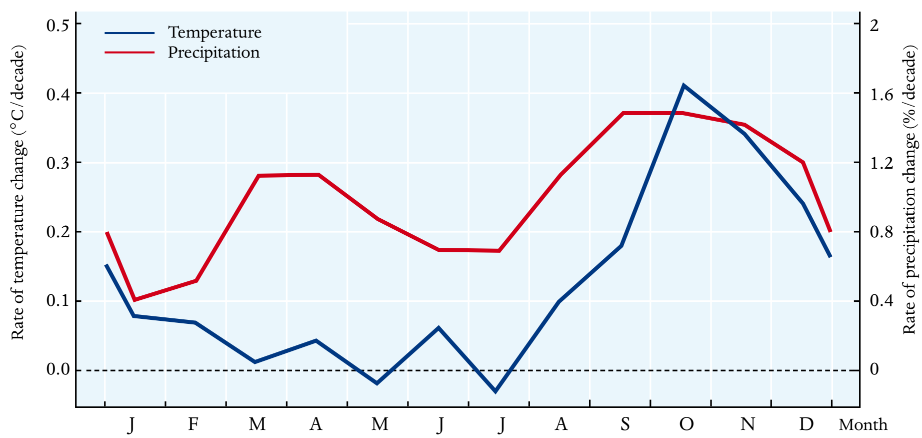


Figure 6.8. Average monthly temperature and precipitation change per decade between the periods 1961–1990 and 2071–2100 for the Icelandic Highlands according to the CE climate change scenario

Glacier mass balance

Glacier mass balance was modelled with degree-day models of different complexity (Jóhannesson *et al*, 2006; Thorsteinsson *et al*, 2006; Schuler *et al*, 2005; Andreassen *et al*, 2006; Radic & Hock, 2006; Reeh & Ahlstrøm, 2007) and, in the case of Storbreen, with an energy balance model (Andreassen *et al*, 2006). In the degree-day models, snow accumulation and ablation are computed from daily temperature and precipitation observations (or estimates) at nearby meteorological stations (or model grid points). Temperature on the glacier is found using a constant vertical lapse rate, and precipitation is computed using horizontal and vertical precipitation gradients, or regular grids with 1×1 km resolution of the spatial precipitation distribution. The energy balance model is calibrated with observations of radiation, temperature, relative humidity and wind speed from an automatic weather station on the glacier and from nearby meteorological stations, and is run using data from meteorological stations outside the glacier.

A special study of precipitation in the Icelandic Highlands was carried out using dynamical downscaling of ERA-40 precipitation (Crochet *et al*, 2006), with a theory of orographic precipitation proposed by Smith & Barstad (2004). The airflow pattern over complex terrain is simulated using linear mountain-wave theory, and the resulting precipitation field is found using a linear cloud physics representation. Glacier mass balance data were used to verify the modelled precipitation distribution. Figure 6.9 shows the modelled distribution of the mean annual precipitation for the years 1961–1990 for Iceland as a whole and for the Vatnajökull ice-cap. The results are in general agreement with what is known about the distribution of precipitation in Iceland, from glacier mass balance measurements and from observations at meteorological stations.

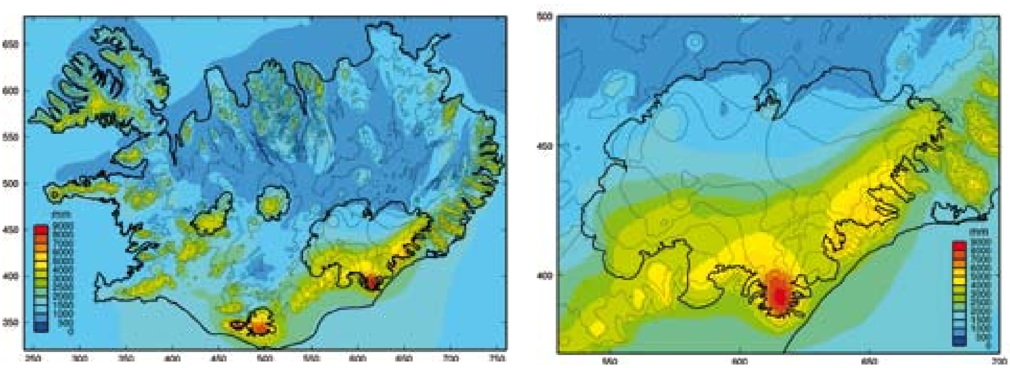


Figure 6.9. Modelled mean annual precipitation for the reference period 1961–1990 for Iceland (left) and the Vatnajökull ice-cap (right) based on a dynamical downscaling of large-scale meteorological fields from the ERA-40 re-analysis using linear mountain-wave theory. Outlines of the four main ice-caps are shown with thick black curves. Thin black curves are 500 m elevation contours.

The static sensitivity of the mass balance of the modelled glaciers to temperature changes (defined as the change in the mass balance that results from a warming of 1 °C) was found to vary from –0.1 to –0.2 $m_{w.e.}a^{-1}{}^{\circ}C^{-1}$ for the Tasersiaq basin, through approximately –0.3 and –0.5 $m_{w.e.}a^{-1}{}^{\circ}C^{-1}$ for Mårmaglaciären and Storglaciären, respectively, –0.6 to –0.7 $m_{w.e.}a^{-1}{}^{\circ}C^{-1}$ for Storbreen and Hofsjökull, and –0.9 $m_{w.e.}a^{-1}{}^{\circ}C^{-1}$ for Engabreen, to –1.1 to –1.3 $m_{w.e.}a^{-1}{}^{\circ}C^{-1}$ for Langjökull and S-Vatnajökull. The glaciers with the longest ablation season and largest mass balance turnover have the largest static sensitivity, as has been found in previous studies (see for example Oerlemans & Fortuin, 1992; de Woul & Hock, 2005; Hock *et al*, 2007). The sensitivity to a 10% increase in precipitation was typically much smaller, so that if future precipitation changes are as small as projected by the CE scenarios, it is estimated that the effect of future temperature changes will dominate that of precipitation changes, except for coastal glaciers in western and northern Norway, where some of the regional climate scenarios suggest that larger precipitation changes may be possible.

Glacier dynamics

The dynamic response of the Icelandic glaciers to the modelled mass balance changes was simulated with the 2D ice flow model developed by Aðalgeirsdóttir (2003) coupled to the MBT degree-day mass balance model (Aðalgeirsdóttir *et al*, 2006) and, in the case of the Norwegian and Swedish glaciers, for the evolution of the ice volume over time based on a volume-area scaling (Radic & Hock, 2006; Andreassen *et al*, 2006). The dynamic response of Tasersiaq basin was not simulated because this is not likely to have much influence on runoff changes in this area within the next 100–200 years due to the large size and long response time of the Greenland ice sheet.

Figure 6.10 shows the simulated ice wastage for the modelled glaciers. The simulations with the 2D ice flow model are run to 2200, but the volume-area scaling simulations are only run to 2100 because of limitations in the applied model. The time evolution of ice volume has a similar character for all the modelled glaciers, except Engabreen and Mårmaglaciären. The modelled ice volume is reduced by more than half within the next 100 years, and the glaciers essentially disappear 100–200 years after the start of the simulations, assuming that the rate of warming remains the same over time. Engabreen retreats more

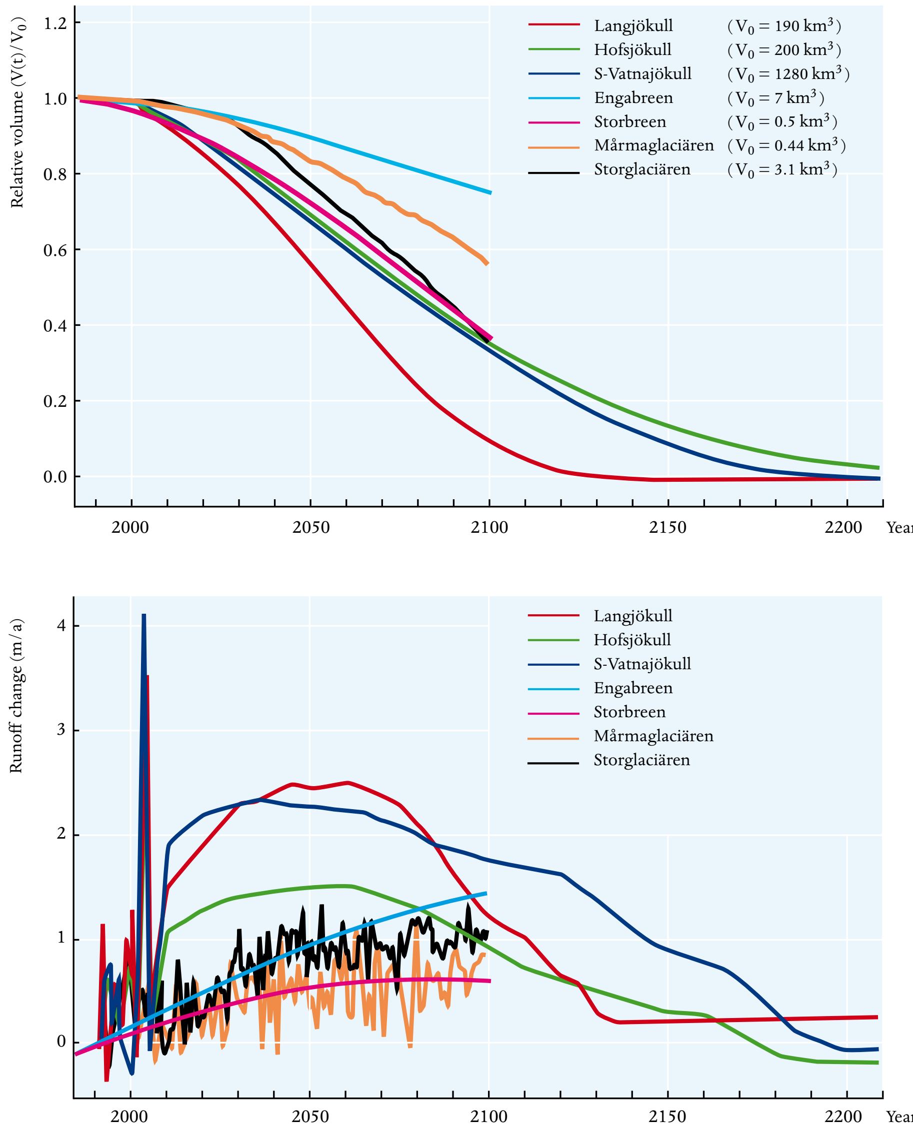


Figure 6.10. Modelled ice volume and change in runoff from the presently glaciated area for seven ice-caps and glaciers in Iceland, Norway and Sweden. The legend for the ice volume figure specifies the approximate volume of ice for each glacier in about the year 2000. The initial ice volume in the dynamic model simulations may be slightly different from the specified volume because the modelled glacier may under- or overestimate the volume of ice.

slowly because of the substantial increase in precipitation that is projected by the CE scenario for the area in which this glacier is located.

Glacial runoff

The projected change in the mass balance of the glaciers leads to a substantial increase in glacier runoff, as can be seen in Figure 6.10, which shows the modelled increase in runoff from the area covered with ice at the start of the simulations. Due to the large amplitude of the projected changes, the changes with respect to the runoff at the start of the simulations are similar to changes with respect to a 1961–1990 baseline, which was not explicitly modelled for most of the glaciers. Around 2030, annual average runoff is projected to have increased by almost nothing for the Tasersiaq basin in Western Greenland, approximately 0.4–0.7 $m_{w.e.}a^{-1}$ for Engabreen, Storbreen, Mårmaglaciären og Storglaciären, and 1.5–2.5 $m_{w.e.}a^{-1}$ for Langjökul, Hofsjökull and S-Vatnajökull. The increase in runoff reaches a comparatively flat maximum between 2025 and 2075 (except for the Teasersinq basin and Engabreen), when the increasing contribution from the negative mass balance is nearly balanced by the counteracting effect of the diminishing area of the glacier. For all the glaciers, this maximum in relative runoff increase is in the 50–100% range with respect to the present runoff from the area currently covered with ice.

For the Icelandic ice-caps, the specification of climate change during the initial decades of the simulation, based on the observed climate of recent years and the seasonality of the climate change with the largest warming in spring and autumn, leads to a rapid increase in runoff with time – much more rapid than in the previous CWE scenario, which was used by Jóhannesson *et al* (2004) and Aðalgeirsdóttir *et al* (2006) in the modelling of Hofsjökull and S-Vatnajökull. The model results for Engabreen show that, although the precipitation increase for the other glaciers is of much smaller importance than the temperature change, the assumed precipitation change can significantly alter the simulation results, in the case of substantial precipitation changes taking place. The fact that this only happens for one of the glaciers highlights the uncertainty of the climate change scenario. The small modelled runoff change for the Tasersiaq basin also highlights the uncertainty of the climate change scenario, although this is partly caused by a cold snowpack and formation of superimposed ice.

These results clearly show large changes in runoff from glaciated areas, which are already projected to have reached significant levels compared with current runoff by 2030. The associated changes that might be expected in diurnal and seasonal characteristics of glacial runoff (de Woul *et al*, 2006; Hock, 2006;) will come on top of the changes in the annual average that are shown in Figure 6.10.

6.6 Uncertainties

The fact that several climate scenarios are used gives an indication of the uncertainties involved; and the fact that the results based on two global models (HadAM3H from the Hadley Centre and ECHAM4/OPYC3 from the Max Planck Institute for Meteorology) differ quite substantially has been useful for analyses of possible uncertainties within the CE project. But the global climate models are not the only source of uncertainty. The total extent of uncertainty in the runoff scenarios is generated by all the components along the production chain, from emission scenarios, via global and regional climate models, through the hydrological models to impact analysis. Each of these steps includes assumptions and model formulations that affect the end result. In addition to this, there are assumptions in the interfaces between the models (for example, the delta change approach between the climate models and the hydrological model), which can be critical.

The impact of the different formulations of this interface between the climate models and the hydrological models has been studied by the Swedish group. It is based on the standard delta change method and a method that uses data from the climate models more directly. The group concluded that the effect of the choice of strategy is not as great for average conditions as for extremes. This means that the delta change method used in the CE project is more reliable for the average conditions shown in the maps in Figure 6.1, but that extreme floods have to be analysed more carefully.

A collection of climate change impact simulations for hydrological processes in Norway was estimated through the combination of results from the two global climate models (HadAM3H from the Hadley Centre and ECHAM4/OPYC3 from the Max Planck Institute for Meteorology), the A2 and B2 emission scenarios, and dynamical downscaling using the RCAO and HIRHAM regional climate models. This procedure resulted in a collection of scenarios of climate conditions. The regional climate model results were further downscaled to meteorological station sites, using two different approaches: the delta change method was applied for the RCAO simulations; and the Reg-

Clim results were downscaled using a statistical adjustment technique that preserves the frequency of precipitation and temperature as predicted by the climate models, aiming at reproducing observed monthly means and standard deviations for the control period (Engen-Skaugen *et al*, 2005). The downscaled regional climate model results were subsequently used for driving the HBV-model, yielding a collection of hydrological simulations for present and future conditions. Although the different climate scenarios agree in terms of the direction of changes, they differ substantially in terms of magnitude, as shown in Figure 6.11.

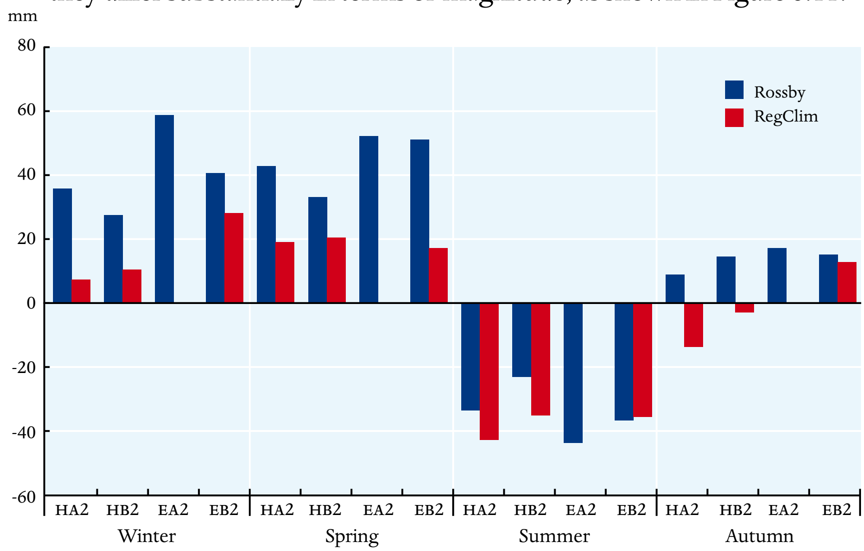


Figure 6.11. Changes in runoff for Nybergsund in Trysilelva / Klaraälven from 1961–1990 to 2071–2100, based on the HadAM3H and ECHAM4 / OPYC3 GCMs, and the A2 and B2 emission scenarios. Downscaling to meteorological station sites used the RCAO model and the delta change approach (Rossby Centre method), and the HIRHAM model and a statistical adjustment technique (RegClim method). ECHAM4 / OPYC3 simulations using the A2 emission scenario have not been downscaled to meteorological station sites with the RegClim method.

6.7 Implications for the hydropower industry

Hydropower is the most important renewable source of electricity in the Nordic Region, and it is strongly affected by climate. The results from the CE project and the related national research programmes show that the impact of this can be quite strong. Global warming will shorten the Nordic winter and make it less stable, and will lengthen the ablation season of glaciers and ice-caps. This will lead to a more evenly distributed river flow the year round – a profitable situation for the hydropower industry, and one which will make it easier to meet the demands of the electricity market. There is also potential for increased hydropower production, as the highest modelled increase in river flow is simulated in areas with extensive development of hydropower, *i.e.* the Scandinavian mountains and the Icelandic Highlands. This implies that the projected hydrological changes may be expected to have practical implications for the design and operation of many hydroelectric power plants, and also for other uses of water, especially from glaciated highland areas.

Inter-annual variation in inflow to the hydropower systems is an issue which is attracting growing attention. Its impact on pricing in the Nordic Region has been clearly demonstrated in recent years. The main method used in the CE project, however, has a serious drawback in this respect. The delta change method lacks potential for the studies of changes in frequency or patterns of dry or wet years, as the results are very much tied to present-day variabilities between years. New methods have to be developed to support this type of analysis.

One negative aspect is that the new annual rhythm in runoff indicated in the simulations will put more stress on the spillways. They will probably have to be operated more often in winter, as the unstable winter climate will generate more frequent sudden inflows when reservoirs may be full. This will also have an impact on the infrastructure, with more frequent flooding problems downstream of the reservoirs. These areas are normally adapted to the present-day climate, which is characterised by its stable winters and lack of high flows from autumn to spring.

Global warming thus adds a new aspect to the dam safety issue. This is already a matter of great concern and a re-evaluation of design floods is being carried out in Norway, Finland and Sweden. It is natural to ask how climate change is to be accounted for in this situation, but it is not easy to give a clear answer. Far-reaching decisions have to be made in the unavoidably uncertain field of climate change scenarios, while being aware that new climate scenarios will appear in the near future. This uncertainty must not hinder the necessary upgrading of the existing hydropower systems.

In summary, the power industry will have to develop a new strategy that is characterised by flexibility. Extra margins must be included as part of the design process, because of the new uncertainty. Flexibility means it must be possible to adapt the operation, or even adapt the design of a structure, to accommodate new scientific findings related to the impact of global warming.

In order to establish an idea of the uncertainties in the assessment of consequences for the power industry, a set of climate scenarios is used by the hydrological models group. These scenarios do not cover the full range of possible variations, however, and newer results from climate modelling are also emerging. It is therefore important to carry out further studies on the impact on both the production and the safety of the hydropower system, along with the arrival of new results from climate modellers. Of particular interest are the results from the ongoing EU-funded ENSEMBLES project.

Any attempt to foresee the future of the hydropower production system needs to be made with the full awareness that, in the future, society will be different. The liberalisation and internationalisation of the energy market is likely to continue, which means that hydropower will be generated to meet demands from an increasing area and a much more diverse mix of customers. The use of electricity for heating may be challenged, along with the development of new technologies. The expansion of wind power and other new sources of electricity will give hydropower a new role, in which full advantage is taken of its outstanding regulation capacity. Finally, the fate of nuclear power in Europe is also an important boundary condition for the future role of hydropower.

6.8 Literature

General references

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7 Wind power

Niels-Erik Clausen, Per Lundsager, Rebecca Barthelmie, Hannele Holttinen, Timo Laakso and Sara C. Pryor

Globally, wind energy is the fastest growing method of electricity production. At the end of 2005, the total amount of installed wind power capacity in Europe was about 40 GW. This is expected to have reached about 150 GW by the year 2020.

In the Nordic countries at the end of 2005, the amount of wind power was: Denmark, 3087 MW; Sweden, 554 MW; Finland, 85 MW; Norway, 225 MW; and Iceland, 0 MW. The amount of wind power is expected to grow significantly in this region. Denmark aims to increase the contribution from renewable energy to 30% in 2025, and Finland's official goal is 500 MW by 2010. The Norwegian government has a target (not legally binding) to producing 3 TWh per year of electricity (corresponding to approximately 1,000 MW) by wind power by 2010. The Swedish Energy Agency (Energimyndigheten) has advised the Swedish government to build sufficient wind turbines to produce 10 TWh annually, in 10 to 15 years.

The Baltic countries began exploiting wind energy this decade, and at the end of 2005 the installed capacity was: Estonia, 30 MW; Latvia, 26 MW; and Lithuania, 7 MW. It is clear that the growth in the Nordic and Baltic countries will be aimed at offshore production, but coastal and even mountainous sites will also be exploited.

7.1 Wind energy and wind turbine technology

Wind is produced by global and local differences in air temperature and pressure. For wind power, the wind in the lowest part of the atmosphere is most important. Local winds are always superimposed on larger scale wind systems, also depend on elements such as surface type and local obstacles, and are influenced by a combination of global and local effects. When larger scale winds are light, local winds can dominate the wind patterns. Thus, the wind climate will be affected by global, regional or local changes in, for example, temperature field or local vegetation.

The power in wind is proportional to the cube of the wind speed, as shown in Figure 7.1. So, for example, a 20% higher wind speed will imply that there is more than 70% additional energy content in the wind.

This also means that the cost of electricity produced is very sensitive to the speed and distribution of the wind, and therefore the choice of a location that offers the best resources is key. An accurate understanding of the wind system – the average wind speed, vertical wind gradient and frequency distribution – is the most important factor when assessing the economic feasibility of a project.

Power in the wind is:

$P_{wind} = 1/2.r.V^3$ [W/m^2]

Wind speed (m/s)	Power in the wind (Watt/m^2)
3	16
6	130
12	1,035

Source: Jos Beurskens, ECN

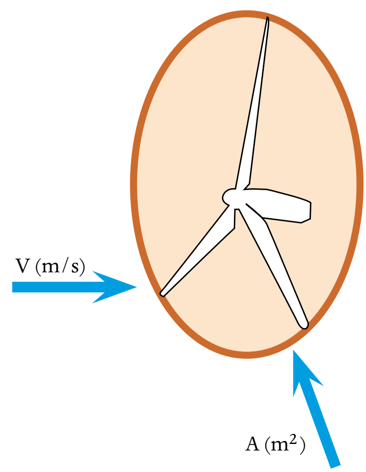


Figure 7.1. Wind power is proportional to the cube of the wind speed. To calculate the power in the wind at a future wind turbine location: 'V' should be the value of the undisturbed wind speed at hub height; 'A' should be the rotor swept area; and 'r' should be the air density. On the basis of flow theory (Betz law) a wind turbine can never extract more than 16/27 (= 59.3%) mechanical energy from the wind. (European Wind Energy Association, 2005).

In the past, in order to facilitate site selection and assess the feasibility of possible projects, wind 'atlases' have been produced, showing wind speed characteristics at different locations, including methods of estimating wind speeds other than those used at a particular location, as well as methods of determining the vertical wind gradient for different levels of terrain roughness (Figure 7.2).

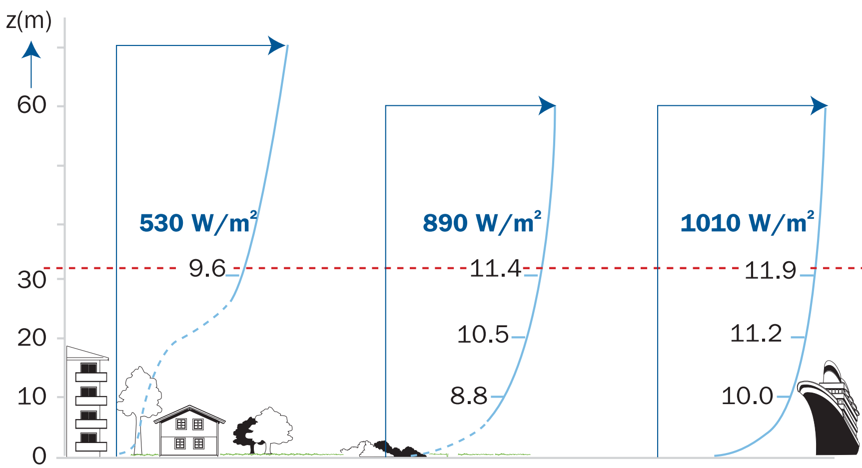


Figure 7.2. The vertical wind gradient for different values of surface roughness (built up area such as the centre of a city, area with scrub vegetation, open flat land or sea surface). Note that the wind power content of the wind at the same height (30 m) varies considerably.

The possible effects of climate change on future wind speeds and their distributions could, therefore, have a significant effect on the economy of future wind energy projects.

The typical wind turbine

Wind turbines transform kinetic energy in the wind into electricity. Almost all commercial wind turbines are 'horizontal axis' machines with rotors using two or three airfoil blades. The rotor blades are fixed to a hub, which is attached to a main shaft, which turns a generator, usually with transmission through a gearbox. Shaft, generator, gearbox, bearings, mechanical brakes and the associated equipment are located inside the nacelle on top of the tower (Figure 7.3). The nacelle also supports and transfers structural loads to the tower, together with which it houses all automatic controls and electric power equipment.

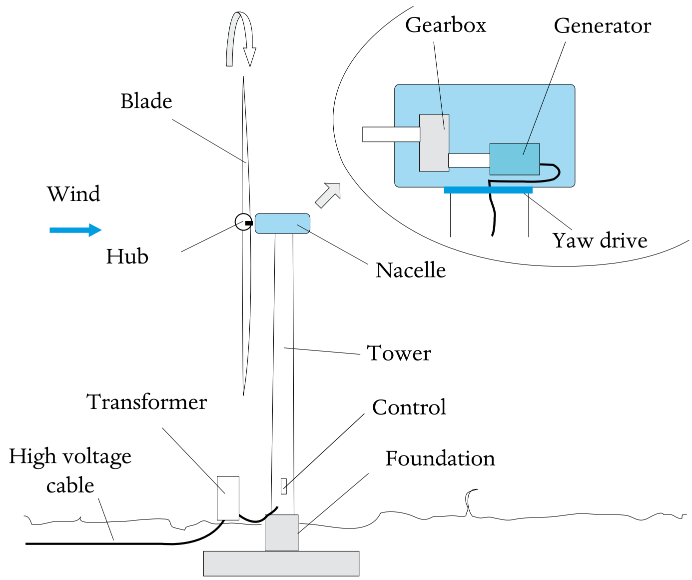


Figure 7.3. Sketch of a modern wind turbine.

Wind turbines automatically yaw the nacelle to face the wind, to facilitate optimal energy production. At very high wind speeds (typically 25 m/s), turbines are stopped to protect them from damage. Depending on the design, rotors may operate at constant or variable speed, but nearly all modern MW-size machines are built on the concept of variable speed. Typical rotor speeds, at rated power, range from 15 revolutions per minute upwards, a factor that influences the visual impact. The larger the rotor is, the lower is its rotational speed, which is done to keep the blade tip speed in the optimal range of 60–80 m/s. As the wind speed changes, power output is automatically regulated, in order to limit loads and optimise power production. A current, state-of-the-art large wind turbine will have:

- Power control by active stall or pitch control (in both cases pitching blades) combined with some degree of variable speed rotor
- Asynchronous generator with variable speed (limited range) or a gearless transmission to a multi-pole synchronous generator and power electronics.

Wind turbines range in capacity (or size) from a few kilowatts to several megawatts. The crucial parameter is the rotor diameter – the longer the blades, the larger the area swept by the rotor and thus the larger the volume of air hitting the rotor plane. At the same time, the taller towers of large wind turbines raise the rotors higher above the ground, where there is higher energy density in the wind. Larger wind turbines have proven to be more cost-efficient, due to improvements in design and economies of scale; they also give a higher energy production per swept m^2, due to their higher towers and better aerodynamic design.

Future design – trends and possibilities

The trend is towards even larger machines, and this is especially the case for offshore applications. The current size range (500–2000 kW) seems quite appropriate for on-land applications, particularly where land availability is not a problem, or where there is a lack of large cranes and other equipment for the very large machines above 2,000 kW.

Source: Jos Beurskens, ECN

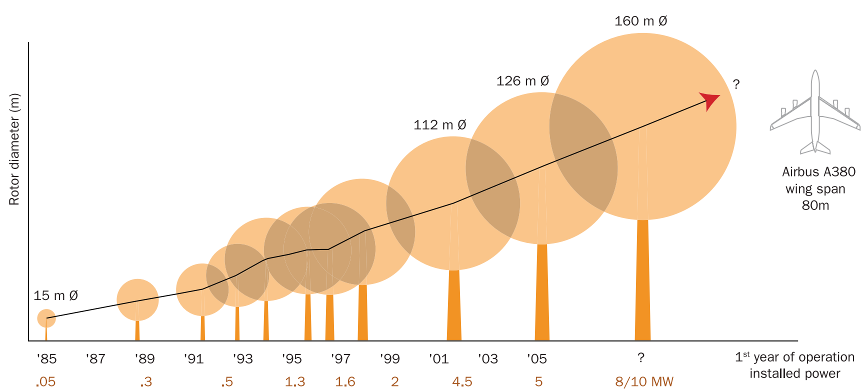


Figure 7.4. The size of wind turbines at the time they were introduced into the market. In mid-2005, the largest wind turbine had a diameter of 126 meters and a rated power of 5 MW.

From research, it is estimated that, in principle, wind turbine blades could be doubled in length using today's technology and materials. Wind turbine units could thus grow four or five times in terms of nominal kW capacity, with a rotor diameter of 250 m and hub height of 200 m. However, the development of wind turbines is not linked to the success of the up-scaling effort alone. There are many wind turbine designs on the market already, but there is still plenty of scope for innovation and technological development. Today, the majority of R&D investment is spent in up-scaling the best-selling products, all of which are three-bladed, up-wind machines with stiff tower and rotor. In order to reduce the top-weight (nacelle and rotor), new design methods and better design tools are being developed. Further development of new, more flexible design concepts that considerably reduce the wind turbine weight is possible, however, and in future these will certainly be seen for wind turbines for on-land applications. The resulting cost reduction may reach 25% within the coming 10 years, if concepts with more flexible rotor structure, transmission and power conversion are introduced. In order for this to happen, the market has to be attractive enough for the industry to pursue new concepts, and there must be investment in research.

Wind energy potential depends heavily on the regional and local wind climate. As the power production of wind turbines is related to wind speed to the third power (cubed), even small changes in average wind speed or wind speed distribution can, in principle, bring about significant changes in the output of wind turbines. Therefore, climate change may have an effect on energy production and turbine design, through the following climate related features:

- Wind speed distributions, average wind speeds, extreme wind speeds, wind direction changes, vertical wind speed profiles and wind speed fluctuations (turbulence patterns)
- Air density, temperatures and humidity (and corrosive agents); objects in the air, such as dust and debris; atmospheric icing.

The main icing process in Scandinavia is rime icing. In certain areas, atmospheric icing has a considerable influence on the performance of wind turbines. In addition to this, the amount of sea ice will affect the planning and design of offshore wind power plants in the northern part of the Baltic Sea. Extreme winds must also be taken into account in the design of rotors. As modern wind turbines have their technical cut-off speed (when the turbine is stopped) at about 25 m/s, an increase in high wind speeds will decrease the time of operation.

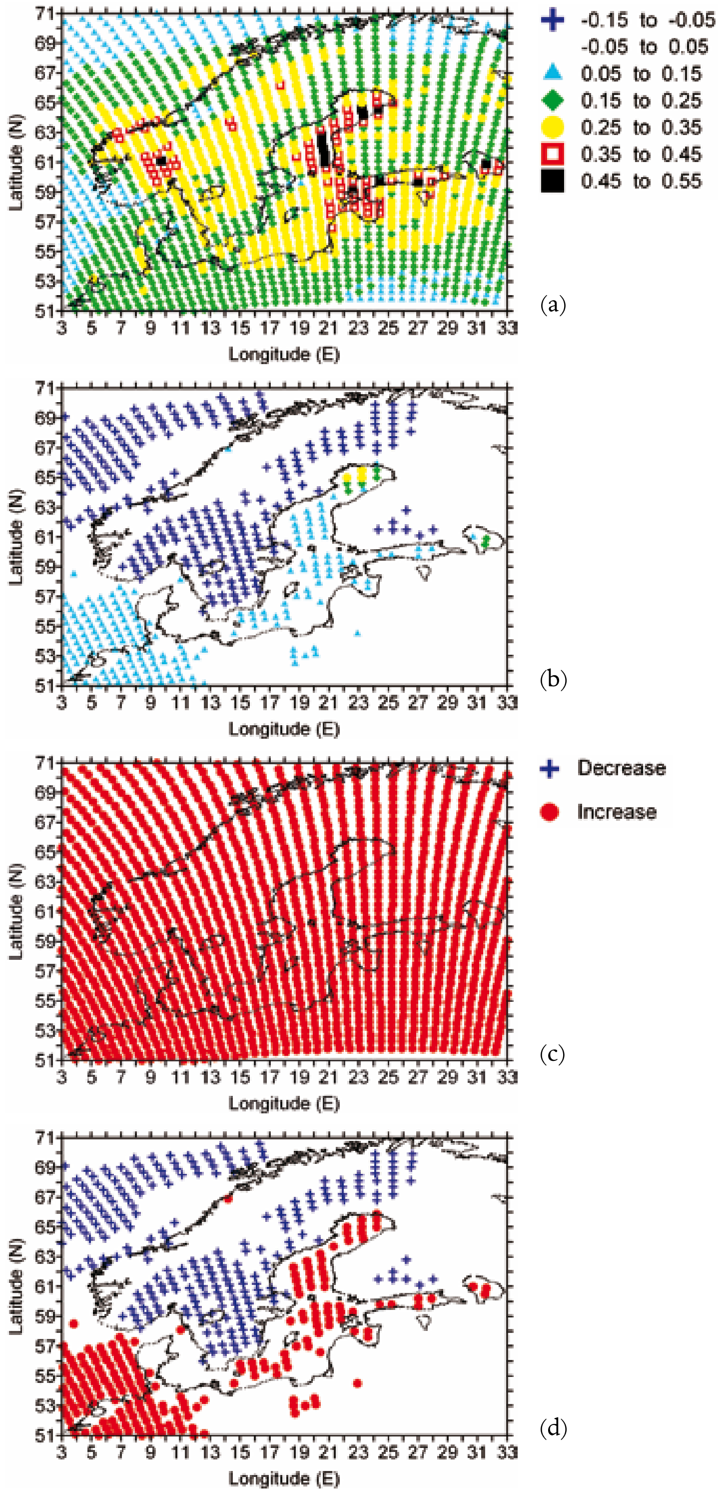
A rough estimate of wind power potential over Europe (and Denmark) is based on the European Wind Atlas (Troen & Petersen, 1990). Similar atlases have been prepared for Finland (Tammelin, 1991) and Sweden (Krieg, 1992). A need for more detailed mappings is obvious. Because much of the future wind power production will be sited offshore, it is important to be able to study offshore areas, coastal regions, inland and mountains separately.

7.2 Changes in wind climate in the Nordic countries

This section describes the wind group's work on developing robust projections of wind energy resources under climate change. In the CE project, we applied two approaches to quantify possible changes in wind speeds and wind energy density over the Nordic Region at relatively high spatial resolution.

In the first approach, the Rossby Centre Regional Climate Model (RCAO) was applied, using output from two global climate models (GCMs) (ECHAM4/OPYC3 and HadAM3H) as boundary conditions. (See Section 4.1 for details.)

Our results indicate that the RCAO generates realistic wind climates of 10 m height during the control period (1961–1990) (Pryor *et al*, 2005a). Simulations conducted using boundary conditions from ECHAM4/OPYC3 indicate increased wind speeds and energy density in the climate projection period (2071–2100) relative to 1961–1990. However, RCAO simulations conducted using boundary conditions supplied from HadAM3H indicate more spatially heterogeneous changes in wind speeds and energy density between 1961–1990 and 2071–2100. In these simulations, some areas show decreasing energy density and others increasing energy density (Figure 7.5). For this reason, it is important that future research uses output from multiple state-of-the-art GCMs to provide boundary conditions for the regional climate simulations.


-0.15 to -0.05
-0.05 to 0.05
0.05 to 0.15
0.15 to 0.25
0.25 to 0.35
0.35 to 0.45
0.45 to 0.55
Decrease
Increase
Latitude (N)
Longitude (E)

(a)

(b)

(c)

(d)

Figure 7.5. (a) and (b) Fractional changes in the wind energy density (W/m^2) from 1961–1990 to 2071–2100 from the RCAO simulations using lateral boundary conditions from (a) ECHAM4/OPYC3 and (b) HadAM3H. The changes are shown as a fractional decrease or increase in 2071–2100 relative to 1961–1990. Hence a value of 0.15 indicates that in the future period, energy density is 15% higher than that during 1961–1990. Frames (c) and (d) show whether the change in energy density in 2071–2100 relative to 1961–1990 is statistically significant at the 95% confidence level (Pryor *et al*, 2005a). If the future period wind energy density is significantly higher than that during 1961–1990, the grid cell is shown with a red dot. If the wind energy density in the future period is lower than the historical period, the grid cell is shown with a plus sign. If neither of these conditions is fulfilled, no symbol is shown. In these figures, results for the period 2071–2100 are based on the A2 emission scenario.

Output from the RCAO provides very useful information regarding possible wind energy changes, but these data still represent spatially averaged wind speeds and energy density, and are highly sensitive to the GCM used. There is also, therefore, interest in generating location-specific projections and in using output from a greater range of GCMs to quantify the differences due to model variations.

Hence, in the second approach of this study, statistical relationships (transfer functions) were developed between large-scale predictions of the climate system (derived from the GCM output) and local wind observations at 46 sites in the Baltic Region. These transfer functions were then applied to develop probability distributions of wind speeds and energy density for 2046–2065 and 2081–2100 (Pryor *et al*, 2006b). This technique was applied to 10 state-of-the-art GCMs. Downscaled results from the majority of GCMs show slightly lower energy density in both of the climate projection periods (2046–2065 and 2081–2100) than during 1961–1990. The projected changes are rather modest and, indeed, the difference in downscaled wind energy density during 2046–2065 differs by less than 10% relative to values during 1961–1990 at all stations studied (Figure 7.6). The mean changes are generally very modest, relative to the inter-annual variability and the uncertainty bounds derived using multiple GCMs. The range of percentage changes in the wind energy density at 44 of the 46 sites studied is less than 20% for 2046–2065 relative to 1961–1990, and less than 35% for

2081–2100 relative to 1961–1990 (Pryor *et al* 2006b).). As with the changes in downscaled mean and 90th percentile wind speed, the results for energy density at each of the stations tend to span zero, with downscaled results from some GCMs showing increases and others decreases (Figure 7.6).

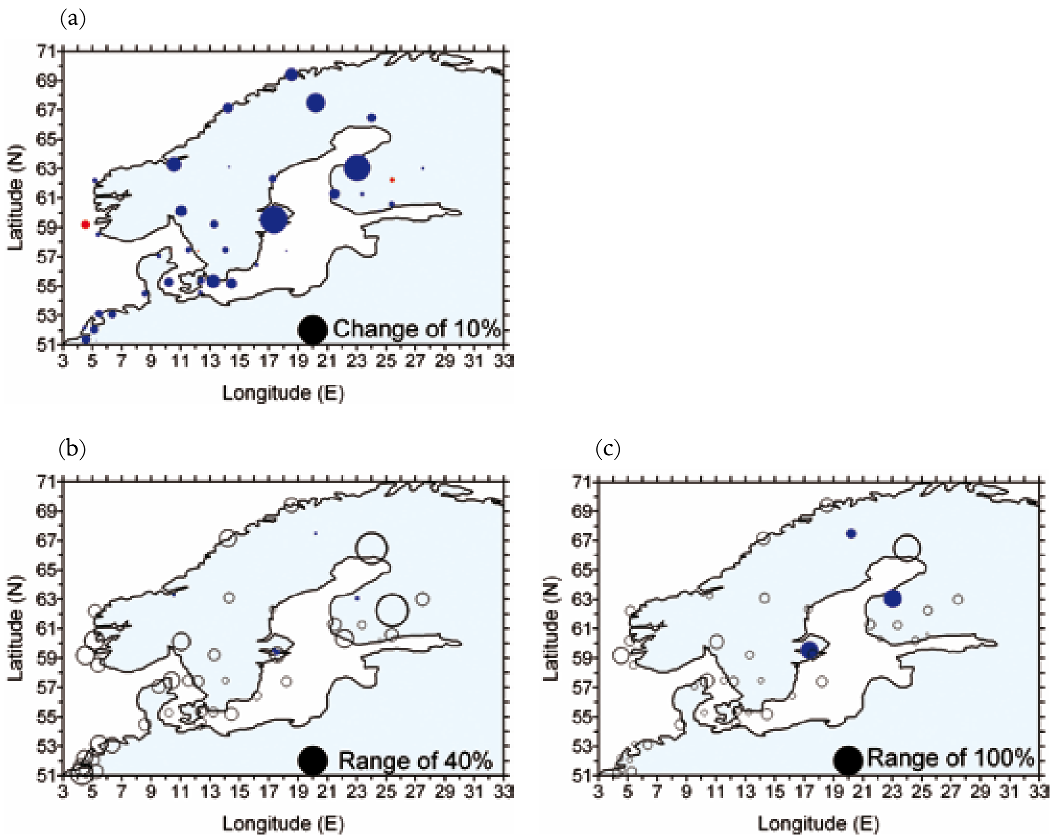


Figure 7.6. (a) The mean change in downscaled energy density (W/m^2) from the 10 GCMs in 2046–2065 relative to 1961–1990. A blue symbol means the results indicate lower energy density in the future period; a red dot means the results for that station indicate higher wind energy density in the future period. (b) and (c) show the change in energy density presented in terms of the range of changes from downscaling of 10 GCMs: (b) for 2046–2065 (*i.e.* ((2046–2065) – (1961–1990))/(2046–2065)); and (c) for 2081–2100 relative to 1961-1990. If all downscaled values declined, the symbol is solid; if the results from the downscaling of different GCMs span zero, the symbol is an open circle. In all frames, the symbol diameter is linearly related to the data range.

Before synthesising and summarising the results of the two downscaling approaches, it is important to note that the GCMs that supplied the boundary conditions for the RCAO simulations were among those used for the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) published in 2001. These models have since been significantly updated and improved, and the GCMs used in the empirical downscaling (second approach of this study) represent the next generation of GCMs developed for the IPCC's fourth assessment report.

The analyses undertaken do not settle on a consistent signal with regard to an increase or decrease of the wind energy density over the Baltic during the 21st century relative to the end of the 20th century, and do not indicate major changes in the average wind energy resource over the Baltic Region during the current century. It is also important to note that the analyses we have conducted on historical data (Pryor *et al*, 2005b) indicate that the high wind energy density observed in the Baltic during the late 1980s and early 1990s are highly atypical and do not present a representative wind climate for this region.

Future work will focus on the development of wind energy projections for the entire 21st century (as an improvement on the time-slice approach used here), as well as wind speeds at the hub height of modern wind turbines (80-120m). As indicated here, these analyses should incorporate multiple state-of-the-art GCMs, emission scenarios and downscaling tools, to better quantify the uncertainty in our projections and to establish the likelihood of possible future wind climates and energy densities.

7.3 Wind energy production capacity and scenarios

As input to the energy system analyses in the CE project (Chapter 10), two scenarios were considered (Table 7.1):

- The wind energy capacity installed in 2010 (business as usual)
- The wind energy capacity installed in 2010 under a high-wind-penetration scenario.

	MW installed		
Country	2005	Scenario 2010	Scenario 2010 HIGH Wind
Sweden	554	1,200	3,300
Norway	225	1,200	3,500
Denmark	3,087	4,100	4,600
Finland	85	500	2,000
Nordic countries	3,951	7,000	13,400

Table 7.1 Status in 2005 and for scenarios for installed wind energy capacity in the Nordic countries. The Baltic countries were not included in this study.

To take the seasonal variability of wind energy production into account, the Rossby Centre time series of wind speed at 10 m.a.g.l. were used to produce regional wind energy production time series for both the reference and climate scenarios. First, the wind speed time series for each grid point was extrapolated to 80 m.a.g.l. to reflect the hub heights of modern wind turbines. The time series were then converted to wind power production by using a multi-turbine power curve (Nørgård & Holttinen, 2004) and the time series were added up to weekly average production instead of the original six-hourly data. Finally, regional time series were formed by adding up the grid points that cover each region. In this process, some offshore sites were taken into account, to get a realistic combination of offshore-onshore sites for each region. Most of the inland grid points were omitted, due to lower wind resource. The grid points used are marked in Figure 7.7. Denmark was divided into west and east Denmark, Sweden and Finland were divided into four regions and Norway was divided into seven regions.

Comparing the regional wind power production time series for the reference period and two climate scenarios also gives some results on wind power production changes due to climate change. The average production for the reference period (1960–1990) and the period 2070–2100 can be seen in Figure 7.8. For the Hadley B2 run, there is no significant change in wind power production, whereas for the Max Planck B2 run, there is more wind in the northern parts (10% increase in north Finland and 6–8% increase in the most northern and southern parts of Norway).

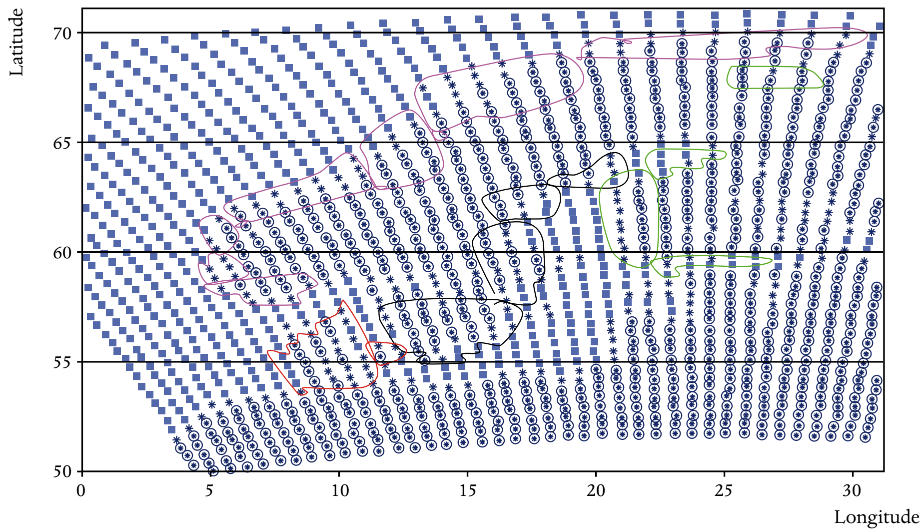


Figure 7.7. The grid points that were chosen to represent regional wind energy production in the Nordic countries. Blue squares are water, circles are land, and crosses are partly land, partly water.

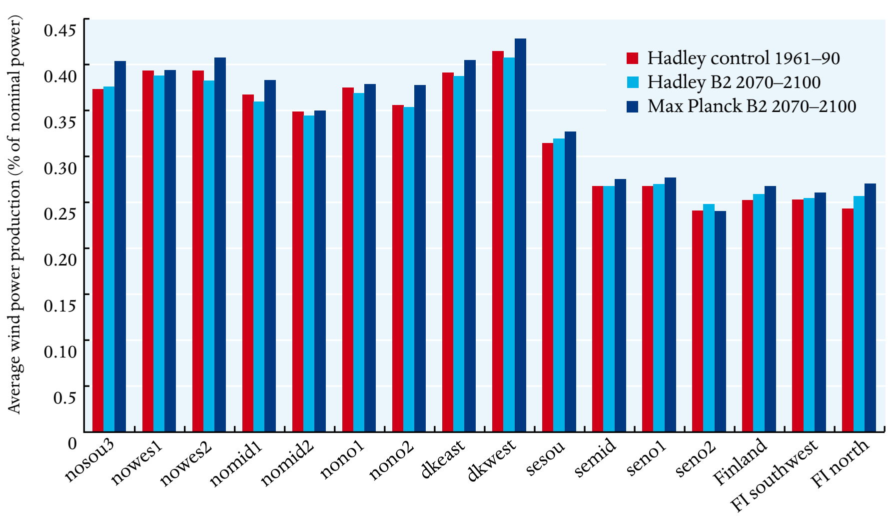


Figure 7.8. Average wind power production in different regions of Nordic countries (no=Norway, dk=Denmark, se=Sweden, fi=Finland).

7.4 Climate impact on icing

The icing of wind turbines has become a more topical issue as increasing numbers of wind turbines are installed at sites where atmospheric icing and low operating temperatures have an effect on the operation of standard wind turbines. The main effects are decreased aerodynamic performance and excess loads triggered by unevenly distributed ice on the blades. Both lead to a loss in energy production and affect the economies of the turbine. Sites prone to atmospheric icing are typically those located at northern latitudes or at high altitude, such as mountain ridges that provide favourable wind conditions.

The effect of climate change on the icing of large wind turbines was studied for heights between 100 m and 150 m above ground level, which corresponds well with the hub heights of modern wind turbines.

According to the results of climate change simulations, the icing climate will change considerably from the present day to the end of this century. Although, in 100 years' time, wind turbines are likely to be bigger than modern wind turbines, it is likely that the increasing mean temperatures over the whole of Scandinavia will reduce the effect of atmospheric icing significantly.

The number of annual icing hours in the reference period is presented in Figure 7.9 and the results for the period 2061–2100 in Figure 7.10. Both figures are based on the results of the ECHAM4 global circulation model.

The results of the reference period (Figure 7.9) correspond fairly well to the results of measurement campaigns in Finland, and represent an indicative icing map at 100 m to 150 m above ground level. However, the local icing climate is strongly affected by local topography and the map should be interpreted with care. The annual icing time in coastal areas is typically 100–200 hours and, due to mild temperatures, it does not cause significant production losses. The same 100–200 hours in Lapland, however, which has low ambient temperatures, may cause considerable production losses as a result of ice.

Currently, the ice risk is significant at elevated areas. The results of this study indicate that the ice risk is diminished in a warmer climate, which may enable wind energy production in areas that are not suitable today.

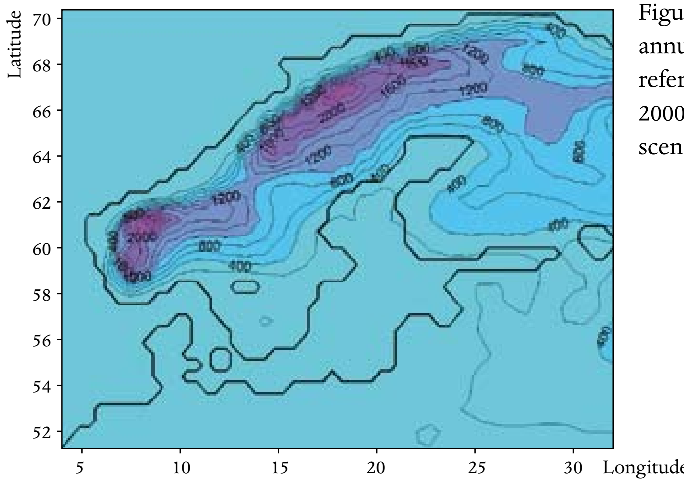


Figure 7.9. Number of annual icing hours, reference period 1961–2000, and ECHAM4 scenario

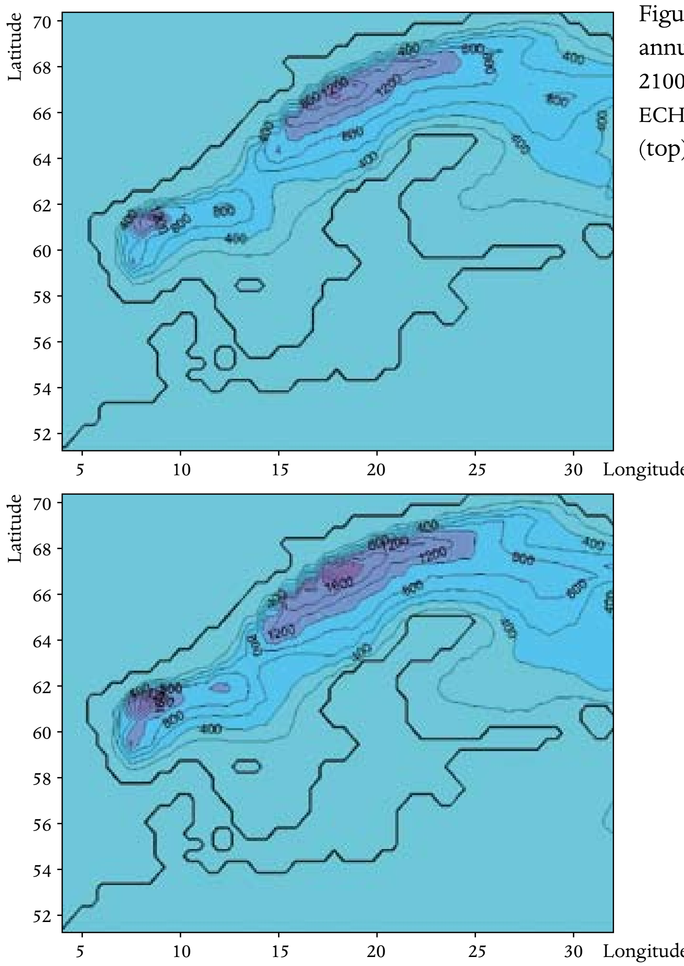


Figure 7.10. Number of annual icing hours 2061–2100 according to the ECHAM4 scenario A2 (top) and B2 (bottom)

The most significant relative changes in annual icing hours are likely to occur in the northernmost part of the Bay of Bothnia and the easternmost part of the Gulf of Finland. The results (see prediction in Figure 7.10) indicate that icing might become unlikely in all coastal areas of the Baltic Sea at 100–150 m.a.g.l.

The climate change simulations indicate that winter temperatures are likely to increase by some 3°C, or even 6°C, by the end of the century. As a result, the time during which icing could affect the operation of wind turbines is likely to decrease by some 5–100% depending on the climate change scenario used, the location and the elevation of the site. According to the results, the near-surface (100–150 m) icing time is likely to become shorter and there is no evidence that more severe icing conditions would occur, even at high altitudes in the mountainous regions of Scandinavia.

7.5 Climate impact on the design of wind turbines

Effects of extreme wind

Land-based wind turbines are mass-produced rather than designed for specific sites, because, economically, this is the most feasible approach. The design of wind turbines is therefore done according to classification standards that define a number of 'wind turbine classes'. Whenever a site has been chosen for the erection of turbines, the wind climate at that site must be evaluated and a suitable wind turbine class that covers this climate must be determined. For offshore turbines, the extra costs entailed by the foundations, together with the fact that they are often built in larger farms, implies that site-specific design of the support structure, including the tower, is generally the only economically feasible option. The rotor-nacelle-assembly, on the other hand, would not be of site-specific design but would continue to be mass-produced. Thus, when evaluating the possible impact of wind climate change on the design of wind turbines, one would have to look both at the change relative to the wind turbine classes and at the change in loads, as these may be derived from the wind climate change at a specific site of concern.

The study of the impact of climate change on the design of offshore wind turbines with a focus on wind generated loads is based on a single example, considering a generic 2 MW turbine at a specific site in the Baltic Sea. Offshore sites in the Baltic Sea experience the larger changes in the extreme wind climate and, consequently, the highest impact. Here, the study concentrates on the impact of climate change on an offshore site located east of the island of Bornholm in the Baltic Sea. The modelled wind speed at 10 m height was extrapolated to hub height (80 m) by the use of standard surface layer scaling. From this time series (data four times daily), the 50-year maximum wind speed U_{50} and average wind speeds at hub height were estimated.

The wind climate at the selected site was considered with reference to the relevant IEC standard (61400-1). Over the scenario period, the site conditions will not extend outside the wind turbine class that was valid at the beginning of the scenario. Thus, comparing the wind speeds derived from the analysis of the 80 m wind in the four different situations to the class definitions, it turns out that, from a classification point of view, the wind climate change has no impact.

When investigating the impact of changes in extreme wind conditions on site-specific design extreme loads generated by the 50-yr wind speed U_{50}, the conditions and fatigue loads derived from the fitted Weiball wind speed distributions are considered. No wave loading was included. The flap and edge blade root moments, plus the overturning moment and base shear, are calculated, as they will be clearly representative of the major trends in the impact on design. The Hadley model (HadAM3H) gives rise to, at most, a 1.5% change in fatigue loads, which is insignificant. The Max Planck model (ECHAM4) gives rise to a 2.5–5.0% increase in fatigue, which is significant but not drastic. While these results are within the uncertainty of the load model and response models, they agree with the trends seen in the wind climate change.

The change in extreme loads for both models represents an increase of about 15%, which is sufficient to change the design of some parts of offshore turbines. Depending on the wind turbine manufacturer, the design of the support structure is either fatigue- or extreme-load-driven, so no general conclusions can be drawn. However, it should be noted that if, in addition to the extreme wind loads, the associated extreme wave loads are also included, which will increase with the extreme wind (dependent on the site-specific bottom topography), then the extreme loads can become significant for the design of the substructure and foundation, *i.e.* for all parts of the support structure below mean water level.

Finally, for turbines on land, as has already been explained, the entire turbine will typically be designed according to wind turbine classes. Because the change in wind climate is smaller on land than offshore, it follows that no change in classification is expected for land-based turbines, and that stronger turbines are not needed.

Effects of sea ice in the Baltic Sea

Today, the Baltic Sea freezes annually. The maximum annual ice extent occurs between January and March, when ice covers 52,000–420,000 km^2 and, on average, 218,000 km^2. At the latitude of Stockholm, the ice probability is 0.5. The ice season lasts between a few weeks in the south and seven months in the north. The thickness of the ice varies between 50–70 cm during normal winters and 80–110 cm during colder winters. In the coastal areas of the Gulf of Bothnia South and the Gulf of Finland, the icing period lasts an average of 100–150 days. South of Stockholm, the icing period is, on average, less than 60 days. In the sea areas around Denmark and the west and south coasts of Sweden, the icing period is, on average, less than 30 days.

For wind turbine foundations, the most critical issue is the thickness of drifting sea ice. In coastal regions, limited ice action is exerted against the foundations, as the ice becomes anchored on the shoreline, rocks, shallows and islands. Early in the winter, ice movements are seen only in thin ice, while during late spring the ice becomes soft and deteriorated, and movements are seen in thick ice. In the northern part of the Baltic Sea, drifting ice can be 0.8 m thick, with significant piling of ice. During winter, the loads on structures are from thermal ice expansion only. After a storm, ice floes that have broken off can move about, causing loading on structures. The larger the solid ice field, the larger the loads. The greatest loads are usually experienced in springtime, when ice starts moving and piling. In the northern part of the Baltic Sea, the pile-up against the turbine's tower and foundation can reach a height of ten meters and may damage tower structures.

The climate scenario results with respect to sea ice are shown in Figure 7.11. As climate change might result in increased temperatures, the area with ice cover will decrease. According to the climate model run results, the duration of sea ice during an average year's icing period will diminish to about half in 100 years. On average, long icing periods (of more than 100 days) would occur only in the northern part of the Gulf of Bothnia and in the Gulf of Finland.

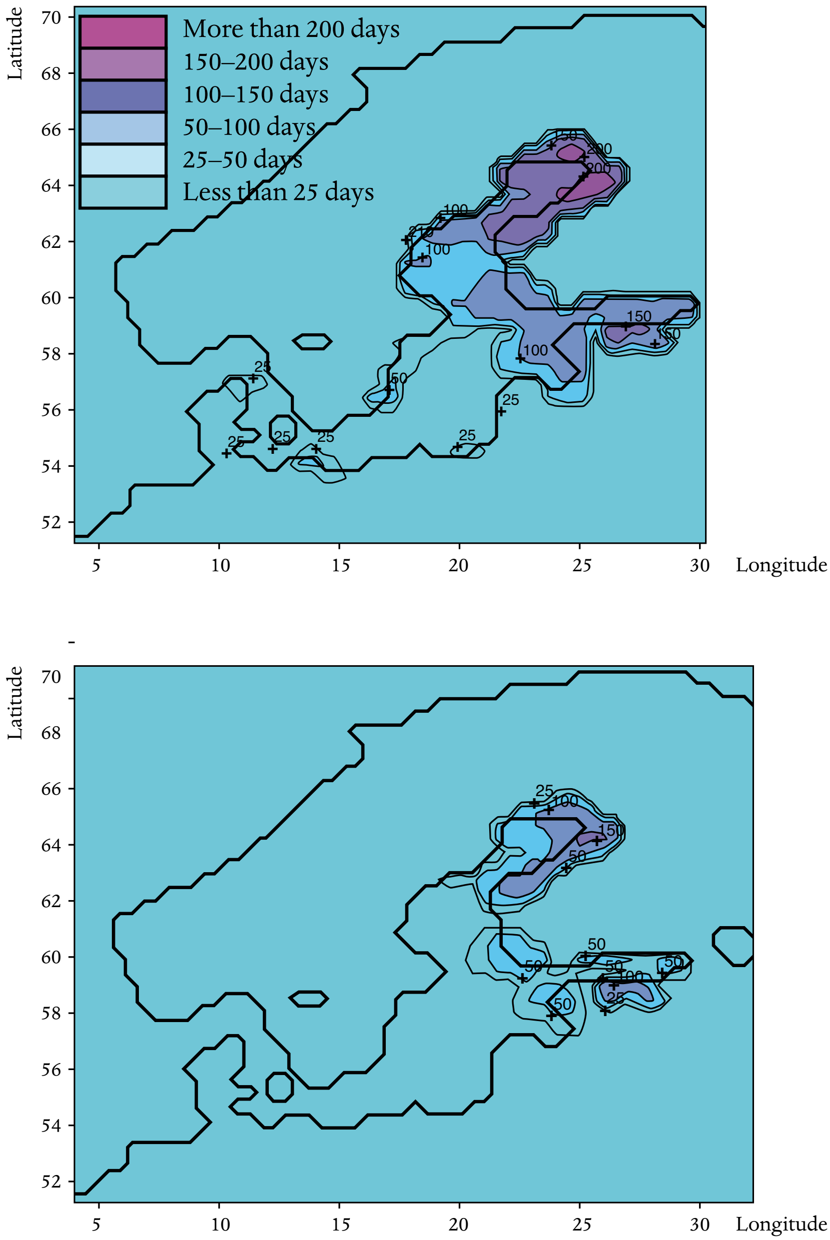


Figure 7.11. Average length of sea ice period, in days, for the Baltic Sea, during reference period 1960–90 (top) and during future scenario 2070–2100, HadAM3H scenario A2 (bottom). Average length of icing period for 30 years is calculated separately for each grid point. (Due to map contour inconsistency, the ice cover does not follow the coastline.)

For offshore wind farms, ice formation will also mean that access during winter is more difficult, or even impossible. If a wind turbine stops due to a fault or other event, such as a lightning strike, it may be necessary to visit the wind turbine. With the expected decrease in sea-ice formation, a larger area of the Baltic Sea will be accessible, even in winter.

7.6 Environmental impact

Wind turbines produce electricity without polluting the environment, eventually leading to a reduction in the emission of carbon dioxide, nitrogen oxides and sulphur dioxide, as well as particles. The use of wind energy may therefore contribute to a reduction, not only of global climate change, but also of local and regional environmental problems such as acid rain and respiratory diseases.

Although the environmental impact of wind energy is obviously lower than that of conventional energy sources, there are some potentially negative effects on the environment, especially when it comes to establishing large wind farms of several hundred large wind turbines. Over the years, the main environmental concerns when constructing wind farms have been about visual impact, noise and the risk of bird collisions.

Today, noise is dealt with in the planning phase and normally poses few problems in terms of building wind turbines close to human settlements. The visual effects of wind turbines may, however, lead to controversy; some people believe them to have a severe negative visual impact on the landscape, while others find them beautiful. Experience shows that it often pays to invest effort in designing a good layout for wind farms using well-defined geometrical patterns and taking the landscape's features into consideration.

The impact on plants and animals is not well established, despite a sizable number of studies, but, as with all power plants, there will be a certain amount of disturbance to flora and fauna. In the case of wind energy, the chief concerns are bird strikes and the possible associated effects on the resident bird population and migration paths.

For all the environmental impacts, experience shows that dealing with them early and openly, and entering into dialogue with relevant stakeholders will normally facilitate a solution that satisfies all parties. Software tools (*e.g.* WindPro, www.emd.dk) are available for the analysis of the environmental impact of wind farms, and include noise calculation, visualisation and photomontages illustrating the visual impact, as well as the calculation of shadow flickering.

7.7 Conclusions

Both climate models predict an increase in extreme winds (maximum wind speed with an recurrence period of 50 years) in the Baltic Sea of up to 15% at the end of this century. In general, for the Nordic countries, the average wind speed (wind resource) will increase according to the A2 scenario and the global model ECHAM4, while for the global model HadAM3H the wind resource will only increase in the northern parts of the Baltic Sea. In other areas, the wind resource will decrease or remain the same as it is today.

Regarding the design of wind turbines, limited influence was found in terms of design for fatigue. However, at some offshore locations, increases of extreme winds in the 10–15% range were found, meaning that, for some parts of a wind turbine, design for extreme loads is likely to be affected.

The A2 scenario as modelled by the HadAM3H predicts significantly less sea-ice formation in the Baltic Sea, in terms of both timescale and geographical coverage. Likewise, the potential for formation of ice on the construction of the wind turbine is expected to be significantly reduced.

7.8 Literature

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8 Solar energy

Audun Fidje and Thomas Martinson

Over the visible part of the spectrum, the energy measured above the atmosphere is about 1,368 W/m^2 (Thomas & Stamnes, 1999). Above the atmosphere, solar radiation is practically constant, but on the ground it varies with latitude, due to atmospheric conditions and earth surface reflection. The maximum value of the solar irradiance on the Earth's surface is between 800 and 1,000 W/m^2 (Solarserver, 2005).

The total amount of solar energy reaching the surface of the Earth is more than 15,000 times total human energy consumption. The sunniest places receive up to 2,500 kWh/m^2 of solar energy per year, measured on a horizontal surface. Further, the energy is more or less evenly distributed over the year.

In the Nordic Region, however, the situation is less favourable, with the annual input varying between 1,100 kWh/m^2 in the south and 700 kWh/m^2 in the north. The annual variations in solar irradiance are also very large. A sunny summer's day without clouds may give about 8 kWh/m^2, whereas a cloudy winter's day can give only 0.02 kWh/m^2 (KanEnergi, 2001).

Nevertheless, all over the world, the conversion of solar energy into heat and electricity is seen as increasingly important. Photovoltaics (PV) have experienced extreme growth during the last decade, with an annual growth rate of about 30%. In the Nordic countries, however, the use of solar energy has so far been restricted to thermal systems and off-grid applications of solar cells. With a reduction in the cost of solar electricity, this situation may well change.

8.1 Issues of scientific interest

The main issues of research interest related to climate change and solar energy are:

- Research activities related to identifying the direct effect that climate change and changing cloud cover have on photovoltaic (PV) cell and solar heating technology, with a focus on potential changes in radiation at a temporal and spatial scale. For instance, cloud cover variability is an important factor for the exploitation of solar thermal energy, as heat may be stored for a shorter period of time.

- PV is especially appealing in remote areas where extending the electricity grid is expensive or impossible. PV panels are installed to quite a large extent in holiday homes, boats etc. To investigate the potential for further penetration of this technology, it is important to assess the impact of climate change on PV potential on a regional scale throughout the Nordic countries. Excess electricity provided by PV in buildings in centralised areas could, on the other hand, be transferred to the grid during periods where production exceeds demand and, on a larger scale, utilities could also use PV to provide power for the centralised grid system. The potential for this to be developed in the light of climate change scenarios could also be investigated.

- On a broader scale, there is a need to look into how climate change might alter the competitive advantages of different energy sources in general, solar energy being one of a number of energy sources.

In this study, the effects of climate change on the use of solar energy have been investigated, comparing climate scenarios for the period 2071–2100 with the reference period 1961–1990. The IPCC SRES A2 and B2 scenarios are downscaled using the regional climate model HIRHAM by the Norwegian Meteorological Institute (Haugen, 2005). In addition to the scenarios from Haugen, Kjellström (2006) provided scenarios from the RCAO model, developed within the CE-project. The model results differ in terms of the relevant parameters, and we have used the results from Haugen (2005) in this analysis. A later rough calculation has shown, however, that the difference is unimportant to the general conclusions. On the basis of average global irradiation data, the total irradiation on a tilted surface is estimated including the direct ground reflected irradiance. Furthermore, the effect of there being a reduced time period with snow cover is illustrated. The irradiation and temperature data were processed by a stochastic weather generator to obtain hourly irradiance data. A model developed in-house has been applied to calculate the effect of climate change on electricity production from PV systems. The effect on passive and active solar thermal systems is estimated using an energy balance approach.

8.2 Solar cells

The main factors causing attenuation of the radiation are atmospheric gases, aerosols and water vapour (clouds). Most solar panels are mounted at an angle to the horizontal surface. For solar energy applications in the Nordic Region, the effect of ground reflection during winter is thus significant, due to reflection from snow. Because we are interested in windows and panels mounted at an angle to the horizontal surface, we use the total irradiance $G_t = G_{gl} + G_{gr,}$ where G_{gr} is the irradiance reflected from the ground.

Existing and emerging technologies

The influence of climate change on solar energy production will mainly be due to changes in irradiation and temperature. Extreme weather events are not likely to have significant influence on energy production from solar panels and collectors; they may affect the cost of complete panels, due to the need for stronger frames, for example, but we do not intend to discuss this further here.

A range of different solar cell technologies has been industrialised, and many more have been developed and investigated in research laboratories throughout the world. The most common solar cells by far are currently made from crystalline silicon (Si) substrates, such as wafers, ribbons and sheets. Thin film technologies, such as solar cells made from amorphous Si (a-Si), cadmium-telluride (CdTe) and Copper Indium Gallium diSelenide (CIGS), make up a relatively small share.

Although relatively high material costs currently represent a major challenge to Si substrate-based technologies, particularly mono- and multicrystalline wafer technologies, these are believed to remain the most cost-competitive in the short run. In the future, however, other technologies may well take over, particularly thin film solar cell technologies that dramatically reduce the consumption of expensive raw materials. A brief introduction to the status and outlook of the various solar cell technologies now follows.

Impacts of climate change on performance of solar cells

Climate change can, in principle, affect the performance of a solar cell in two ways. Firstly, the current delivered by a solar cell depends on the irradiance of the incoming sunlight. Secondly, solar cells are very sensitive to changes in temperature. These changes can be caused by changes in the overall ambient temperature, changes in the irradiance or changes in the amount of wind cooling the solar panel.

Changes in the amount of sunlight that falls upon a solar cell will affect its performance in two ways. Firstly, the heating of the solar panel will depend upon the irradiance. More importantly, the current produced by the solar cell is determined by the irradiation. It is common to assume that the short-circuit current depends linearly upon the irradiance. It is also commonly assumed that the open-circuit voltage only depends on the temperature of the solar cell and will decrease linearly with increasing temperature.

8.3 Solar thermal systems

Solar thermal systems can be divided into three main categories:

1. *Passive solar energy* is the accumulation of heat from solar irradiation through windows in buildings. The net energy balance of a window is the difference between the transmission of incoming short-wave solar energy and the outgoing long-wave heat radiation. New window technology with higher insulating capacity may allow for a larger window area, but may also increase the demand for cooling in warm summer periods, and thus increase electricity consumption.

2. In *active systems*, the solar energy is converted to heat in a collector and transported to heat storage (*e.g.* a hot water tank) or a heat consumer (*e.g.* a radiator).

3. In *concentrator systems*, the solar radiation is concentrated through curved mirrors of trough-shaped reflectors. The intensity may be up to 60 times the surrounding radiation. These are high-temperature systems and may also include a mechanical tracking device to keep the collector pointed towards the sun throughout the day. Compound parabolic concentrating collectors also use

the diffuse radiation and therefore maintain higher efficiency without a tracking device.

The technologies evaluated in this study all include a glass-covered collector (which could be a window). The net energy balance is the difference between the transmission of solar energy and conductive heat loss. It is dependent on both technological parameters and climatic parameters. Standard reference values are, thus, not available. On the basis of calculations made for Canada, we can draw some general conclusions about the energy balance in passive solar energy systems (Natural Resources Canada, 2004). With single-glazed windows, there is an annual net thermal energy loss in the Nordic countries. Double-air-insulated-glazing with a U-value of about 3 $Wm^{-2}K^{-1}$ is about neutral, and double-heat-mirror-glazing with argon insulating gas, at about 1 $Wm^{-2}K^{-1}$, generally provides a net solar gain. Future window technology may include inert-gas-filled triple-glass windows, or vacuum-glass windows with energy reflective film on the glass. The U-value of such glazing may be as low as 0.4 $W/m^2 K^{-1}$.

The passive solar thermal energy input in south-facing rooms may exceed heating needs for large parts of the year. The net contribution to maintaining comfort temperature within the building thus also depends on the ability to distribute the energy to other rooms through a ventilation system, the ability to store energy on a diurnal basis, or the ability to remove the heat from the building. A larger window area may thus increase energy service needs, due to cooling during summer, unless the construction provides shading.

The most common active solar collector is a glazed, flat-plate type, with a liquid heat transport medium. Unglazed, liquid flat-plate collectors are commonly used to heat swimming pools, and evacuated collectors are used for high temperature generation. The utilisation of the energy contribution capacity of an active solar thermal system is also limited, to a large extent, by the ability to distribute and store heat. The focus of technological development today is mostly on the construction of solar panels that can be integrated into building construction at a low cost.

The change in thermal energy is a balance between the change in irradiation (ΔG_t) and the change in ambient temperature (ΔT). The output *increases* with irradiation and *decreases* with the temperature:

$$\Delta Q = Q_{scenario} - Q_{reference\ period} = k_1\ \Delta G_t + k_2\ \Delta T$$

8.4 Use of solar energy in the Nordic countries

PV installations in the Nordic Region are mainly small, off-grid installations. In total, 16 MW PV was installed in 2003 (IEA PVPS Programme, 2005). In the Nordic Region, PV panels could achieve a utilisation time of about 800 hours. Thus, the annual energy production could reach about 13 GWh.

Passive utilised solar thermal energy in the Nordic Region has been estimated by the SOLGAIN project to be about 28 TWh (SOLGAIN, 2003). Further, it is estimated that passive solar energy covers 10–18% of the heating demand in residential buildings. In total, the installed capacity of active solar thermal installations in the Nordic Region in 2005 was about 483 MW.

Impact on the energy resource

To analyse the effect of climate change in the Nordic Region, we have used data for a number of cities from the south to the north of the Nordic Region. The average solar radiation for the selected cities is shown in Table 8.1. In all cases, the climate changes give a reduction in radiation, but it is evident that there are large differences between the percentage changes in the selected locations, ranging from a few per cent in Copenhagen to 16% in the A2 scenario for Helsinki.

	Ref. W/m^2	A2 W/m^2	B2 W/m^2	A2 delta %	B2 delta %
Copenhagen	98.0	96.4	95.9	–1.7	–2.1
Oslo	86.8	85.2	83.4	–2.0	–3.9
Trondheim	67.8	59.4	61.5	–12.4	–9.3
Tromsø	61.1	54.9	55.4	–10.1	–9.3
Helsinki	91.8	77.1	83.8	–16.0	–8.7

Table 8.1. Average solar radiation and relative changes in selected cities in the reference period (1971–1990) and in the A2 and B2 scenarios (2071–2100).

Change in the ambient temperature

In Table 8.2, changes in annual mean temperature are shown. The table shows that mean temperature changes are at the same level in the A2 and B2 scenarios. The ranges are from about 3°C in Trondheim to nearly 5°C in Helsinki. The differences between the two scenarios are most evident in Oslo, where the temperature rises by 3.7°C in the A2 scenario and 2.9°C in the B2 scenario.

	Ref. °C	A2 °C	B2 °C	A2 delta °C	B2 delta °C
Copenhagen	8.3	11.5	11.0	3.2	2.7
Oslo	5.5	9.2	8.4	3.7	2.9
Trondheim	3.7	6.7	6.2	3.0	2.5
Tromsø	–1.0	2.7	2.2	3.7	3.2
Helsinki	5.3	10.0	9.9	4.7	4.6

Table 8.2. Average temperatures and changes in selected cities in the reference period (1971–1990) and in the A2 and B2 scenarios (2071–2100).

Changes in snow cover

In the Nordic Region, the irradiation will be influenced by a change in ground reflectance (albedo), particularly on a tilted surface. Due to a change in the amount of time with snow cover, the reflectance from the ground may change dramatically and thus the total irradiance may be reduced. Reduced snow cover is one of the results of a changing climate. The albedo used is listed in Table 8.3.

	Oslo			Trondheim			Tromsø		
Mounth	Ref.	A2	B2	Ref.	A2	B2	Ref.	A2	B2
Jan	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Feb	0.5	0.5	0.5	0.5	0.25	0.5	0.5	0.5	0.5
Mar	0.5	0.25	0.1	0.5	0.1	0.1	0.5	0.5	0.5
Apr	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.1	0.1
May–Nov	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Dec	0.5	0.1	0.1	0.1	0.1	0.1	0.5	0.1	0.25

Table 8.3. The albedo used in the calculations of ground reflected irradiance on a tilted surface. An average albedo of 0.5 is used for ground with more than 50% snow cover and 0.1 is used for ground without snow cover. When less than 30 days have more than 50% snow cover, an average albedo of 0.25 is used. (After Roald *et al*, 2006.)

PV

The solar radiation on a tilted surface is calculated using the Hay, Davis, Klucher, Reindl (HDKR) model (Duffie & Beckman, 2001). The annual energy production of a PV panel is calculated by the use of a one-diode PV model developed in-house. The model applied here is a modified version of the PV simulator part of the HYDROGen Energy ModelS (HYDROGEMS) (Ulleberg & Glöckner, 2002). The annual electricity production for the selected cities in the two scenarios is given in Table 8.4.

		I_global, hor. kWh/m²	I_surface kWh/m²	E_ PV/m² kWh/m²	Eta PV %	Utilisation h	I_surf. red. %	El out. red. %
Cph	Ref	863	978	106	10.87	882		
	A2	851	956	102	10.64	844	2.3	4.3
	B2	846	957	102	10.68	848	2.1	3.8
Oslo	Ref	761	922	101	11.00	841		
	A2	750	888	95	10.74	791	3.6	5.9
	B2	732	869	94	10.79	778	5.7	7.5
Trondheim	Ref	599	694	76	11.01	634		
	A2	531	598	64	10.78	535	13.8	15.6
	B2	548	628	68	10.85	565	9.4	10.8
Tromsø	Ref	538	662	74	11.23	617		
	A2	488	576	63	10.94	523	12.9	15.2
	B2	491	589	65	11.01	538	10.9	12.7
Helsinki	Ref	810	953	105	11.01	871		
	A2	682	766	81	10.57	672	19.6	22.8
	B2	741	849	91	10.68	752	10.9	13.6

Table 8.4 Radiation and electricity production from a PV panel on a surface tilted 45 degrees at different locations in the Nordic Region.

In Figure 8.1, the solar energy on a surface tilted 45 degrees is shown, together with the electricity output of a PV panel located in Oslo. The figure shows that the reduced global radiation will reduce the effects of PV on an annual basis from 101 to 98 kWh/m^2. Further, when the increased temperature is included, the annual electricity production declines to 96 kWh/m^2. Finally, when the effect of reduced ground reflection is also included, the annual output is reduced to 95 kWh/m^2. In total, the effect of climate change on the annual output of PV system in this example was reduced by 6% when the global radiation was reduced by 2%.

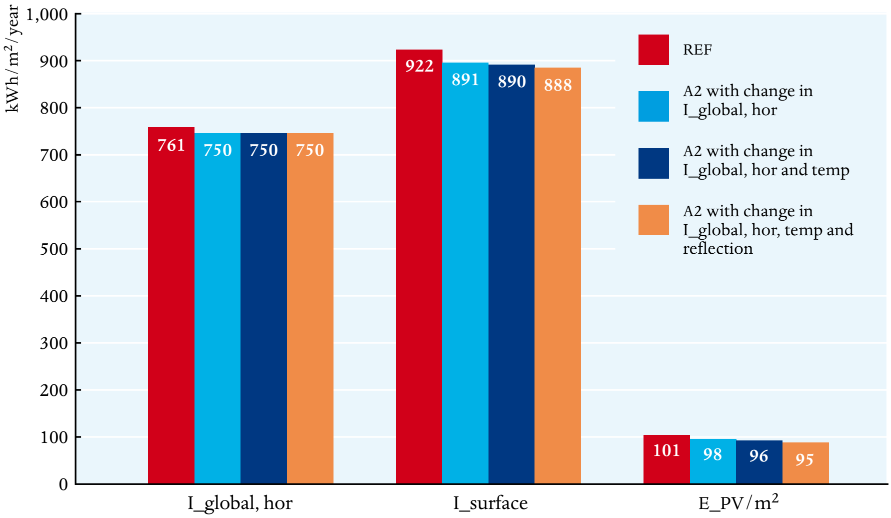

Figure 8.1. Radiation and electricity production from PV for a panel in Oslo with a slope of 45 degrees in the reference period and A2 scenario, with and without temperature change.

Solar thermal

The energy balance for a passive and active solar thermal collector is calculated as the accumulated net change. Assuming that all buildings in scenario B2 use windows developed with today's best available technology, with a U-value of 1.1 W/m^2 K, there is a net gain in passive solar energy from July to December, and a net reduction from February to June, in the specific thermal energy balance for Oslo. For the heating season as a whole (October to April), there is a small net reduction of about 4,600 Wh/m^2. More significant is the increase during the summer months of July and August. A closer look at the diurnal cycle shows a significant increase in the thermal energy provided during the hours of daylight. The net increase in passive solar thermal energy at this time of year will increase the need for shading or cooling, and may thus increase the use of electricity (Figure 8.2).

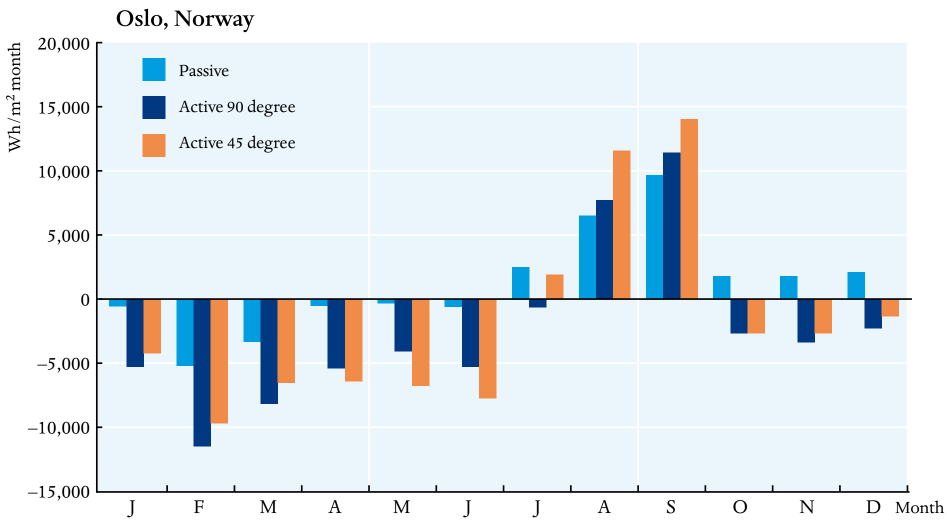

Figure 8.2. Change in monthly average energy balance for Oslo, Norway. The passive solar energy (vertical window) and active solar collector (mounted at 45 degree and 90 degree angles to the horizontal respectively) is the difference between the IPCC SRES B2 scenario for the period 2071–2100 compared to the reference period 1961–1990. The relatively large reduction for the active 45-degree solar panel in April–June is because of the irradiation in the reference period being above the selected cut-off value, while in the scenario it falls below it.

Active solar thermal energy collectors mounted vertically in Oslo exhibit a reduction during the winter season and an increase in the summer. The most significant difference between a 45-degree and a 90-degree mounted solar collector is found in the summer months, when the heat production capacity is generally much larger than the sum of energy service needs and storage capacity.

Based on the analysis described here, it is clear that climate change will have a negative influence on both PV and solar thermal systems. However, for PV systems, we anticipate that future technological development will be more important.

8.5 Literature

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9 Biofuels

Seppo Kellomäki

Bioenergy covers a wide selection of energy sources, from logging waste to straw and waste from the wood processing industry. The total amount of energy produced with biofuels in the Nordic and Baltic countries is currently 900 PJ per year, which is about 20% of total gross inland energy consumption.

To date, there have been very few studies on the impact of climate change on bioenergy potentials. Venäläinen *et al* (2004) found that the peat production potentials could increase by 20% under climate change, due to the production season lengthening as evaporation increases. The impact of climate change on the forest biomass available for the energy industry has not yet been studied systematically. Bergh *et al* (2003), however, found that forest growth in the Nordic countries may increase, especially in the northern parts, where precipitation is still likely to be high enough for forest growth in the future. In the southern parts of the Nordic countries and in the Baltic countries, more frequent drought episodes could limit forest growth to a greater extent than elsewhere (Lasch *et al*, 2005).

This sub-project asks how the projected climate change will influence:

- The potential for peat production
- The production potentials of biofuels in forestry
- The potential to produce agricultural residues energy crops on agricultural lands.

'Biofuels' refers here to the biomass produced in agriculture and forestry, and to peat excavated from mires and used to produce energy.

9.1 Potential impacts on peat production

Peat lands are mainly a feature of the landscape in central and northern Scandinavia, but are also common in the Baltic countries. The total area of peat land in these countries is 20.8 million hectares (as can be seen at www.worldenergy.org/wec-geis/publications/reports/ser/peat/peat.asp).

In the current production of peat, the drying of the peat is entirely dependent on solar energy, so unfavourable weather conditions can severely hamper production. The same methods are used to produce horticultural peat and peat for energy, so the results are valid for any sort of milled peat.

Data and methods

Most of the peat used in power plants is milled peat, which is produced from the bog surface and dried in situ. The drying of milled peat is therefore completely dependent on weather conditions. One harvest cycle, from milling to storing, requires two days under conditions of high evaporation and no rain. In this study, the number of harvest cycles was indicated by the number of days when the soil is dry for harvest, as indicated by the fire risk index. The DRYPEAT model (Heikinheimo & Koskela, 1991) was applied in the calculations.

For the current study, a number of sites were selected from the Nordic and Baltic countries (Figure 9.1). Based on the climate scenarios, the number of harvesting cycles was calculated for each of the sites. Each harvesting cycle is equivalent to an average production of 40 m^3 per hectare. The energy content of milled peat is on average 0.9 MWh/m^3; *i.e.* energy production in each harvest cycle is 36 MWh/ha.

The climate model used in this study was the RCAO model, and the data for the climate scenario were downloaded from the EU-project PRUDENCE's data distribution server (http://prudence.dmi.dk/). The model runs used to produce the data sets available at the PRUDENCE data distribution centre have been described by Räisänen *et al* (2003, 2004). The model runs represented the SRES emission scenarios A2 and B2 (IPCC, 2000). Emission scenarios A2 and B2 are not the most extreme ones, but they still cover a fairly large range of possible emissions. The future conditions studied were those for 2071–2100, which were compared with the reference model climate (1961–1990).

Figure 9.1.
The study locations.

Results

The year-to-year variation in the number of harvest cycles was large, both in the control climate and the scenario climate (Figure 9.2). The difference between the control climate and the B2 scenario was small, and even negligible at some locations such as Joensuu, Frösön and Tartu. The northernmost locations, Sodankylä, Ivalo, Frösön and Gällivare, remain unfavourable for profitable peat production even in future, despite the fact that they showed a large increase in the number of harvesting cycles. The average increase in peat production potential was 12% for Finland (21% for A2, 4% for B2), 16% for Sweden (22% for A2, 10% for B2) and 9% for the Baltic countries (12% for A2, 5% for B2). This implies that the increase in production potential would be 2,400 GHz for Finland, 480 GWh for Sweden, 90 GWh for Estonia, 36 GWh for Latvia and 18 GWh for Lithuania.

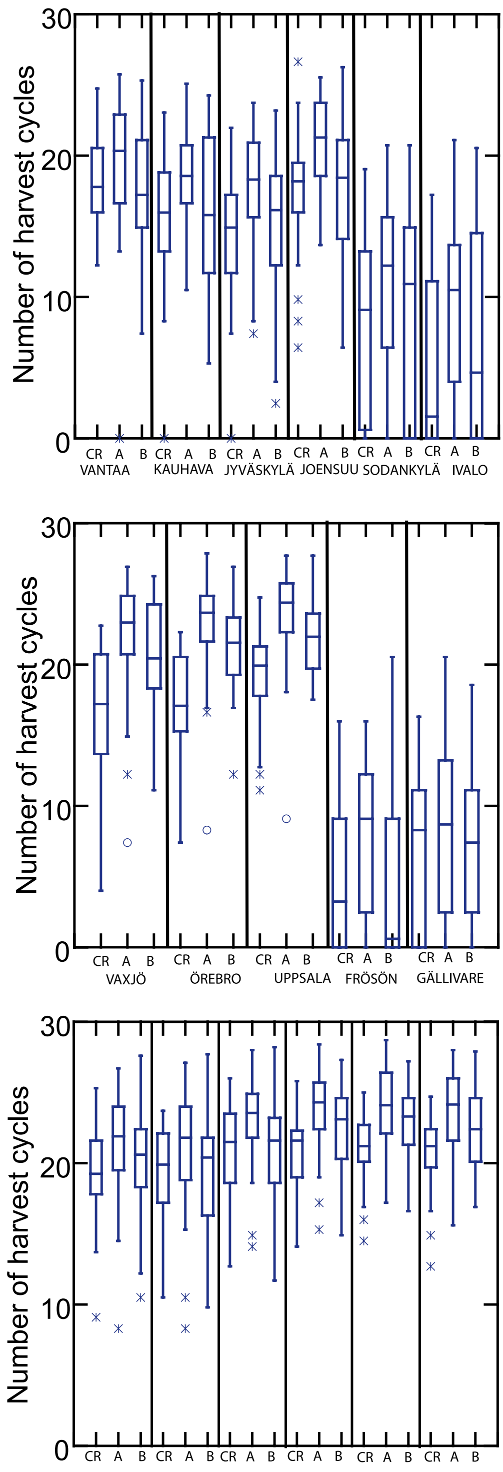

Figure 9.2. Variation in the number of annual peat harvesting cycles during a 30-year period, according to the RAO climate model control climate CR and according to emission scenarios A2 (A) and B2 (B). The simulations give an estimate of climate conditions at the end of this century (2071–2100) and the control run corresponds to the present day climate.

9.2 Impact of climate change on forest growth

In the Nordic and Baltic countries, forest accounts for about 65 million hectares (49% of the total land area), of which nearly half is found in Finland and Sweden. Most of these forests are managed for forestry. Growth exceeds cuttings throughout the Nordic and Baltic Regions, with increasing stocking and maturing of the forest resources. The total forest resources in the Nordic and Baltic countries currently amount to 7,700 million m^3, which is equivalent to 5,770 million Mg biomass, including stems, branches, foliage and roots (www.fao.org/forestry/site/fra/en).

This section aims to examine the influence of climate change on forest growth and the potentials to produce biofuels in forestry. The assessment was made in two steps. First, in order to have a large-scale overview of how climate change may affect forest growth, the assessment was extended over the entire Nordic and Baltic Regions, using the statistics on timber resources and a process-based model. In the second step, in order to assess the biofuel potentials in the context of forestry, it focused on Finland, using ground-truth measurements of timber resources to assess the biofuel potentials. In both cases, the assessments were based on model simulations.

Data and methods

Assessing forest growth over the Nordic and Baltic countries

In the first phase, the biomass model described by Freeman *et al* (2005) was used. This uses a daily time-step model, which requires daily meteorological inputs in the form of short-wave radiation, maximum and minimum air temperature, precipitation and air humidity. Gross primary production is calculated from a radiation interception in the canopy and net primary production is obtained by subtracting the autotrophic respiration. The model was parameterised for Norway spruce, Scots pine and birch.

Three 30-year simulations were run with RCAO: a control run representing the period 1961–1990, and two scenario runs representing the period 2071–2100. The two scenario runs were based on the IPCC Emission Scenario B2 (IPCC, 2000; 2001). The climate data were available in a 49 km × 49 km grid (Bringfelt *et al*, 2001; Döscher *et al*, 2002; Räisänen *et al*, 2002). In order to specify the biomass in stems, branches and roots, the forest resources were divided into three different age classes in the model runs: (i) young open stands, 5–35 years; (ii) middle-aged closed stands, 35–65 years; and (iii) old stands, 65–95 years. To simplify the calculations, a constant values-of-leaf-area index (LAI = 3) was used, regardless of the age class or tree species.

Biofuel potentials in forestry and timber production

In the second step, a growth and yield oriented forest ecosystem model (Sima) was applied (Kolström, 1998), using the forest inventory data available from the permanent sample plots of the Finnish Nation Forest Inventory. The plots are located in a 16 km x 16 km grid in southern Finland and a 32 km × 32 km grid in northern Finland. In the simulations, management included regeneration, thinning and final harvest in the form of clear cut. After the clear cut, the site was planted with the same tree species as had occupied the site before the cut. Planting density was 2000 seedlings per hectare, regardless of the tree species. Trees removed in thinning and terminal cut were converted to saw logs and pulp wood, and the logging residue (the rest of the stem and other parts of tree biomass) was considered as biofuel.

The simulations used the current climate data (1991–2000) given in 10 km × 10 km grids and the climate scenarios in 50 km × 50 km grids (Ruosteenoja *et al*, 2005; Venäläinen *et al*, 2005). The climate change scenarios were given for three periods, 1991–2020, 2021–2050 and 2070–2099 (Ruosteenoja *et al*, 2005). Projections were composed separately for the SRES A2, where the projections were directly model-derived. Under the A2 scenario, mean temperatures are projected to increase by almost 4 °C in summer and more than 6 °C in winter by 2070–2099. The concentration of CO_2 in the atmosphere increased during the simulations, starting from 352 ppm in 1990 and ending at 841 ppm in 2099.

Results

Forest growth in the current and projected climate

Figure 9.3 shows the annual stem volume growth (upper part) and the annual dry matter growth (lower part), including stem, foliage, branches and stumps, per tree species, over the Nordic and Baltic countries. With the exception of the forest areas above the Arctic Circle and in the Scandinavian mountains (temperature sum < 900 day × degrees, with 5 °C threshold), the stem wood growth is 2–6 m^3/ha/yr, with the highest values representing central and southern Finland and Sweden, southern Norway and the Baltic countries. Productivity is highest in Denmark and southernmost Sweden, with up to 10 m^3/ha/yr. These values are equivalent to a total annual dry matter production of stem wood of 2–5 Mg/ha/yr.

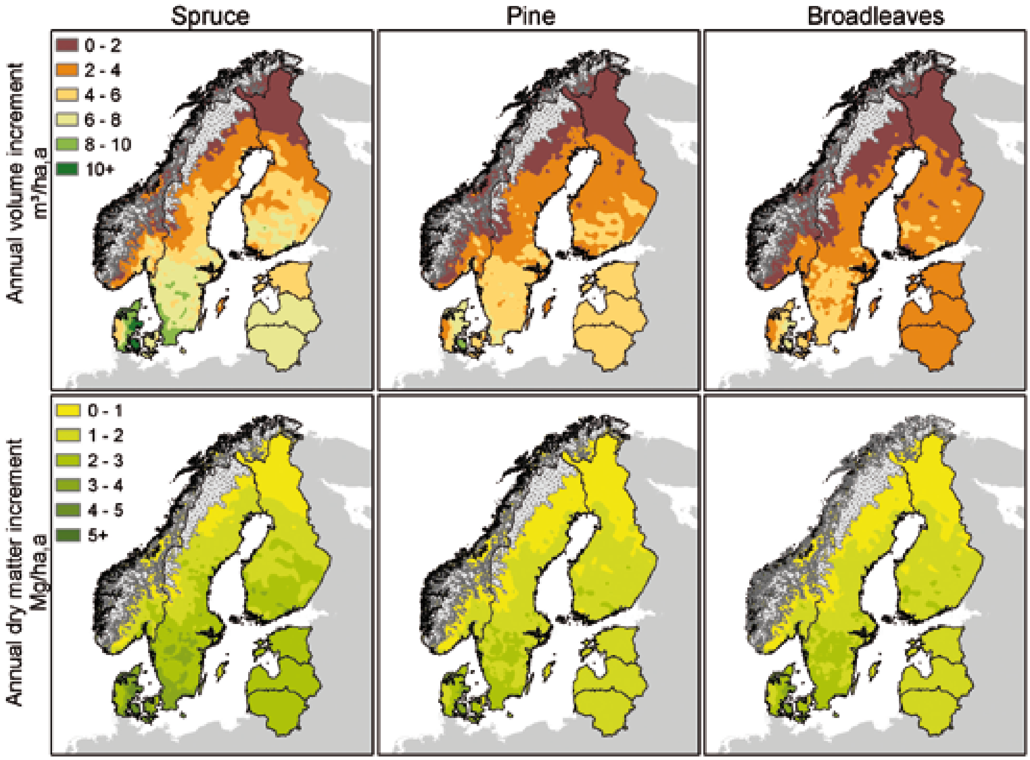

Figure 9.3. Annual mean stem volume growth (upper graphs) and annual dry mass growth of stem wood (lower graphs)

Due to climate change, total biomass growth increases between 20% and 25% over large areas of Finland and Sweden. An even larger increase of up to 35% was seen in maritime conditions. The increase was smaller under continental conditions because of more frequent drought episodes. This pattern was similar for the Baltic countries. Assuming that the management systems and the use of timber are the same as for today, an increase of 20% in biomass growth would mean that the total biomass available for forest and energy industries in the Nordic and Baltic countries may increase to 760 million Mg during this century. In terms of annual stem volume growth, the increase is roughly 50 million m^3/yr.

Biofuel potentials in forestry and timber production

Over the whole of Finland, an increase of 44% in growth per hectare was obtained by applying a growth and yield oriented model. This implies an increase of 82% in the potential cutting drain per hectare. Over the whole country, the potential cutting drain increased from 46 million m^3/yr (excluding cutting on peat lands) to 83 million m^3/yr in such a way that 53 million m^3/yr would be obtainable from southern Finland and 27 million m^3/yr from northern Finland. Consequently, the total yield of harvest residues from terminal cuts could increase to 7.2 million Mg/yr in southern Finland and 3.3 million Mg/yr in northern Finland by the end of this century (Table 9.1). Over the whole country, this amounts to 10.5 million Mg/yr, an increase of more than 200% compared to the yield under the current climate, indicating that the large-scale maturing of tree stands for terminal cut, in both southern and northern Finland, is affecting the current distribution of age classes in forests.

The total yield of potential logging residues was converted to energy by assuming percentage moisture of 45% and energy content of 1.5 MJ/kg, regardless of the component of logging residue. The potential amount of logging residues over the whole country is currently equivalent to 1.3 TWh of energy. By the end of this century, the value could increase to 4.4 TWh.

	Total yield of logging residue, million Mg/yr			
Region	Current	1990–2020	2021–2050	2050–2099
Southern Finland	2.6	3.1 (19)	5.2 (100)	7.2 (177)
Northern Finland	0.5	0.7 (40)	1.9 (280)	3.3 (560)
All of Finland	3.1	3.8 (23)	7.1 (129)	10.5 (239)

Table 9.1. Total yield of logging residues in terminal cuts, currently and for different time slices under climate change, divided between southern and northern Finland. In parentheses are shown the percentage changes in relation to the current climate.

9.3 Impact on the production of biofuels in agriculture

The acute political, scientific and environmental challenges posed by the generation and use of energy and power for transport are evident, both nationally and globally. Environmental and economic issues are central, and include global warming, energy security, the development of technological exports and the development of rural areas; all are important contributors to future human welfare in the Nordic and Baltic Regions. A key economic concern will be how to maintain the security of energy supply in these regions, as well as Europe. In this respect, using biomass for energy is one of the best substitutes for fossil fuels in the transport sector, where the substitution of other renewable energy sources is notoriously difficult.

This section reports the potential for producing biofuels on agricultural land in the Nordic and Baltic countries. First, sources of biomass are identified, with estimates of efficient cropping systems and the absolute upper limit to the production of biomass for energy in the Nordic and Baltic countries. Second, calculations are made, based on current agricultural cropping areas and total above-ground biomass crop yields, in order to estimate the maximum amount of biomass energy and/or biofuels in the form of ethanol that could be produced, on the assumption that all the current agricultural area is used for biomass production of energy.

Data and methods

The general methodology was to estimate the current possible production of arable and forage crops for bio-energy production in the Nordic and Baltic countries, and then to apply a simple model to calculate how such a potential might change under conditions of elevated CO_2. Calculations were restricted to arable and forage crops, and calculations of available biomass energy from Nordic and Baltic agriculture were made using a number of sources. Land use areas and production figures for cereals, sugar beet, oil seed rape and forage crops for different countries were obtained from www.fao.org and http://europa.eu.int/comm/agriculture/agrista/2004/table_en/en41.htm. Conversion from biomass production to primary energy content is based on standard tables. Information on oil consumption came from www.cia.gov/cia/publications/factbook/docs/noteanddefs.html. A function, derived from Olesen & Bindi (2002), in which results from a series of experiments with wheat are summarised, was used to estimate that a doubling of pre-industrial CO_2 concentration to *ca.* 550 μmol mol^{-1} would lead to a mean increase in crop yield of 25%.

Results

Table 9.2 gives the agricultural and cropping areas in the Nordic and Baltic countries and shows that, of a total of 1.43×0^8 ha, there are nearly 1.2×10^5 ha of permanent crops such as fruit trees; 4.65×10^6 ha of permanent pasture; and 1.33×10^7 ha of arable land. This gives a total agricultural area of 1.81×10^7 ha of agricultural land.

Country	Total country area	Permanent crops	Permanent Pasture	Arable land	Agricultural area
Denmark	4,310	8	358	2,280	2,650
Finland	33,800	4	21	2,190	2,210
Sweden	45,000	3	447	2,710	3,160
Norway	32,400	0	163	873	1,040
Iceland	10,300	0	2,270	700	2,280
Estonia	4,520	16	268	545	829
Latvia	6,460	29	621	1,820	2,470
Lithuania	6,530	59	499	2,930	3,480
Total	143,000	119	4,650	13,3000	18,100

Table 9.2. Agricultural land-use (1000 ha) in the Nordic and Baltic countries.

Taking whole crop and forage production as the relevant agricultural products for biomass production for energy shows that the Nordic and Baltic countries could produce 4.45×10^7 Mg/yr of whole crop cereals, 7.58×10^5 Mg/yr of oil seeds, 2.11×10^6 Mg/yr of whole-crop beets and 1.90×10^7 Mg/yr of forage in the form of maize, grass and clover-grass (Table 9.3). The total potential primary agricultural production of energy crops is estimated to be 6.6×10^7 Mg/yr.

Country	Cereals	Cereals whole crop	Oil seed rape	Sugar beat	Sugar beet whole crop	Forage
Denmark	7,690,000	17,100,000	326,000	616,000	770,000	2,960,000
Finland	3,220,000	7,150.000	86,100	196,000	245,000	1,670,000
Sweden	4,550,000	10,100,000	119,000	547,000	683,000	5,040,000
Norway	1,090,000	2,430,000	10,400	–	–	2,000,000
Iceland	–	–		–	–	486,000
Estonia	430,000	955,000	63,700	–	–	958,000
Latvia	792,000	1,760,000	110,000	117,000	146,000	3,320,000
Lithuania	2,230,000	4,950,000	42,900	215,000	269,000	2,550,000
Total	20,000,000	44,000,000	758,000	1,690,000	2,110,000	19,000,000

Table 9.3. Production totals (Mg/yr) of cereals, oil seed rape, sugar beet and forage crops in the Nordic and Baltic countries.

Agricultural crops have a gross energy content of 35–44 MJ kg^{-1} dry matter, which is reduced to a net value by the energy cost of cultivating the crops and processing them into usable fuels, such as oil and ethanol. Taking these reductions into consideration, Table 9.4 shows the annual potential net primary energy content of arable and forage crops in the Nordic and Baltic countries. The annual total gross energy production is 1.42×10^9 GJ or 1.42 EJ.

Country	Cereals	Cereals whole crop	Oil seed rape	Sugar beat	Sugar beet whole crop	Forage
Denmark	1.45×10^{11}	3.23×10^{11}	7.85×10^{9}	1.08×10^{10}	1.35×10^{10}	8.19×10^{10}
Finland	6.08×10^{10}	1.35×10^{11}	2.07×10^{9}	3.44×10^{9}	4.29×10^{9}	4.63×10^{10}
Sweden	8.59×10^{10}	1.91×10^{11}	2.87×10^{9}	9.56×10^{9}	1.20×10^{10}	1.39×10^{11}
Norway	2.07×10^{10}	4.59×10^{10}	2.50×10^{8}	–	–	5.52×10^{10}
Iceland	–	–	–	–	–	1.34×10^{10}
Estonia	8.12×10^{9}	1.80×10^{10}	1.53×10^{9}	–	–	2.65×10^{10}
Latvia	1.50×10^{10}	3.32×10^{10}	2.65×10^{9}	2.05×10^{9}	2.56×10^{9}	9.18×10^{10}
Lithuania	4.21×10^{10}	9.36×10^{10}	1.03×10^{9}	3.76×10^{9}	4.70×10^{9}	7.04×10^{10}
Total	3.78×10^{11}	8.40×10^{11}	1.83×10^{7}	2.96×10^{7}	3.70×10^{7}	5.25×10^{8}

Table 9.4. Primary energy contents (MJ) of arable and forage crops grown in the Nordic and Baltic countries.

One barrel of oil contains about 6.1 GJ of energy; *i.e.* the agricultural primary energy production in the Nordic and Baltic countries is equivalent to 2.3×10^8 barrels of oil (Table 9.5). This translates to 58% of the total annual oil imports to the Nordic and Baltic area. Converting the biomass for the transport sector would yield 3.3×10^7 Mg, or 3.3×10^{10} litres of ethanol plus 4.2×10^5 Mg oil, or 4.6×10^8 litres.

Variables and dimensions	Value
Net total of energy production from agriculture, EJ/y1	1.42
Power density, J s-1m-2	0.677
Equivalent barrels of oil from biomass per year	2.33×10^{8}
Current Nordic oil consumption, bbl yr-1 or litres	3.98×10^{8} or 6.33×10^{10}
Proportion of current oil consumption potentially provided by biomass	0.584
Total ethanol production from biomass, Mg or litres	3.28×10^{7} or 3.70×10^{10}
Total diesel oil biomass from biomass, Mg or litres	4.24×10^{5} or 4.5×10^{8}

Table 9.5. Summary of findings.

Considering the impact of climate change on biofuel production on agricultural and arable land, an increase of 25% in crop yields might be expected for a CO_2 level of 550 μmol mol^{-1}. Thus, the above estimates of production and energy yields and their consequences need to be revised upwards by 25%. If the 25% increase is accepted, this would raise the potential oil substitution level from 58% to *ca*. 70% of current fossil fuel consumption. Management, particularly in terms of the addition of nitrogen fertiliser, would have to match predicted yield increases. It should be noted that these percentages assume that all agricultural land in the Nordic and Baltic countries is used for biomass for energy production.

9.4 Conclusions

The results of the study indicate that the projected climate will be more favourable for milled peat production. The average increase in peat production potential is 12% in Finland, 16% in Sweden and 9% in the Baltic countries. The increase in production potential would be 2,400 GWh in Finland, 480 GWh in Sweden, 90 GWh in Estonia, 36 GWh in Latvia and 18 GWh in Lithuania.

The productivity of the forest ecosystems will show the largest increase in the middle boreal forests, such as in central Finland and Sweden. In the southern part of Scandinavia and in the Baltic countries, the more frequent drought episodes may reduce the increased growth otherwise induced by the elevation of temperature and CO_2. On average, forest biomass production in the Nordic and Baltic countries could increase by 10–20% as an effect of the projected climate change.

The total potential primary agricultural production of energy crops in the Nordic and Baltic Regions is 8.23×10^7 Mg/yr. Agricultural crops have an energy content of between 13 and 22 MJ/kg, with a consequence that the total annual primary energy production from cereals, sugar beet, whole crops, oil crops and forage is 1.34×10^9 GJ or 1.34 EJ.

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10 Energy system analyses

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The following sections discuss the impact of climate change on the Nordic energy system, with a focus on electricity generation and demand. Several types of climate-change impact are considered:

- Changes in average climate properties (average values for temperature, wind and precipitation), which influence, for example, demand for electricity and electricity production from hydro and wind power.
- Changes in extreme climate events, like storms, heavy rain and long periods with unusually high or low temperatures; these can have a serious impact on the energy system. Extreme climate events threaten the security of supply, and present challenges in terms of dam security, backup for wind power and reliability of overhead lines. There exists only limited information 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. An ambitious energy policy could limit CO_2 emissions, tax fossil fuels, and support renewable energy sources and energy efficiency.
- Economic activities may be directly influenced by climate change. For example, agricultural production could expand or relocate as a result of climate change. Economic activities in energy-intensive industries could be reduced as a result of energy policies that have been altered because of climate change.

The first type of impact (the direct impact of changes in average climate variables) can be assessed quantitatively, but seems to be limited compared to the technical and economical development that can be foreseen from a 50-year perspective. However, the other three types of impact can have a vast influence on the energy system. A discussion of these impacts and the general development of the energy system follows.

A major drawback of some renewable energy sources (especially wind power) is that they fluctuate constantly. This can be compensated to some extent by linking systems at different locations, and is as such more or less an economic problem. A further possibility is the development of steering systems that, on the basis of weather forecasts, fit the output from different sources into the general production scheme. In this respect, the various sources can substitute each other; and biofuels and hydropower especially, can act as buffers.

10.1 Quantitative analysis approach

For the quantitative part of the energy system analysis, a given electricity system is simulated for today's climate and compared with simulations for two different climate scenarios. The climate scenarios represent two possible futures for the period 2071–2100. It is difficult to make quantitative forecasts of what the electricity system will be like 70 to 100 years from now, and there will be other developments that have much greater impact than the forecast climate change. In order to isolate the consequences of climate change, therefore, an assumed electricity system for the year 2010 is used, and is subjected to the different climates. Even if the future electricity system is very different, the existing hydro-generation system will still exist, and the results show the capabilities of this system under changed climate conditions. The results also show relevant consequences or tendencies in the present situation, assuming that changes in the direction of the future scenarios have already begun.

The results from the analysis reflect how the generation and demand characteristics of a fixed system configuration change for assumed changes in precipitation, temperatures and wind speed, and how this influences other quantities, such as exchanges with continental Europe.

For 2010, assumptions about demand, generation and transmission capacities are based on existing forecasts and known plans. Assumptions are also made about fuel costs and exchange prices with continental Europe. The simulation of the system is done by using the EMPS model (Wolfgang *et al*, 2005). The EMPS model is applied by most of the major players in the Nord Pool market, to market analysis, hydro-scheduling, and generation and transmission investment planning.

The EMPS model simulates the balance between supply and demand in the Nord Pool electricity market for a selection of historical weather years, which represent hydrology, temperature and wind speed variations. For the reference scenario, weather data from the historical period 1961–1990 are used. Two alternative model forecasts for the period 2071–2100 are the basis for the future climate scenarios.

The basic input to the simulations of the Nord Pool market (Sweden, Norway, Finland and Denmark) consists of time series for inflow, wind and temperature. The time series that represent future climate scenarios are generated by the HadAm and ECHAM climate models. In this analysis, the scenarios HadAm-B2 and ECHAM-B2 were used (cf. Section 4.1). The time series for inflow (Mm^3/week) to different reservoirs are calculated by the hydrological model group, the time series for wind energy production (GWh/week) are calculated by the wind power group (Chapter 7), and temperatures (°C) are calculated by the climate scenarios group (Chapter 4).

Simulations with the EMPS model consist of two phases. In the first ('strategy') phase, 'water values' for the hydro reservoirs are calculated. In essence, these give the resource cost of the water in the reservoir as a function of the reservoir level and the time of the year. In the 'simulation' phase, the water values are used to simulate an optimal dispatch of the system, taking into account the costs of thermal generation, imports, exports and flexible demand options. Transmission constraints between areas are taken into account, and exchanges with countries outside the Nord Pool area are also modelled. A model with 23 separate areas for the Nord Pool system was used, reflecting the major transmission constraints and hydrological diversity. The basic time step for the simulations is one week, which is subdivided into seven periods to describe the variation in demand over the week. Reported values reflect the average of the 30 simulated historical weather years.

Inflow data are input to the hydro-reservoirs in the EMPS model. Changes in inflow will directly influence the simulated generation from the hydro plants, but a change in inflow is not necessarily matched by a corresponding change in generation, because there will also be changes in spillage. Wind data are input to calculate wind generation. Because wind cannot be stored, changes in wind speed are directly reflected by changes in wind generation, apart from limitations caused by maximum wind speed. Temperature data are used to calculate demand in the model. Because there is significant use of electricity for heating purposes, demand depends on temperatures. Changes in temperature will therefore result in changes in demand. The use of air conditioning is not modelled, and a potential increase in demand caused by an increased use of air conditioning in summer due to higher temperatures is, therefore, not taken into account.

Demand also depends on prices. Because all simulations are done on a fixed system configuration, increased hydro and wind generation, combined with lower demand, leads to lower prices, which result in an increase in demand. The reduction in demand caused by higher winter temperatures is therefore partly offset by an increase caused by lower prices.

Two different cases with respect to the system configuration were considered. In the base case, the most probable configuration of the generation system in 2010 was used. In an alternative case, a configuration with an additional 7,000 MW (21 TWh) of wind generation was used. In the latter case, thermal plants producing a corresponding amount of energy were removed from the model.

10.2 Data description

Electricity demand is based on recent forecasts for the Nordic countries for 2010: Sweden, 156.0 TWh; Norway, 130.3 TWh; Finland, 96.4 TWh; and Denmark, 39.3 TWh. These estimates include all network losses. Installed generation capacity is based on Nordel statistics as of 31 December 2004, corrected for known and expected changes. The resulting capacities are given in Table 10.1. The major changes compared with the present system are:

- An increase of almost 1,300 MW in the capacity of existing nuclear plants in Sweden
- One gas-fired plant and more than 700 MW increased hydro capacity in Norway
- A new, 1,600 MW nuclear plant in Finland
- A more than 3,000 MW increase in wind power, over all countries.

	Denmark	Finland	Norway	Sweden	Nord Pool
Installed capacity[1]	13,530	18,788	30,693	35,297	98,308
Thermal power	8,728	12,794	551	16,320	38,393
• Nuclear	–	4,271	–	10,167	14,438
• Other thermal[2]	8,728	8,523	551	6,153	23,955
∘ Condense and CHP district heating	8,077	6,627	438	4,038	19,180
∘ CHP industry	381	996	49	492	1,918
∘ Gas turbines etc	270	900	64	1,623	2,857
Renewable energy[3]	4,802	5,994	30,142	18,977	59,915
• Hydropower	11	2,986	28,928	16,137	48,062
• Other renewable	4,791	3,008	1,214	2,840	11,853
∘ Wind	4,102	499	1,200	1,142	6,943
∘ Biomass	418	2,378	96	1,545	4,437
∘ Waste	271	131	27	153	582
∘ Geothermal					98,308

1 Sum of installed capacity in all units. This is considerably higher than available capacity at any given time
2 Fossil fuels, such as coal, oil and gas
3 Biomass and waste are used in CHP plants that produce district heating

Table 10.1. Assumed installed capacity in the Nord Pool area in 2010.

In an alternative scenario, 7,000 MW / 21 TWh, more wind generation is assumed. This is compensated by a corresponding reduction in thermal generation. For Sweden and Denmark, the reduction in thermal generation is equal to the increase in wind generation. For Norway, it was not possible to reduce thermal generation with the assumed 2,300 MW increase in wind power. Part of this reduction was therefore made in Finland to obtain an overall reduction of 21 TWh thermal generation in the Nord Pool area.

Interconnection capacities were modelled with their present capacities, modified for expected and known changes before 2010. These include an increase of 600 MW of the interconnection between Finland and Sweden (Fenno-Skan 2) and the interconnection between Denmark and Norway (Skagerrak IV), as well as new interconnections between east and west Denmark (600 MW) and between Norway and the Netherlands (700 MW).

Water values, system dispatch and economic calculations in the model depend on the cost assumptions that are made. A crucial parameter for all energy costs is the expected oil price. Although oil prices have fluctuated recently between 60 and 70 USD/barrel, long-term projections by the IMF suggest a level of 36 USD/barrel (IMF, 2005). This is roughly equal to the average oil price in 2004 (38 USD/barrel). Fuel price estimates were therefore based on average 2004 oil and coal prices. Prices for exchange with Germany, Poland and the Netherlands were also based on 2004 prices for power exchanges in Germany and the Netherlands. CO_2 emission quota costs were not taken into account.

10.3 Results of the quantitative analysis

Base case, expected generation system

Table 10.2 shows regional inflow for the Nord Pool area.

	Reference			HadAM			ECHAM		
Area	Winter	Summer	Year	Winter	Summer	Year	Winter	Summer	Year
East Norway	9.2	44.2	53.3	15.5	35.1	50.6	18.8	31.9	50.8
West Norway	5.7	32.2	37.9	13.9	31.2	45.1	23.5	36.2	59.6
Central Norway	2.8	11.1	13.9	4.5	8.1	12.6	7.2	9.0	16.2
North Norway	2.9	15.9	18.8	6.7	12.2	18.9	10.5	15.0	25.5
Sum Norway	20.6	103.4	124.0	40.7	86.6	127.3	60.0	92.2	152.1
North Sweden	6.5	41.7	48.2	12.6	39.5	52.1	19.0	42.0	61.0
Central Sweden	2.7	8.6	11.3	4.7	7.9	12.6	6.3	6.9	13.2
South Sweden	3.2	3.2	6.4	4.2	2.4	6.6	5.2	2.3	7.5
Sum Sweden	12.5	53.5	66.0	21.5	49.9	71.4	30.5	51.2	81.6
North Finland	1.9	6.3	8.2	3.4	6.3	9.6	4.2	7.1	11.3
South Finland	2.2	2.9	5.2	2.7	2.7	5.4	3.3	3.2	6.5
Sum Finland	4.1	9.3	13.4	6.0	9.0	15.0	7.5	10.3	17.9
Total, Nord Pool Area	37.2	166.2	203.4	68.3	145.4	213.6	98.0	153.7	251.6

Table 10.2. Regional inflow, average values (TWh), to the Nord Pool area for current climate (reference) and two future climate scenarios (HadAM and ECHAM).

For the simulation period 1961–1990 in the reference scenario, the total annual inflow to the Nord Pool area in 2010 is 203 TWh. With the inflow given by the HadAM scenario in 2070, the inflow to the same hydropower generation system would increase to 214 TWh (+5.0%). The corresponding number for the ECHAM scenario is 252 TWh (+23.6%). In the HadAM scenario, the largest increase is in Sweden, with 5.6 TWh, and the major proportion of this comes from north Sweden. In the ECHAM scenario, the largest absolute increase is in Norway (28.1 TWh); 22 TWh of this increase comes in west Norway. Finland has the smallest absolute increase because it has the smallest system, but the relative increase is largest in Finland with 34% in the ECHAM scenario. All the increase occurs in winter – in fact, a considerable decrease in summer inflow is expected for both scenarios, with the exception of Finland in the ECHAM scenario. In Norway, the main increase occurs in west Norway. For Sweden, both relative and absolute changes are largest in the north, with a 192% increase in winter inflow in the ECHAM scenario. Especially in the south, Sweden has a significant relative decrease in summer inflow (25% and 28%). In Finland, the expected changes are generally larger in the north than in the south, and the major increases again occur in winter (+121% for north Finland in the ECHAM scenario).

Figures 10.1 and 10.2 show the relative changes for each season and region for the climate scenarios. The figures illustrate the large relative increases in winter inflow, especially for west and north Norway and north Sweden for the ECHAM scenario. The two main reasons for these large relative increases are:

- Because of the increase in average winter temperatures, more precipitation falls as rain instead of snow, and more snow melts during the winter season.
- Winter inflow is small in the reference case, typically 15% of annual inflow for the areas mentioned above.

The first effect leads to a considerable absolute increase in winter inflow. As a result of the second effect, the increases are particularly large, relative to the reference winter inflow.

Table 10.3 shows simulated hydro generation for each country.

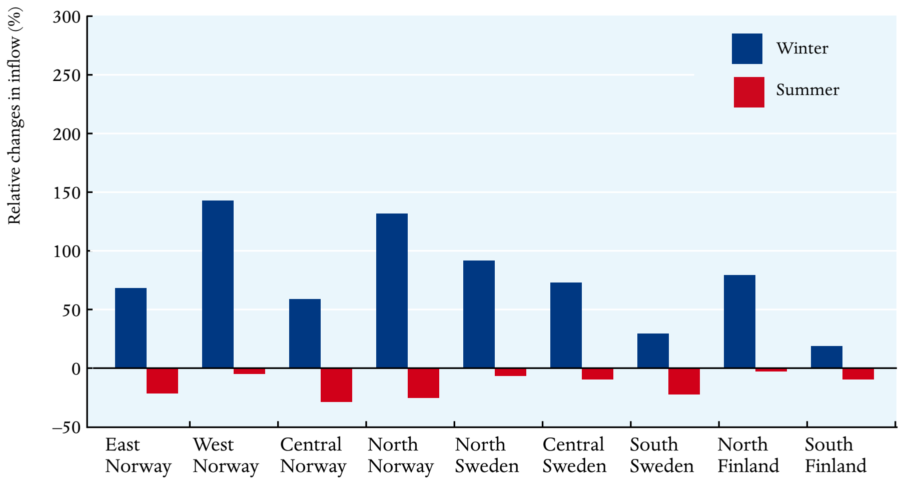

Figure 10.1. Expected relative changes in inflow, HadAM-B2.

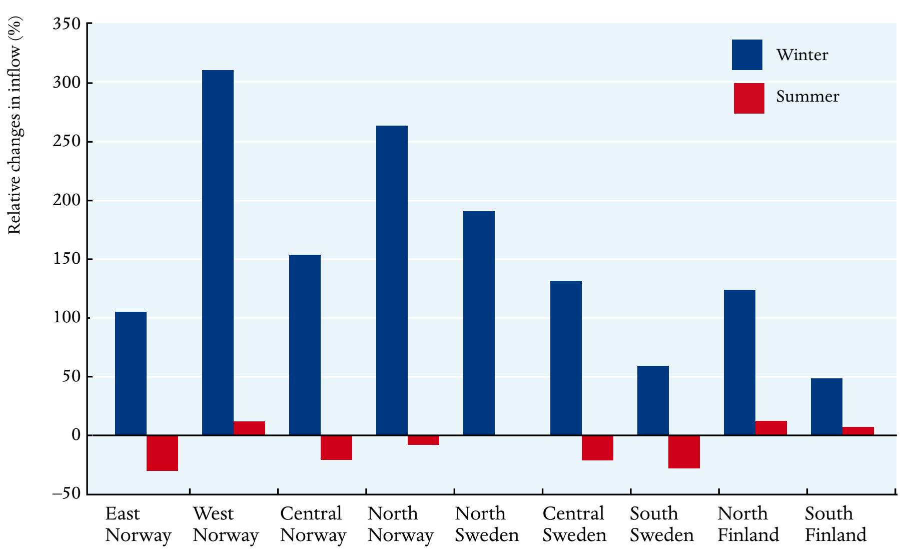

Figure 10.2. Expected relative changes in inflow, ECHAM-B2.

	Reference			HadAM			ECHAM		
Area	Winter	Summer	Year	Winter	Summer	Year	Winter	Summer	Year
Norway	67.4	47.9	115.3	68.6	49.4	117.9	76.2	59.0	135.3
Sweden	34.2	28.2	62.3	34.8	31.5	66.3	39.1	35.3	74.4
Finland	6.0	6.3	12.3	7.3	6.8	14.1	8.1	7.9	16.0
Sum, Nord Pool Area	107.5	82.4	189.9	110.7	87.6	198.3	123.5	102.2	225.7

Table 10.3. Simulated hydro generation (TWh) in the Nord Pool area for current climate (reference) and two future climate scenarios (HadAM and ECHAM).

Total hydro generation increases by 36 TWh in the ECHAM scenario, considerably less than inflow, indicating a significant increase in overflow. In the HadAm scenario, the largest increase occurs in Sweden (4 TWh), while Norway has the largest increase in the ECHAM scenario (20 TWh). The respective changes in the winter and summer generation shares of total generation are quite small compared with the changes in inflow. This is a natural result of the fact that, to a large degree, generation must follow demand, the profile of which is not assumed to change significantly. The increase in spillage is confirmed by the figures in Table 10.4.

	Reference			HadAM			ECHAM		
Area	Winter	Summer	Year	Winter	Summer	Year	Winter	Summer	Year
Norway	0.8	7.4	8.1	3.1	5.6	8.7	7.3	8.9	16.2
Sweden	0.7	2.7	3.3	1.6	3.1	4.7	2.8	4.0	6.9
Finland	0.1	1.0	1.1	0.3	0.7	0.9	0.6	1.3	1.9
Sum, Nord Pool Area	1.5	11.0	12.6	5.0	9.4	14.4	10.8	14.2	25.0

Table 10.4. Simulated spillage (TWh) in the Nord Pool area for current climate (reference) and for two future climate scenarios (HadAM and ECHAM).

Only minor changes in wind generation are expected, as shown in Table 10.5. Although the change in annual generation is small, there is a shift towards more winter generation in the ECHAM scenario.

Area	Reference			HadAM			ECHAM		
	Winter	Summer	Year	Winter	Summer	Year	Winter	Summer	Year
Norway	2.3	1.8	4.1	2.2	1.8	4.1	2.6	1.7	4.3
Sweden	2.0	1.8	3.8	2.2	1.9	4.1	2.3	1.6	3.9
Denmark	8.4	7.3	15.7	8.6	7.7	16.3	9.3	6.8	16.2
Finland	0.8	0.8	1.6	0.7	0.7	1.4	0.9	0.6	1.5
Sum, Nord Pool Area	13.4	11.6	25.1	13.8	12.1	25.9	15.1	10.8	25.9

Table 10.5. Simulated wind generation (TWh) in the Nord Pool area for current climate (reference) and two future climate scenarios (HadAM and ECHAM).

Table 10.6 shows simulated thermal electricity generation for each country.

Area	Reference			HadAM			ECHAM		
	Winter	Summer	Year	Winter	Summer	Year	Winter	Summer	Year
Norway	2.5	2.2	4.7	2.4	2.0	4.4	2.0	1.7	3.7
Sweden	45.3	36.4	81.7	44.9	35.5	80.4	42.9	33.4	76.3
Denmark	20.5	22.1	42.6	20.0	21.0	41.1	18.6	18.7	37.3
Finland	37.5	31.5	69.1	34.7	29.0	63.7	29.8	24.8	54.6
Sum, Nord Pool Area	105.8	92.3	198.1	102.0	87.6	189.5	93.2	78.6	171.8

Table 10.6. Simulated thermal electricity generation (TWh) in the Nord Pool area for current climate (reference) and two future climate scenarios (HadAM and ECHAM).

In the reference scenario, simulated thermal generation in the area is 198 TWh. Due to more hydro-production, this is reduced by almost 8 TWh in the HadAM scenario, and by more than 26 TWh to 171.8 TWh in the ECHAM scenario. The major share of the reduction in thermal generation is in Finland, and this is a result of assumptions about generation costs that have been made. The reduction in thermal generation is evenly distributed between winter and summer.

Total demand is 426 TWh in the reference scenario and 417 TWh in both the HadAM and ECHAM scenarios. Temperatures are slightly higher in the latter scenario, but the effect on demand is offset by lower prices.

Finally, Table 10.7 shows each country's resulting energy balance, including net imports.

Reference	Hydro	Thermal	Wind	Net import	Demand
Norway	115.3	4.7	4.1	6.7	130.7
Sweden	62.3	81.7	3.8	11.6	159.4
Denmark	0.0	42.6	15.7	–18.9	39.4
Finland	12.3	69.1	1.6	13.5	96.5
Nord Pool Area	189.9	198.1	25.1	12.9	426.0

HadAM	Hydro	Thermal	Wind	Net import	Demand
Norway	117.9	4.4	4.1	1.6	128.0
Sweden	66.3	80.4	4.1	5.0	155.8
Denmark	0.0	41.1	16.3	–17.8	39.5
Finland	14.1	63.7	1.4	14.5	93.6
Nord Pool Area	198.3	189.5	25.9	3.2	416.9

ECHAM	Hydro	Thermal	Wind	Net import	Demand
Norway	135.3	3.7	4.3	–16.5	126.8
Sweden	74.4	76.3	3.9	2.0	156.5
Denmark	0.0	37.3	16.2	–13.8	39.6
Finland	16.0	54.6	1.5	22.3	94.3
Nord Pool Area	225.7	171.8	25.9	–6.1	417.3

Table 10.7. Energy balance for each country (TWh) in the Nord Pool area for current climate (reference) and two future climate scenarios (HadAM and ECHAM).

Denmark is a large exporter for all scenarios. This reflects both the balance between demand and supply in the other countries and the price assumptions that have been made, as well as the large amount of wind power in Denmark. If higher costs had been assumed in Denmark, and/or lower costs for the alternatives, Denmark would have exported less, although still a considerable amount because of the amount of wind power.

The most important results of this analysis are related to the changes in the energy balance in the Nord Pool area caused by climate change. Finland is the largest importer in all scenarios, including 10.5

TWh that comes from Russia under contracts that are assumed not to depend on the market situation. The reason for the increased imports to Finland is that more hydropower becomes available in Norway and Sweden, and this is transported to Finland, as being the country with the highest generation costs on the margin. Sweden imports 11.6 TWh in the reference case, 5.0 TWh in the HadAM scenario and only 2.0 TWh in the ECHAM scenario. The biggest changes occur for Norway, because of the large increases in hydro generation, especially in the ECHAM scenario. Norway imports 6.7 TWh in the reference case, but exports 16.5 TWh in the ECHAM scenario.

Alternative case, increased wind generation

In the alternative case, 7,000 MW more wind power is assumed in the Nordic area, producing 21 TWh of electricity. This increase is compensated by a corresponding reduction in thermal capacity. Table 10.8 shows wind generation for this case.

	Reference			HadAM			ECHAM		
Area	Winter	Summer	Year	Winter	Summer	Year	Winter	Summer	Year
Norway	6.5	5.2	11.7	6.4	5.3	11.7	7.5	5.1	12.6
Sweden	5.6	4.9	10.5	6.1	5.4	11.5	6.4	4.5	10.9
Denmark	9.4	8.2	17.5	9.7	8.6	18.3	9.6	8.5	18.1
Finland	3.1	3.2	6.4	2.9	2.7	5.6	3.5	2.6	6.0
Sum, Nord Pool Area	24.6	21.5	46.1	25.1	22.0	47.1	26.9	20.7	47.6

Table 10.8. Simulated wind generation, alternative case (TWh).

The substitution of wind for thermal generation has some impact on hydro generation. Because of increased uncertainty, hydro reservoir levels are slightly higher on average, resulting in an increase in spillage. This leads to a reduction in hydro generation of 0.5–2 TWh, depending on the scenario. There is also a small increase in demand, caused by slightly lower prices in winter. The major differences with the base case are in thermal generation and exchange between countries, as shown in Table 10.9.

Reference	Hydro	Thermal	Wind	Net import	Demand
Norway	114.2	1.2	11.7	3.0	130.1
Sweden	61.9	74.1	10.5	11.9	158.5
Denmark	0.0	39.8	17.5	–18.0	39.4
Finland	12.2	61.6	6.4	16.4	96.6
Nord Pool Area	188.4	176.8	46.1	13.4	424.6

HadAM	Hydro	Thermal	Wind	Net import	Demand
Norway	116.2	1.0	11.7	–1.6	127.4
Sweden	66.0	74.0	11.5	4.1	155.6
Denmark	0.0	38.2	18.3	–17.1	39.5
Finland	13.9	56.4	5.6	17.0	92.9
Nord Pool Area	196.2	169.6	47.1	2.5	415.4

ECHAM	Hydro	Thermal	Wind	Net import	Demand
Norway	134.5	0.5	12.6	–20.7	126.9
Sweden	74.0	71.3	10.9	0.5	156.7
Denmark	0.0	33.6	18.1	–12.2	39.6
Finland	15.7	49.0	6.0	23.5	94.3
Nord Pool Area	224.2	154.5	47.6	–8.9	417.5

Table 10.9. Energy balance for each country, alternative case (TWh).

For the reference scenario, the reduction in thermal generation compared with the base case is equal to the increase in wind generation, 21 TWh. For the HadAM and ECHAM scenarios, the reduction in thermal generation is slightly less, 19.9 TWh and 17.3 TWh as compared to a 21 TWh increase in wind generation. The reason for this is that the remaining thermal generation has a marginal cost level below export prices, resulting in increased export rather than reduced thermal generation. In the reference scenario, Norway imports 4 TWh less, while Finland imports almost 3 TWh more than in the base case (without additional wind power) shown in Table 10.7. Denmark exports 1 TWh less. This is mainly caused by the fact that part of the compensation for the increased wind generation in Norway was made in Finland, because there was no more thermal generation in Norway to reduce. A very similar effect is seen in the HadAM and ECHAM scenarios. Sweden imports between 0.4 and 1.7 TWh less than in the base case, resulting in a zero net exchange for the ECHAM scenario.

Concluding remarks

The analysis shows that total inflow to the Nord Pool area will increase significantly because of climate change. The ECHAM-B2 scenario shows a more substantial increase than the HadAM-B2 scenario. The increase in total inflow will occur during winter, which will reduce the seasonal inflow variations. The forecast temperature changes give warmer winters and, thus, less winter demand and less seasonal variations in demand. Both of these factors reduce the need to use reservoirs to move summer inflow to winter production. Because wind energy and hydro energy are based on natural resources and produced at almost zero marginal costs, other changes in the electricity balance will be due to the changes in these two natural resources. The climate scenarios give only slight changes in wind energy production.

10.4 Possible development of the Nordic energy system

In the quantitative analyses described above, the energy system for the year 2010 was used. Towards years 2050 and 2100, major changes in the energy system can be foreseen; however, actual developments can be difficult to predict. In this section, a broad qualitative analysis of the relationship between climate change and the long-term development of the electricity system is presented. The focus is its possible development until 2050. The long-term development of the energy system is described by three scenarios:

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

The three scenarios are used to illustrate how economic and technological conditions could be radically different in comparison to today. For all the 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 an annual mean temperature for Scandinavia and Finland that is 4–5°C higher during the period 2071–2100 compared to 1961–1990. The warming is larger in winter than in summer. At the end of the century, precipitation will probably be reduced in southern Scandinavia (most clearly in summer) but will probably be about 30% higher in the north, especially in winter but also in spring and autumn. Wind may increase by a few per cent, primarily in winter (Rummukainen *et al*, 2006).

These results indicate that the long-term regional consequences include higher temperatures, more precipitation and more wind, which brings about the melting of 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). From a Nordic perspective, these changes will be in the order of 10% of current electricity production.

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

Possible economic and technological developments

The consequences of climate change seem small compared to the economic, technical, and political changes that could take place:

- The EU expects electricity demand to increase by 1–2% per annum. In 45 years, this will amount to an increase of 60–140%, but current Nordic electricity consumption per capita is much higher than the EU average.

- Wind power and biomass supply 8% of current Nordic electricity demand. This share could multiply before 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, could 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, such as wind power.
- New communication and computing technologies make it possible to activate small-scale generation and demand to react to system needs in real time. Demand could be delayed for some hours and, in that way, reduce the need for peak production.

The described changes in energy demand and supply that are directly due to climate change can, with little difficulty, be absorbed by the energy system over a 50-year timespan. 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 during the next 50–100 years, with technologies that appear promising. The study encompasses the stationary energy system with a focus on the electricity system. First, the main, medium-path scenario is presented.

Energy demand in 2050

In the medium-path scenario, global energy demand is likely to increase, due to industrialisation and an 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 concerns and cost increases. The use of renewable energy sources may increase, primarily in the forms of biofuel, wind power and solar energy, for which technologies are already more or less commercial (IEA, 2003). Harmful climate-change consequences may emphasise the use of policy instruments; taxes and emission allowances could raise the cost of fossil fuels, while green certificates and feed-in tariffs could promote renewable electricity.

Energy is likely to be used more efficiently in Nordic industry, buildings and electric appliances (IEA, 2003). Heat can be recovered for repeated use in industrial processes and for heating. Thus, the primary energy supply could decrease without reducing the comfort, benefit or utility for which energy is used (IVA, 2003; Eon, 2006). Climate change will reduce heating demand and its seasonal variations (*e.g.* Skaugen & Tveito, 2002). This complex interplay is presented in Figure 10.3.

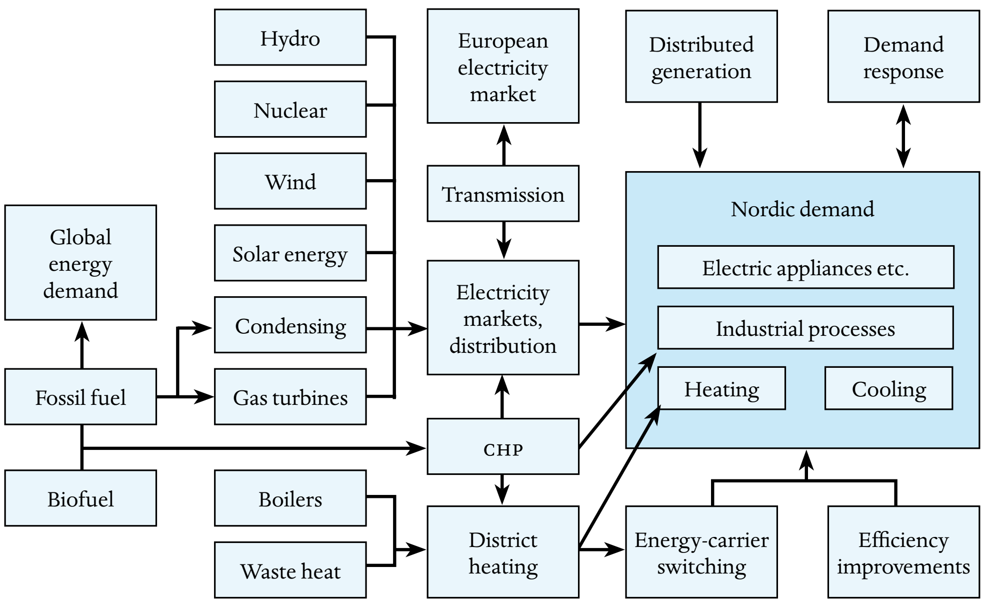

Figure 10.3. There is continuous interplay among the various components in the stationary energy system, from energy sources, via conversion and distribution units, to demand, which may be influenced in several ways.

An integrated system

The Nordic electricity market is part of a common European market, and Nordic power grids will be more linked to the continental power system. This will raise Nordic electricity prices to levels that are similar to continental Europe, which will dampen electricity consumption (Eon, 2006), especially for purposes for which other energy carriers can easily be used. The interplay between power generation and electricity consumption in the Nordic countries and continental Europe also means that Nordic electricity use influences continental electricity generation. Any occasion that raises electricity consumption in the Nordic countries normally increases the operation of, and carbon dioxide emissions from, the committed power plants with the highest operational costs. Most of these plants are now coal-fired (but will in the future probably be natural-gas-fired) condensing plants.

It is very uncertain what the level of electricity consumption will be in 50 years' time. By then, the complete stock of power plants and transmissions lines could have been renewed. New electronic equipment and new information and communication technologies could empower consumers as players in the electricity system and influence the demand for energy supply. Demand response, and advanced markets with dynamic nodal pricing, could reduce the required peak generation capacity (Nordel, 2004). With nodal pricing, each location has its own price, dependent on the marginal impact of losses, capacity constraints and general energy markets. Any surplus or deficit because of local production, like wind power or micro generation, can be signalled through the price. Since the prices show larger variations, the motivation to adapt demand to actual prices is strong and, for example, micro-generation can benefit from timing 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 heating would reduce the seasonal variations of electricity consumption. Industrial electricity consumption is likely to become more similar to that in continental Europe, where less electricity is normally used by manufacturing. Swedish industries could reduce electricity consumption substantially (*e.g.* Trygg & Karlsson, 2004).

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

New energy supply technologies could 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 be used without climate degradation. Hydrogen can be derived through gasification of biomass or electrolysis and could be used as an energy carrier where it is preferable to electricity, for example as vehicle fuel.

To secure energy supply, many different energy sources and technologies can be used, with a preference for local resources, which are often 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, which 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). The adaptation of electricity consumption through demand response could help absorb wind variations. New technologies, such as high temperature superconducting materials, power electronics, electricity storage and automated demand response from consumers could revolutionise the way the electricity system works (EPRI, 2003).

High-growth scenario

In the 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 a 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 conditioning common. Energy efficiency is only 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 (such as fuel cells) in low-energy buildings with internal DC micro grids.

10.5 Conclusions

The scenarios illustrate that the way forward is difficult to predict and can take many forms. It is probable that events will occur that we cannot even imagine today, including unexpected shocks in international relations.

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

In 50–100 years' time, technical, economic and political conditions are likely to be radically different. Until then, it can only be imagined that there will be extensive technological innovation. Increasing global demand for limited energy supplies might promote emerging technologies for renewable energy and energy conservation. The use of fossil fuels might be reduced by high market prices and policy instruments. More efficient energy use might decrease the primary energy supply.

It is believed, therefore, that the direct impact of average climate change on energy supply and use will be small compared to the technical, economic and political changes that are possible.

Increased precipitation will be the most significant impact of climate change on energy supply. Total water inflow will increase significantly, which will enhance hydropower generation. Another substantial influence will be the fact that warmer winters will reduce heating demand and its seasonal variations. Better conditions for biomass growth may help to increase the use of biofuel. Climate change may increase winds slightly. Expanding wind-power production can largely be balanced by hydropower dams and demand response.

The Nordic energy situation is likely to undergo a change, because the Nordic and continental electricity systems are linked. Higher electricity costs could promote a switch from electricity to fuels, district heating or solar energy for heating. Local renewable resources can help to secure energy supply. An expansion of district heating enables more combined heat and power production, which has high efficiency.

10.6 Literature

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11 Conclusions

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By and large, the projected climate changes for the 21st century are beneficial for the development of renewable energy sources in the Nordic Region. The largest impacts are those estimated for the production of biomass. An increase in hydropower is also anticipated, although in some cases this may decrease again in the long run, with the melting of glaciers. The impact of climate change on wind power is found to be modest. The impact on solar power is least certain and could be negative, depending on cloud cover. However, the expected technological developments in energy production, distribution and consumption will, in all probability, be more important than the impact of actual climate changes, and these aspects need to be considered together.

For all energy sources, it will be necessary to adapt to changed conditions. Increased production of biomass can require more use of fertilisers, with their attendant possible environmental impact; changes in runoff will mean changes in the construction of hydro-power plants. Similarly, changes in wind pattern may require changes in the construction of wind turbines. Changes in some solar cells may also be necessary.

In all probability, the projected climate changes will be slow in comparison to the time it takes to replace energy production facilities. It will therefore be possible to replace them gradually. This, however, will require constant surveillance of the development of the climate.

Since we cannot know with certainty what the future has in store in the form of climate changes and technological developments, it is not possible to give definite recommendations, but it is clear that the world is moving towards greater integration, and this will also apply to the production, distribution and consumption of energy. In the long run, the problems described in this report should therefore be treated in a broader – at least European – context.

Appendix

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Abbreviations and acronyms

AOGCM	Atmospheric Ocean General Circulation Model
CE	The present Climate and Energy project
CHP	Combined heat and power
CWE	Climate, Water and Energy project
DRYPEAT	Model for calculation of harvest cycles of peat
ECHAM4/OPYC3	A global climate model from the Max Planck Institute for Meteorology in Hamburg, Germany
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSEMBLES	EU project on climate change and impacts
ERA40 – ECMWF	A 40-year re-analysis project
FACTS	Flexible Alternating Current Transmission System
GCM	General circulation model, a.k.a. global climate model
GDP	Gross domestic product
HadAM3H, HadCM3	Global climate models from the UK Meteorological Office's Hadley Centre
HBV	The hydrological model used in most of the hydrological simulations
HIRHAM	A regional climate model used at the Danish Meteorological Institute and the Norwegian Meteorological Institute
HIRLAM	High Resolution Limited Area Model
HYDROGEMS	Hydrogen Energy Model
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change (see www.ipcc.ch)
MM5	PSU/NCAR mesoscale model
MOGCM	Mixed layer ocean general circulation model

Mtoe	Megatons of oil equivalents
NAO	North Atlantic Oscillation
PRUDENCE	Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects, an EU-funded research project (see http://prudence.dmi.dk)
PV	Photovoltaic(s)
RCA	A regional climate model used at the Rossby Centre of the Swedish Meteorological and Hydrological Institute. RCA comes in different versions, such as RCA3 and RCAO.
RCAO	Rossby Centre Regional Atmosphere – Ocean model
RCM	Regional climate model
Sima	A growth and yield oriented ecosystem model
SOLGAIN	Project about passive solar gain in residential buildings in EU
SRES	Special Report on Emission Scenarios
WaSIM – ETH	Water Balance Simulation Model

RESUME P8 DANSK

Virkninger af klimaændringer på vedvarende energikilder – Deres rolle i det nordiske energisystem

Det er almindeligt accepteret at det menneskeskabte udslip af drivhusgasser påvirker varmebalancen i Jord–atmosfæresystemet og derigennem fører til globale klimaændringer. Størrelsen af disse ændringer vil afhænge af det fremtidige udslip af klimagasser og vil være forskellig i forskellige områder af Jorden. Men et centralt skøn for det nordiske område i år 2100 er at temperaturen vil være steget 3 °C, at det i gennemsnit vil regne omkring 10 % mere, og at havets vandstand kan være steget 40 cm.

Sådanne ændringer vil påvirke produktionen af vedvarende energi som spiller en vigtig – og voksende – rolle i de nordiske lande. Samtidigt vil temperaturstigningen påvirke forbruget af energi, i det væsentlige i form af energi brugt til opvarmning. Et studie af disse virkninger har været emnet for et projekt med flere underprojekter under *Nordisk Energiforskning.*

Klimamodeller

I det væsentlige benyttes to globale emissionsscenarier: IPCC scenarierne A2 og B2. Disse scenarier har været anvendt i globale klimamodeller, der typisk har en arealmæssig opløsning på nogle få hundrede kilometer. Det er imidlertid ikke nok for detaljerede studier, fordi indvirkningen af topografi, vejrfronter og forskellige former for ekstremer ikke tages tilstrækkeligt i betragtning. I dette projekt har klimagruppen derfor fremstillet forskellige regionale klimascenarier (produktionsscenarier) til brug for de grupper, der har arbejdet med forskellige former for vedvarende energi. Nedskaleringen blev i princippet udført ved at indlejre mere detaljerede regionale klimamodeller i resultaterne fra globale modeller.

De resulterende regionale klimascenarier indeholder en lang række klimaparametre. De grundlæggende resultater er i form af net af tids-serier, men findes også som middelværdier eller højere ordens statistik. Særlig vigtige er temperatur, nedbør og vind data, men også evapo-transpiration, sne og solstråling er vigtige for projektet.

De regionale klimascenarier dækker hver for sig (i) det nordiske landområde, Nordvestrusland og de baltiske stater, (ii) Island og (iii) Grønland med en 50 km opløsning. I alle tilfælde sigter scenarierne på perioden 2071–2100. For (i) er et mindre sæt af to scenarier tilgængelig for hele det 21. århundrede. Anvendelsen af forskellige modeller gav noget forskellige resultater, hvilket minder os om at klimaet – bortset fra forventningen om et signifikant ændret klima i fremtiden – ikke kan forudsiges nøjagtigt. Når man arbejder med klimaændringer og deres virkninger, er en erkendelse af forskellige scenarier en nødvendighed. Samtidig skal klimaforskning fokusere på usikkerheder.

Det erkendes at IPCC (Det mellemstatslige klimapanel) har udarbejdet en ny (fjerde) vurdering, som bliver udgivet i 2007. I betragtning af den generelle usikkerhed i effektstudierne betragtes de reviderede vurderinger som værende af mindre betydning for dette projekt.

Statistiske analyser

Studier af klimaændringer inkluderer vurderinger af scenarier for fremtiden og forsøg på at finde klimaændringssignaler i historiske data. Gruppen for statistiske data har fokuseret på det sidste. Tendenserne i historiske afstrømningsdata og klimaobservationer fra de nordiske og baltiske områder viser at tendenserne i års-afstrømningen styres af ændringer i nedbør, medens tendenser i sæson-afstrømningen og ekstremer i højere grad er påvirket af ændringer i temperatur. Det ses også, når man sammenligner regionale tids-serier af temperatur, nedbør og afstrømning. Således påvirker den observerede temperaturstigning kraftigt de hydrologiske regimer i de nordiske lande. Det indebærer, at hvis temperaturstigningen er et resultat af menneskeskabte klimaændringer, har afstrømningen ændret sig af samme årsag.

En kvalitativ sammenligning mellem resultaterne fra den statistiske analyse gruppe og de tilgængelige scenarier for afstrømning fra gruppen for hydrologiske modeller viste at de kraftigste tendenser svarer til de ændringer der forventes som følge af temperaturstigninger i scenarieperioden – fx øget vinterafstrømning og tidligere snesmeltnings-flom. Imidlertid er der også forventede ændringer som indtil nu ikke er afspejlet i tendenserne, fx den forventede vækst i efterårsafstrømning og efterårsflom. Det er ændringer, som i det væsentlige skyldes en forventet vækst i nedbør.

Foreløbige undersøgelser tyder på at variationer i vindenergi og vandkraft er positivt koblet i nogle områder via deres afhængighed af det synoptiske klima og storskala klimaet og således viser en fælles kilde til variationer.

Vandkraft

Vandkraft er p.t. den vigtigste vedvarende kilde til elektricitet i det nordiske område og er den vedvarende kilde, der er stærkest påvirket af klimaet. Den globale opvarmning vil afkorte den nordiske vinter og gøre den mindre stabil, og den vil forlænge afsmeltningssæsonen for gletsjere og indlandsis. Dette vil medføre en mere jævnt fordelt flodafstrømning henover året – en gunstig situation for vandkraftindustrien. Der er også et potentiale for forøget produktion af vandkraft, da den højest modellerede vækst i flodafstrømning simuleres i områder med kraftig udvikling af vandkraft dvs. de skandinaviske bjerge og Islands højland. Dette medfører at de fremskrevne hydrologiske ændringer kan forventes at have virkninger på design og drift af mange hydroelektriske kraftværker, og også på andre typer af brug af vand – i særdeleshed fra isdækkede højlandsarealer.

Det er en ulempe at den ny årlige rytme i afstrømning, der indikeres i simuleringerne, vil give et større pres på overfaldsdæmningerne. De må formentlig benyttes oftere om vinteren, da det ustabile vinterklima vil bevirke oftere pludselig indstrømning, når reservoirerne er fyldt op. Det vil også have en virkning på infrastrukturen med hyppigere oversvømmelsesproblemer for nedstrømsreservoirerne. Disse arealer er normalt tilpasset det nuværende klima med stabile vintre uden kraftig afstrømning mellem efterår og forår.

Global opvarmning giver således et nyt aspekt ved spørgsmålet om dæmningssikkerhed. Allerede i dag er dette en sag med stor bevågenhed og vurdering af design oversvømmelser udføres i Norge, Finland og Sverige. Vidtrækkende beslutninger skal træffes under stigende usikkerhed. Det må imidlertid ikke forhindre den nødvendige opgradering af det eksisterende hydroelektriske system. Kort sagt må kraftværksindustrien udvikle en ny strategi, som karakteriseres ved fleksibilitet. Fleksibilitet betyder at der må være muligheder for at ændre driftsplaner og korrigere designet af en struktur efter nye videnskabelige resultater med relation til virkninger af global opvarmning

De klimascenarier, der opstilles med forskellige modeller, varierer kvantitativt – i særdeleshed hvad angår i de områder der er mest udviklet med vandkraft i Norge og Sverige. Generelt er ændringer i afstrømning fra indlandsis en af de vigtigste konsekvenser af klimaændringer i Island, på Grønland og i nogle isdækkede områder i Skandinavien. Dette vil ikke alene påvirke vandkraftindustrien, men også veje og andre kommunikationslinier.

I det store og hele kan den årlige afstrømning fra gletsjere og indlandsis vokse 50–100 % indtil midten af dette århundrede og kan så, fordi voluminet af gletsjere aftager, igen falde. Nuværende værdier kan passeres omkring år 2200.

Vindkraft

Virkningerne af klimaændringer på vindenergi er mere beskedne end på vandkraft. Ændringer i den gennemsnitlige vindhastighed påvirker energiproduktionen, medens ændringer i ekstreme vindhastigheder, dække med havis og isdannelse på vindturbiner påvirker belastningen af møllerne og således deres design og pris. Derfor er klimaændringer i relation til produktionen af vindkraft i det væsentlige en forudsigelse af gennemsnit og ekstrem værdier af vindhastigheder.

Klimaændringer er analyseret med scenarier genereret med SMHI Rossby Centrets regionale atmosfære-ocean model. Inputtet fra klimamodellerne og scenarierne er af vindgruppen implementeret i værktøjerne for vurdering af vind ressourcer og design.

Ændringerne i den gennemsnitlige vindhastighed og i vindenergi potentialet i de nordiske lande forventes at blive beskedne. Af de to RCAO simuleringer i projektet, der bruger grænseværdier fra henholdsvis modellerne ECHAM4 og HadAM3H viser den første en tilvækst på 10–15 % i vindkraft potentialet, medens den sidste indeholder store områder med såvel stigninger som fald.

Der er fundet begrænset indflydelse på design for træthedsfænomener i vindmøller. Imidlertid blev der på nogle »off shore« lokaliteter fundet en vækst i ekstreme vinde i 10–15 % området, hvilket betyder at designet for ekstreme belastninger sandsynligvis vil blive påvirket for nogle dele af en vindmølle.

Resultaterne angiver signifikant mindre isdække i Østersøen både hvad angår varighed i dage og geografisk udstrækning. Dette kan til en vis grad påvirke vindenergien.

Solenergi

De mest solbeskinnede steder på Jorden modtager op til 2500 kWt/m^2 per år målt på en horisontal overflade. I det nordiske område er situationen mindre gunstig. Den årlige energidensitet varierer mellem 1100 kWt/m^2 i den sydlige del og 700 kWt/m^2 i den nordlige del. En solbeskinnet sommerdag uden skyer kan give omkring 8 kWt/m^2, medens en overskyet vinterdag kun giver 0,02 kWt/m^2. Derfor har brugen af solenergi i de nordiske lande indtil nu været begrænset til termiske systemer og »off-grid« solceller. Med en reduktion af omkostningerne ved produktionen af solceller kan denne situation ændre sig.

Påvirkningen fra klimaændringer på produktionen af solenergi skyldes i det væsentlige ændringer i indstråling (dvs. skydække) og temperatur. Ekstreme vejrbegivenheder kan kræve stærkere konstruktioner, men det vurderes at være af mindre betydning.

Termiske solsystemer er af tre principielt forskellige typer: Opsamling af varme gennem vinduer, omdannelse af varme i en kollekter og koncentration af solstråling i forskellige typer af reflektorer. Med enkeltlags vinduer er der et netto årligt tab af energi til omverdenen i de nordiske lande. Dobbelt lags isolerende glas er stort set neutralt, medens tre lags ruder med argon isolerende gas giver en netto energigevinst af solenergi. En yderligere udvikling kan fx være påfyldning af ædle gasser i tre lags vinduer, men større arealer af sådanne vinduer kan give for meget opvarmning om sommeren og kræve specielle systemer til distribution eller oplagring af varme. Forskellige typer af kollekter systemer bruges fx til at fremstille varmt vand eller til at opvarme svømmebassiner. Den teknologiske udvikling er i det væsentlige koncentreret om paneler, som kan integreres i bygningskonstruktioner.

Klimainducerede ændringer i energibalancen er blevet beregnet for Oslo og viser en lille netto gevinst i oktober-december og en netto reduktion i februar–april. Mere vigtig er en signifikant vækst i sommer månederne juli–august, som kan forøge behovet for afskygning eller køling og således forøge brugen af elektricitet.

Medens klimaændringerne således forøger outputtet fra termiske solsystemer, er situationen omvendt for fotoelektriske solceller, hvor outputtet aftager med temperaturen. Et reduceret snedække kan reducere refleksionen fra jordoverfladen og således den totale indstråling. Alt i alt kan det elektriske output blive reduceret fra nogle få procent i København til omkring 14–23 % i Helsingfors alt efter det anvendte scenario.

Biobrændsler

Indtil nu har der kun været få studier af klimaændringers virkning på potentialet af bioenergi. Dette delprojekt behandler følgende emner: Hvordan vil de fremskrevne klimaændringer påvirke: potentialet for produktion af tørv? potentialet for biobrændsler i skovbrug? og potentialet for overskudsproduktion af energiafgrøder på landbrugsjord? Biobrændsler betyder her biomasse produceret i landbrug og skovbrug og tørv udvundet i moser og anvendt til energiproduktion. I det store og hele vil de fremskrevne klimaændringer forøge potentialet for produktion af biobrændsler.

Produktionen af tørv afhænger af antallet af mulige høstkredsløb og vokser således med temperaturen. Den gennemsnitlige vækst i tørveproduktionen er 12 % i Finland, 16 % i Sverige og 9 % i de baltiske lande. Væksten i produktionspotentialet er 2400 GWt i Finland, 480 GWt i Sverige, 90 GWt i Estland, 36 GWt i Letland og 18 GWt i Litauen.

Produktiviteten i skovøkosystemer vokser ligeledes, mest i de centrale boreale skove fx i det centrale Finland og Sverige. I den sydlige del af Skandinavien og i de baltiske lande kan tørkeperioder dog reducere den væksttilvækst, som i øvrigt induceres af stigende temperatur og koncentration af CO_2. I gennemsnit vil biomassevæksten stige 10-20 % i de nordiske og baltiske lande.

Den totale primære produktion af potentielle energiafgrøder i det nordiske og baltiske område er 82 mio tons per år. Landbrugsafgrøder har et energiindhold fra 13 til 22 MJ / kg. Følgelig er den totale primære årlige energiproduktion af størrelsesordenen 1,3 EJ.

Energisystem analyse

Det er et væsentligt spørgsmål, hvordan disse klimabetingede ændringer vil påvirke det samlede energisystem. Som en forenkling er her kun behandlet elektricitetsdelen. I et første forsøg er virkningen på energisystemet i 2010 undersøgt. Her kan man gøre rimelige antagelser om efterspørgsel, fremstilling og transmissions kapacitet. Der kan også gøres antagelser om brændselsomkostninger og udvekslingspriser for det kontinentale Europa.

Analysen viser at den totale vandindstrømning til Nord Pool området vil vokse signifikant på grund af klimaændringer. Væksten i den totale indstrømning vil optræde om vinteren, hvilket vil reducere den sæsonbetingede variation. De fremskrevne temperaturændringer giver varmere vintre og således en mindre efterspørgsel efter energi og en mindre årstidsvariation. Begge disse faktorer vil reducere behovet for reservoirs til at flytte sommerindstrømningen til vinter produktion. Da vindenergi og vandkraft er baseret på naturlige ressourcer og produceres næsten uden marginale omkostninger, vil andre ændringer i elektricitetsproduktionen skyldes ændringer i disse to naturlige ressourcer. Klimascenarier giver kun mindre ændringer i produktionen af vindenergi.

På langt sigt (50–100 år) kan man forestille sig en væsentlig teknologisk udvikling. En åbenlys mulighed er lokale elektroniske systemer som moniterer netfrekvensen og udkobler køleskabe og andet udstyr i tilfælde af overbelastning. Dette vil i vidt omfang kompensere for variationer i energiproduktionen.

For at demonstrere mulighederne i udvikling er der opstillet tre scenarier for de næste 50 år. I det *centrale scenario* benyttes mange forskellige kilder til at sikre energiforsyningen med hovedvægten på lokale – ofte vedvarende – ressourcer. Tilpasning af elektricitetsforbruget ved demand/response kan hjælpe til at absorbere variationer i vindenergi. I et *høj vækst* scenario er kravet om elektricitet og andre energiformer meget højt og ny teknologi bruges til at transportere elektricitet over lange afstande, da konkurrencen finder sted i europæisk skala. Storskala teknologi til fremstilling dominerer. I et *grønt scenario* derimod er udviklet meget effektive teknologier og tung industri er mindre dominerende. Der er stærkt fordelt energiproduktion i lavenergi bygninger.

Scenarierne er ikke udviklet i detaljer, men i alle tre er der åbenlyse muligheder for tilpasning, da en moderat stigning i vandkraft og vindkraft produktion eller et aftagende behov for opvarmning og en stigning i air-condition kun vil have marginale konsekvenser for energisystemet. Også højere energipriser kan reducere forbruget.

Generel konklusion

I dette projekt har det ikke været muligt at behandle de forskellige energikilder ensartet, men den generelle konklusion er, at de forventede klimaændringer i løbet af de næste 100 år vil have signifikante virkninger på produktionspotentialet, specielt for vandkraft i det nordiske område. Disse virkninger må tages i betragtning i den kommende energiplanlægning. *De fleste virkninger er gunstige og ingen er katastrofale*. Den teknologiske udvikling i produktion, distribution og forbrug af energi vil imidlertid sandsynligvis være vigtigere og vil generelt set lette en tilpasning.

Vi ved ikke i detaljer, hvordan verden vil udvikle sig, og klimafremskrivninger er derfor kun tentative. Yderligere må det erkendes at vi lever i en verden som i stigende grad bliver integreret – også hvad angår produktion, fordeling og brug af energi. Derfor er en isoleret vurdering af situationen i det nordiske område udover nogle få årtier tvivlsom, og en løbende vurdering af situationen er påkrævet.

Hvad der sker i de kommende århundreder ligger uden for målsætningen i dette projekt. Det skal blot erkendes at klimaændringer sandsynligvis ikke stopper i år 2100 – og det gør de nødvendige tilpasninger heller ikke.