Comparative assessment of hydrogen storage and international electricity trade for aDanish energy system with wind powerand hydrogen/fuel cell technologies

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Final Report

Energy Research Programme of the Danish Energy Authority, project EFP05 033001/033001-0021

Comparative assessment of hydrogen storage and international electricity trade for a Danish energy system with wind power and hydrogen/fuel cell technologies

by
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Preface

This report is the final outcome of a project entitled “Comparative assessment of hydrogen storage and international electricity trade for a Danish energy system with wind power and hydrogen/fuel cell technologies”, carried out for the Danish Energy Agency under its Energy Research Programme EFP05 (2005-2007).

In addition to the present final report, the project has spawned out a number of research articles and conference papers:

Forord

Den foreliggende tekst udgør slutrapport for et projekt med titlen ”Sammenlignende vurdering af brintlagring og international elektricitetshandel for dansk energisystem med vindkraft og brint/brændselscelle-teknologier”, gennemført for Energistyrelsens Energiforskningsprogram EFP05 (2005-2007).

Udover nærværende slutrapport har projektet indtil nu affødt fgl. forskningspublikationer og konferenceindlæg:

B. Sørensen. Scenarios for the roles of hydrogen in a future energy system based on renewable energy. In Proc. 5th int. Conf. Hydrogen economy and hydrogen treatment of materials, Donetsk, Ukraine, May 2007, Vol. 1, pp. 77-83. (and submitted for publication in IJHE).

B. Sørensen. Large-scale renewable energy and hydrogen scenarios using power trade or energy storage to cope with supply-demand mismatch. In Proc. Hydrogen & Fuel Cells, Vancouver, Canada, CD-ROM May 2007.

B. Sørensen. Guest editorial: Renewable and hydrogen energy technologies. *Int. J. Energy Res.* (2007) Published online on www.interscience.wiley.com DOI: 10.1002/er.1370

B. Sørensen. A sustainable energy future: construction of demand and renewable energy supply scenarios. *Int. J. Energy Res*. (2007). Published online on www.interscience.wiley.com DOI: 10.1002/er.1375

B. Sørensen. A renewable energy and hydrogen scenario for Northern Europe . *Int. J. Energy Res.* (2007). Published online on www.interscience.wiley.com DOI: 10.1002/er.1376

B. Sørensen. Underground hydrogen storage in geological formations, and comparison with other storage solutions. In Proc. Hydrogen Power Theoretical and Engineering Int. Symposium (HYPOTHESIS VII), Merida, Mexico, CD-ROM March 2007.

The above papers by Bent Sørensen can be downloaded from http://energy.ruc.dk

K. Karlsson, P. Meibom. Integration of Hydrogen as Energy Carrier in the Nordic Energy System. In Proc. World Hydrogen Energy Conference, Lyon, France, CD-ROM May 2006

K. Karlsson, P. Meibom. Optimal investment paths for future renewable based energy systems – Using the optimisation model Balmorel. Conference, Dubrovnik, 2007

K. Karlsson, P. Meibom. Optimal investment paths for future renewable based energy systems – Using the optimisation model Balmorel, *Int. J. Hydrogen Energy* (Accepted)

Copies of his report may be downloaded from the **Roskilde University Digital Archive** at http://rudar.ruc.dk/handle/1800/2431 or at http://energy.ruc.dk under reports.

1. Overview of the project and its results.

The requirements of the project assignment may be summarised as follows:

- Simulation of an energy system with a large share of wind power and possibly hydrogen, including economic optimisation through trade at the Nordic power pool (exchange market) and/or use of hydrogen storage. The time horizon is 50 years.
- Formulating new scenarios for situations with and without development of viable fuel cell technologies.
- Updating software to solve the above-mentioned problems.
- Dissemination of results through conferences and publications.

We addressed the three first items as described in the following chapters, the content and main conclusions of which are briefly described here. Dissemination efforts in addition to this report (available on the web) are through the articles mentioned in the preface. The project is a follow-up of the earlier project "Hydrogen as an energy carrier – scenarios for future use of hydrogen in the Danish energy system", finished in 2001 (English summary is referenced in Ch. 2 below).

The current project has identified a range of scenarios for all parts of the energy systems, spanning most visions of possible future developments (Chapter 2). Detailed time-simulations have been made for a few of them. They are presented in Chapter 3. The single scenario of the 2001-study found that fluctuations in wind power production could be handled with a hydrogen store capable of storing 3 weeks of average power demand. The current project looks at the prospects for increasing the energy production from wind and biomass, in order to create a surplus for export (likely to Germany, because that country finds it difficult to cover all energy demands by renewable energy). That decreases the storage need to one week of average demand, for Denmark in isolation.

1. Oversigt over projektet og dets resultater

Projektbeskrivelsens krav kan sammenfattes således:

- Simulering af energisystem med stor vindandel og evt. brint, inkl. økonomisk optimering ved handel på den Nordiske elbørs og/eller ved brug af brintlagring. Tidshorisont 50 år.
- Formulering af nye scenarier for situationer med og uden udvikling af rentable brændselscelleteknologier.
- Til ovenstående formål nødvendige opdateringer af modeller.
- Formidling via konferencer og tidskriftsartikler.

Vi har løst de tre første opgaver som beskrevet i de følgende kapitler, hvis indhold og hovedkonklusioner kort beskrives her. Formidlingsaspektet er varetaget gennem denne på nettet tilgængelige rapport, samt gennem de i forordet nævnte artikler. Arbejdet skal ses som en forlængelse af det tidligere projekt afsluttet i 2001 med slutrapporten "Scenarier for samlet udnyttelse af brint som energibærer i Danmarks fremtidige energisystem" (RUC: Tekster fra IMFUFA nr. 390 og engelsksprogede artikler nævnt i referencelisten sidst i Kapitel 2).

En vifte af nye scenarier er opstillet (kapitel 2) og udvalgte blandt dem er simuleret tidsmæssigt over året (kapitel 3). De vises alle at være gennemførlige. Det tidligere projekt så kun på Danmark og fandt at indførelsen af brint produceret fra vindkraft kunne klares med en brintlagerkapacitet på 3 ugers middelforbrug. Ved at forøge den danske vindkraftproduktion med blik på eksportmulighederne (især til Tyskland, som ikke selv har vedvarende energi til at dække hele sit energibehov), finder nærværende projekt at der kun er brug for en lagerkapacitet på én uges middelforbrug, hvis vindkraftens fluktuationer i Danmark alene håndteres gennem lagring.

Increased energy production implies a lower requirement for energy storage, As seen from the power duration curves in Chapter 3, even the dispersed placement of wind turbines within Denmark is enough to avoid zero power production for more than at most a few hours a year. Thus the coverage of domestic demand increases, if exports are confined to hours of higher production. This is indeed possible, because the importing country, Germany, would primarily use this power for hydrogen production (to use in transportation sector).

Alternatively, the handling of fluctuating wind power production may be done be operating a coordinated Nordic energy system, where large-scale import and export of power is enabled. All Nordic countries are assumed to have wind power installations in suitable locations (with a swept area of at most 0.1% of the land surface area) and to produce biofuels from biomass residues (from agriculture or forestry). The countries currently possessing hydropower are assumed to maintain it at unaltered capacity. The presence of reservoir-based hydropower further diminishes the problem of wind power fluctuations, without noticeable impact on reservoir water levels. It is found that for most demand scenarios, the Nordic countries can more than satisfy the German renewable energy deficit by a combination of electricity and biofuel exports, without using the identified maximum potential. This also means that variations in each of the resources between years are not likely to pose a problem. As a result, a very robust energy system is available for the North European region, based on 100% renewable energy.

The Balmorel model (www.balmorel.com) has been used to analyse the long-term integration of wind power production focusing on the possibilities given by:

- Hydrogen production and hydrogen storage
- Power exchange between countries

For this purpose the Balmorel model has been extended to include production, storage and consumption of hydrogen.

At forøget produktion nedsætter lagringsbehovet for den danske del af systemet følger klart af at varighedskurven for en udspredt lokalisering af de danske vindkraftanlæg altid er positiv, dvs. over nul (se Figur 6 i Kapitel 3). Herved bliver antallet af timer med produktion under dansk efterspørgsel formindsket, når den installerede effekt vokser.

Hvis de Nordiske el-systemer i stedet samkøres i et scenarie hvor der bruges vedvarende energi i alle landene, findes at forskelle i vindproduktions tidslige variationer yderligere minimerer behovet for energilagring. De Nordiske lande vil ved en udbygning af vindenergi begrænset til under 0.1% af landarealerne samt anvendelse af residuer fra land- og skovbrug få en overskudsproduktion ca. dobbelt så stor som det underskud der i et tilsvarende scenarie findes i Tyskland (pga. mindre areal egnet for vindproduktion). Herved åbnes muligheden af en betydelig eksportindtægt. Da det yderligere fortrinsvis er el til produktion af brint (til transportsektoren), som Tyskland efterspørger, betyder det mindre at overskudsvindkraften varierer. Men selv om det skulle ses som et problem, fx for prisdannelsen, kan det nemt afhjælpes ved at de Nordiske landes vandkraft varierer sin produktion i modfase med vindens fluktuationer. Som tidligere undersøgelser har vist, giver det kun marginale variationer i vandstanden af de Nordiske vandkraft-reservoirer. Der bliver således tale om et meget robust system, både i tilfælde af andre forbrugsscenarier end de her betragtede, og også i forsyningssikkerhed, på grund af forsyningsanlæggenes udspredte karakter og fordi vind og biomasse supplerer hinanden i transportsektoren, så variationer i vindkraft, vandkraft og biomasseproduktion fra år til år kan udglattes. Det er nemlig ikke sandsynligt at alle tre energikilder vil være lave i et givet år.

Balmorel-modellen (www.balmorel.com) er blevet brugt til at analysere integration af vindkraft på langt sigt med fokus på mulighederne givet ved:

- Hydrogen produktion og lagring.
- Eludveksling mellem lande.

Two studies have been carried out with Balmorel and are presented in Chapter 4:

1. Investigation of a possible long term investment path from 2005 until 2050 for the Nordic energy system focussing on renewable energy in the supply sector and on hydrogen as the main fuel for road transportation, covering up to 70 percent of all road transport in 2050. The transformation during time from a mainly fossil fuel based to a mainly renewable energy based energy system was the focus of this study.

2. Calculation of the economic optimal power system configuration for the Nordic countries and Germany in 2060 assuming a nearly 100% coverage of the energy demands in the power, heat and transport sector with renewable energy sources. Different assumptions about the future success of fuel cell technologies have been investigated as well as different electricity demand assumption.

The results of both studies depend on the assumptions done which among other thing encompass the energy demands for electricity, heat and transport, and the technology data e.g. investment costs. Making studies covering 2050-2060 off course make such assumptions very uncertain. The studies performed should therefore more be seen as illustrations of future energy systems that due to the modeling methodology are the most costs efficient under the assumption made, while obeying a number of technical restrictions concerning demand-supply matching and the usage of power plants and transmission lines.

A main conclusion of study 1 is that with an oil price at 100 US$/barrel and technology costs as listed in table 3, it is economical optimal to cover 95 percent of the power and district heat production in the four Nordic countries by renewable energy in 2050. Only remaining non-renewable plants are the new Finnish nuclear power plant and a few natural gas fired heat boilers. The modelled energy system supplies the transport sector with hydrogen produced by electrolysis and steam reforming of natural gas. In 2050 this means

Balmorel-modellen er derfor blevet udvidet til at inkludere produktion, lagring og forbrug af hydrogen. To studier er blevet gennemført og præsenteres i kapitel 4:

1. Undersøgelse af et muligt investeringsspor fra 2005 til 2050 for det Nordiske energisystem med fokus på vedvarende energi i forsyningssektoren og hydrogen som det dominerende brændsels indenfor vejtransport dækkende op til 70 % af al vejtransport i 2050. Transformationen i løbet af tidsperioden fra et fossilt domineret til et vedvarende energi domineret energisystem var hovedformålet med dette studie.

2. Beregning af den økonomisk optimale konfiguration af energisystemet i de Nordiske lande og Tyskland i 2060 under forudsætning af næsten 100 % dækning af energibehovene i el-, varme- og transportsektorerne med vedvarende energikilder. Forskellige antagelser angående den fremtidige succes af brændselscelleteknologierne samt forskellige antagelser angående udviklingen i el- og varmebehovene er blevet undersøgt.

Resultaterne af begge studier afhænger af de gjorte antagelser bl.a. angående energibehovene for el, varme og transport samt angående teknologidata f.eks. investeringsomkostninger. Den lange tidshorisont for studierne, 2050-2060, gør disse antagelser meget usikre. De udførte studier skal derfor mere vurderes som illustrationer af fremtidige energisystemer, som pga. modelleringen er de mest omkostningseffektive under de gjorte antagelser, samtidig med at de overholder en række tekniske restriktioner angående balancering af efterspørgsel og forbrug samt brug af kraftværker og eltransmissionslinier.

En hovedkonklusion i studie 1 er at forudsat en oliepris på 100 US$/tønde og teknologiomkostninger som angivet i Tabel 3, er det økonomisk optimalt at dække 95 % af el- og fjernvarmeproduktionen i de fire Nordiske lande med vedvarende energi i 2050. De eneste eksisterende værker i 2050 som ikke benytter vedvarende energikilder er det nyeste Finske kernekraftværk og nogle få naturgasfythat 65 percent of the transport work in the Nordic countries is based on renewable energy. A system power price can be derived from the model and in 2050 the yearly average power price in the scenario is 55 €/MWh and hydrogen is produced at a price around 17 euro/GJ (yearly average).

The study of the all renewable energy scenarios for the energy, heat and transport sectors in Germany and the Scandinavian countries in 2060 showed that under the assumptions made, it is feasible to fulfil the energy demands with renewable energy sources coming from within the countries. Furthermore a doubling of the electricity and heat demand relatively to the base case could be covered with renewable energy sources. Germany is the big consumer of energy relatively to the Scandinavian countries, so there is a large import of electricity into Germany coming from hydropower in Norway and Sweden and wind power from mainly Denmark, and a large import of biomass from the forests of Sweden, Finland and Norway. The need for electricity imports into Germany leads to a significant increase in the transmission capacities between Norway and Denmark, and between Denmark and Germany.

Germany uses solar panels and CHP plants using biomass to produce heat, whereas the Scandinavian countries use electricity in heat pumps.

The variability of wind power production was handled by varying the hydropower production and the production on CHP plants using biomass, by power transmission, by varying the heat production in electric heat boilers, and by varying the production of hydrogen in electrolysis plants in combination with hydrogen storage. Investment in hydrogen storage capacity corresponded to 1.2% of annual wind power production in the scenarios without a hydrogen demand from the transport sector (ESTO and NOFC), and approximately 4% in the scenarios with a hydrogen demand from the transport sector (FC and HDFC), i.e. only a small fraction of the wind energy production was needed to be stored as hydrogen. The storage capacities of the electricity storages

rede varmekedler. Det modellerede energisystem forsyner transportsektoren med hydrogen produceret ved elektrolyse og dampreformering af naturgas. Dette betyder at 65 % af transportarbejdet i 2050 i de Nordiske lande er baseret på vedvarende energi. En systempris for el bliver beregnet af modellen og i 2050 er den årlige gennemsnitlige elpris 55 Euro/MWh. Den årlige gennemsnitlige produktionspris i 2050 for hydrogen er 17 euro/GJ.

Studiet af vedvarende energiscenarierne for el-, varme- og transportsektorerne i Tyskland og de Skandinaviske lande i 2060 viste at under de gjorte antagelser er det muligt at tilfredsstille energibehovene med vedvarende energikilder, der eksisterer indenfor landene. Endvidere kunne en fordobling af el- og varmebehovene i forhold til basisniveauet dækkes af vedvarende energikilder. Tyskland er den store energiforbruger i forhold til de Skandinaviske lande, så der er en stor import af el til Tyskland produceret på vandkraftværkerne i Norge og Sverige samt vindkraft produceret hovedsageligt i Danmark, samt en stor import af biomasse fra skovene i Finland, Norge og Sverige. Behovet for elimport til Tyskland leder til en kraftig forøgelse af eltransmissionskapaciteterne mellem Norge og Danmark, og mellem Danmark og Tyskland.

Tyskland bruger solvarme og biomassefyrede kraft-varmeværker til at producere varme, mens de Skandinaviske lande bruger elvarmepumper.

Variabiliteten i vindkraftproduktionen bliver håndteret ved at variere vandkraftproduktionen og produktionen på biomassefyrede kraftvarmeværker, ved eltransmission mellem landene, ved at variere varmeproduktionen fra elvarmekedler, og ved at variere hydrogenproduktionen i elektrolyseanlæg i kombination med hydrogenlagring. Der investeres i hydrogenlagre svarende til 1.2 % af årlig vindkraftproduktion i scenarierne uden hydrogenefterspørgsel fra transportsektoren (ESTO og NOFC), og ca. 4 % i scenarierne med hydrogenefterspørgsel fra transportsektoren (FC og HDFC), dvs. kun en lille provided by plug-in hybrid electric vehicles in ESTO were too small to make hydrogen storage superfluous.

Overall, we find that the question of energy storage is less important in a system with generous surpluses of renewable supply options (despite variability), when trade options allow energy exchange between regions having different profiles of potential-supply variations.

Chapter 2 discusses sustainable energy futures in broad generality, by construction of demand and renewable energy supply scenarios under a wide range of social assumptions for a period of 50 years ahead.

In Chapter 3, a renewable energy and hydrogen scenario for northern Europe is constructed, and supply-demand matching simulations are carried using the NESO software out to determine how much each country can do by itself, and how much energy import/export is needed.

Economic optimisation using BALMOREL software are presented in Chapter 4, basically for the CHP (combined heat and power) sector but with aggregate energy supply for transport. Sensitivity to price assumption is demonstrated.

Work on a more detailed modelling of the transportation sector in the BALMOREL software is described in Chapter 5.

An Appendix gives selected technology assumptions specific to the present project. (i.e. those different from what is available in the standard technology catalogues provided by the Danish Energy Authority).

andel af vindkraftproduktionen behøves at blive lagret som hydrogen. Ellagringskapaciteterne af ellagrene i plug-in hybrid elektriske elbiler i ESTO var for små til at gøre hydrogenlagring overflødig.

Imidlertid forekommer spørgsmålet om lagring mindre vigtigt and vi forestillede os ved projektets start, fordi det mindre totalbehov for lagring som de rigelige produktionsmuligheder bevirker gør at projektets resultater udnævner handelsmulighederne med den deraf følgende udbygning af transmissionskapacitet mellem landene som de mest interessante løsninger til energipolitisk overvejelse.

Kapitel 2 leverer en bred diskussion af bæredygtige energifremtider gennem konstruktioner af scenarier for hver del af energisystemet., for en bred vifte af samfundsmæssige udviklinger over de næste 50 år.

I kapitel 3 opstilles et vedvarende energiscenarie for Nordeuropa, og der foretages tidssimuleringer med programmet NESO, først for hvert land isoleret, og derefter med mulighed for energihandel mellem landene.

Kapitel 4 leverer optimeringskørsler med programmet BALMOREL, for en model med nogle sektorer aggregeret. Uafsluttet arbejde på en udvidet transportmodel i BALMOREL beskrives i kapitel 5.

Opdaterede teknologidata (relativt til Energistyrelsens) nødvendige for dette projekt gives i et appendix.

Chapter 2: A sustainable energy future: Construction of demand and renewable energy supply scenarios.*

SUMMARY

The creation of energy scenarios, usually describing future situations of interest, involves three steps: 1: Determining the activities in the target society that involves energy of one or another form. Examples of carrying out such an analysis are presented, with end-use demands distributed on energy forms (qualities) as the deliverable outcome. 2: Determining the available energy resources in the society in question. This is done for renewable energy resources and presented as potential energy supply, with a discussion of the aggressivity of exploiting such sources. Finally 3: Matching demand and supply under consideration of the energy forms needed, with use of intermediate conversions, storage and transmission, and signaling unused surpluses that may be exported from the society in consideration, or deficits that have to be imported. An example of such a matching is presented in an accompanying article.

KEY WORDS: scenario technique, energy modelling, demand analysis, supply assessment, resource appraisal

1. ENERGY SYSTEM MODELLING – GENERAL CONSIDERATIONS

The aim of the present work is to model a range of options for the future energy system of a given society, say a country, with consideration of the surrounding energy systems (such as those of neighbouring countries) that may come into play by exchange of energy including purchase of fuels or other energy services. Due to the considerable inertia in the system, caused by existing equipment and infrastructure, the time horizon is chosen as around fifty years, in order to capture the possibility of a complete change in the mix of energy sources and the ways of converting, transmitting and using energy in society. It is thus the target of the study to provide material for decision-makers that may help them in selecting an optimal energy solution with high economic benefits for the society in question. On the other hand, going thus far into the future induces uncertainties and necessitates the formulation of assumptions that may turn out to be incorrect. For this reason, the methodology selected is that of scenario analysis, renouncing on finding a single optimal solution and instead analysing a number of alternative scenarios for their advantages and disadvantages. This will enable decision-makers to apply their preferred weights describing the importance of various factors such as direct economy, environmental impacts including climate change, supply security and robustness against (at least some) errors in assumptions. The scenarios contemplate a number of solutions based on equipment or strategy not fully developed or tested. Although surprises in terms of new solutions appearing within the planning period are possible, the method employed makes them less probable, because the 50-year horizon is short enough to make it highly likely that all technologies that can be made ready within that period are already known at present, in some (possibly early) stage of development and readiness.

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2. ENERGY SYSTEM MODELLING – METHODOLOGY

2.1 Demand options

The definition of energy demand used here is true *end-use energy*, i.e. the energy derived after the final conversion taking place at the end-user for supplying some demanded energy service. This energy can be defined rigorously once the demand of energy services is determined, on the basis of a vision of the activities of the future society (Sørensen, 2004, Chapter 6).

This definition is independent of the efficiency of the possibly several energy conversion steps taking place between primary energy and end-use energy service. These important aspects will be discussed in section 2.2, and together with the end-use energy they determine the entailed requirement for primary energy supplies.

In order to model energy trade between the country focussed upon and its neighbours, the patterns of surplus and deficit must be determined (as function of time) for each region. This implies that demand scenarios and conversion efficiency assumptions have to be made not only for say Denmark, but also for the energy exchange partners such as the Nordic countries and Germany, which are already connected to Denmark by electric power grids. If the primary interest is on a single country, the demand models for the neighbouring countries do not have to be as detailed as for the primary country, but in many cases, simultaneous studies of a croups of countries with energy-connections is the objective.

The following is a list of relevant precursor end-use demand scenarios, using Denmark and its neighbouring countries as an example but still retaining a level of generality. By "precursor scenarios" is meant a set of preliminary scenarios, out of which final scenarios may be selected for closer investigation. The basis for the precursor scenarios are assumptions regarding desirable activity levels and energy intensities of the activities, as they have appeared in the energy debates in recent years, in Denmark and in Europe broadly. They claim no completeness, but try to display enough diversity to serve as a useful span of the challenges facing the energy planner. Out of these, a more limited number of scenarios will typically subsequently be selected or reformulated for closer discussion and concrete simulation efforts.

a) Run-away precursor scenario.

In the run-away scenario, the energy demand grows at least as quickly as the overall economic activity (measured e.g. by the gross national product). This has historically been the case during periods of exceptionally low energy prices, notably in the years around 1960. Conditions for this scenario, in addition to low energy prices, would include measures such as encouraging transportation work (many passenger-kilometres facilitated by more roads, cheap air connections and decentralisation of the locations of homes, work places and leisure facilities, many ton-kilometres of freight haul facilitated by decentralisation of component production and shipment of small-size cargos). In the building sector, more square metres of living space and more square metres per unit of economic activity, and in the electricity sector, more appliances and other equipment. Building style developments could create a perceived need for air conditioning and space cooling. For industry, there could be increased emphasis on energy-intensive production, although this is hardly relevant for countries such as Denmark. However, service sector activities and their energy use could increase substantially, with retail shopping areas greatly increased and use of business-promotion by light and other energy-demanding displays. For leisure activities, traditional nature walks or swimming could be replaced by motocross, speedboat use and other energy-demanding activities, similar to the habits already seen to expand in North America.

b) High energy-growth precursor scenario.

The high energy-growth scenario is similar to the run-away scenario, but with a slower increase in energy demand. This could in the transportation sector be due to a certain saturation tendency in transport activities, due to higher value placed on the time lost in travelling on more congested roads and in more congested air space. For industry, continued decrease in energy-intensive production may lead to a demand growing less than the economic activity. In buildings, heat use may increase less than floor area, due to zoning practices etc. Generally, activity level and energy demand may see a certain amount of decoupling, reflecting the fact that the primary demands of a society are goods and services, and that these can be provided in different ways with different energy implications. A certain effect of this type damps the energy demand in the high energy-growth scenario as compared with the run-away scenario, but due more to technological advances and altered Danish industry mix than to a dedicated policy aimed to reduce energy demand.

c) Stability precursor scenario.

The stability scenario assumes that the end-use energy demand stays constant, despite rearrangements in specific areas. Specifically, the energy demand in the building sector is assumed to saturate (considering that the number of square metres per person occupying the building, whether for work or living, will not continue to increase, but reach a natural limit with enough space for the activities taking place, but not excessive areas to clean and otherwise maintain). In the industry sector, an increasingly knowledge-based activity will reduce the need for energy-intensive equipment, replacing it primarily by microprocessor-based equipment suited for light and flexible production. Industrial energy use will decline, although industry like the service and private sectors will continue to add new electronic equipment and computers. In other sectors, dedicated electricity demand will increase substantially, but in absolute terms more or less compensated for by the reductions in the industry sector. For transportation, saturation is assumed both in number of vehicles and number of passenger- or ton-kilometres demanded, for the reasons outlined above (in the section on the high energy growth scenario). Reasons for considering this possible could include the replacement of conference and other business travel by video conferencing, so that an increase in leisure trips may still be included. Presumably, there has to be planned action for this to be realistic, including abandoning tax-rebates for commercially used vehicles and for business travel, and possibly also efforts in city planning to avoid the current trend of increasing travel distances for everyday shopping and service delivery. The stability scenario was used as the only energy demand scenario in an earlier study on the possibilities for hydrogen in the Danish energy system (see Sørensen *et al.*, 2001; 2004, Sørensen, 2005).

d) Low energy-demand precursor scenario

In the low energy-demand scenario, full consideration is paid to the restructuring of industry assumed for countries such as Denmark, from goods-orientation to service-provision. Already today, many Danish enterprises only develop new technology and sometimes test it on a limited Danish market: once the technology is ready for extended markets, the production is transferred to other companies, usually outside Denmark. This change in profit-earning activities has implications for the working conditions of employees. Much work can be performed from home offices, using computer equipment and electronic communications technology and thereby greatly reducing the demand for physical transportation. Also in the retail food and goods sector, most transactions between commerce and customer will be made electronically, as it is already the case in a number of sub-sectors today. An essential addition to this type of trade is the market for everyday products, where the customers until now has made limited use of electronic media to purchase grocery and food products, probably by reasons of a perceived need to e.g. handle the fruit to see that it is ripe before buying it. Clearly, better electronic trade arrangements with video inspection of actual products could change the reservations of current customers. If everyday goods are traded electronically, the distribution of such goods will also be changed to an optimal dispatch requiring considerably less transport energy that today's personal shopping. All in all, a quite substantial reduction in energy demand will emerge as a result of these changes, should they come true. The economic development is further de-coupled from energy use and may continue to exhibit substantial growth.

e) Catastrophe precursor scenario.

In the catastrophe scenario, a reduced energy demand is due to the failure to achieve a desirable economic growth. In the case of Denmark, reasons could be the current declining interest in education, particularly in those areas most relevant to a future knowledge society. In this scenario there would be a lowering of those enabling skills necessary for participating in the international industry and service developments, and the alternative of importing these intellectual skills is seen as having been missed by an immigration policy unfavourable to precisely the regions of the world producing a surplus of people with technical and related creative high-level education. Although there are pessimists that see this scenario as the default, i.e. the situation Denmark is moving towards unless strong policy measures are taken in the near future, the stance here is that the traditional openness of the Danish society will also this time work to overcome the influence of certain negative elements. A key reason that this may be likely is the smallness of the Danish economy in the global picture, implying that even if Denmark should choose to concentrate on less education-demanding areas such as coordination and planning jobs in the international arena (requiring primarily language and overview skills), these could easily provide enough wealth to a nation of open-minded individuals willing to serve as small wheels in larger international projects. This would make the economic decline a passing crisis to be followed by the establishing of a small niche existence for Denmark, which in energy terms would imply returning to one of the central scenarios described above. Only in case Denmark becomes internationally isolated, will this option fade away and the catastrophe scenario become reality. For other countries, some aspects of these threats are also evident, but the discussion will have to be repeated for each country on its specific premises.

2.2 Energy conversion system

Countries such as Denmark have a long tradition for placing emphasis of efficient conversion of energy. Following the 1973/4 energy crises, particularly detached homes (where the occupants are also the owners making decision on investments) were retrofitted to such an extent that the overall low-temperature heat use in Denmark dropped by 30% over a decade. CO_2- and pollution-taxes on electricity has probably been a significant cause of the appliance-purchasing pattern, where the lowest energy-consuming equipment has taken a dominant part of the market. The same trend is at least partially seen in automobile purchasing, where a non-linear energy-efficiency dependent annual registration tax has made the sale of the most energy-efficient vehicles much higher in Denmark than in other European countries with similar fuel costs. This trend is only partial, because there is still a substantial sale of luxury cars and 4-wheel-drive special utility vehicles not serving any apparent purpose in a country with hardly any non-paved roads. If the initial registration tax on automobiles were similarly made energy efficiency-dependent, the effect would be much greater. The Danish utilities are known for constructing some of the highest-efficiency conventional power-and heat plants in the world (using coal, natural gas and wood scrap or other biomass-based fuels), and Danish wind turbines are also known for high efficiency. The transmission losses are fairly low, but Denmark currently has a smaller coverage with underground coaxial cables that many other European countries, resulting in continued vulnerability during storms, for the remaining overhead lines. This, however, is finally in the process of being remedied.

Upon this background, it is expected that the conversion efficiency will continue to improve in all areas, from primary over intermediate to end-use conversion. However, it might still be a good idea to consider more than one scenario, for Denmark and particularly for other countries that are currently not very far along the route to energy efficiency. The following are three precursor scenario suggestions:

α) Laisser-faire precursor scenario

In the laisser-faire scenario, conversion efficiencies are left to the component and system manufacturers, which would typically be international enterprises (such as vehicle and appliance manufacturers, power station and transmission contractors, and the building industry). The implication is that efficiency trends follow an international common denominator, which at least in the past has meant lower average efficiency than suggested by actual technical advancement and sometimes even lower than the economic optimum at prevailing energy prices. Still, the efficiency does increase with time, although often for reasons not related to energy (for example, computer energy-use has been lowered dramatically in recent years, due to the need to avoid component damage by the excess heat impact from high-performance processors). The gross inadequacies of the current system, deriving from the tax-exemption of international travel and shipping by sea or air (as imposed by the WTO) and its impact of choice of transportation technology, are assumed to prevail.

β) Rational investment precursor scenario

In the rational investment scenario, the selection of how many known efficiency measures, that will actually be implemented through the technologies chosen at each stage in the time development of the energy system, will be based on a lifetime economic assessment. This means that the efficiency level is not chosen according to a balancing of the cost of improving efficiency with the current cost of energy used by the equipment, but with the present value of all energy costs incurred during the lifetime of the equipment. This assessment requires an assumption of future average energy costs and it is possible by choice of the cost profile to build in a certain level of insurance against surprises from higher-than-expected energy prices. The important feature of the rational investment scenario is that it forces society to adopt a policy of economic optimisation in the choice of energy-consuming equipment and processes. This is partially implemented at present, e.g. through the energy provisions in building codes, through appliance labelling and through vehicle taxation. In the latter case, there is a distinction between the efficiency optimisation for a vehicle with given size and performance, considered here, and the question of proper vehicle size and performance characteristics dealt with in the previous section on end-use energy. The current energy taxation for passenger cars does not make such a distinction, and the tax reduction for commercial vehicles actually counters rational economic considerations and should rather be characterised as taxpayers subsidising industry and commerce.

γ) Maximum efficiency precursor scenario

The maximum efficiency scenario could be based on the idea that every introduction of new energy-consuming equipment should be based on the best current technical efficiency. This would imply selecting the highest-efficiency solution available at the marketplace, or even technology ready for but not yet introduced into the commercial market. Higher-efficiency equipment under development and not fully proven would, however, not be implemented, except for as parts of demonstration programmes. This “best current technology” approach was used in several previous scenario studies (Sørensen, 2004; 2005; Sørensen and Meibom, 2000; Sørensen *et al.*, 1999, 2001, 2004) with the reasoning, that the currently best-efficiency technology would be a good proxy for the average-efficiency technology some 50 years into the future. Depending on the assumptions regarding future energy prices, the rational investment scenario could be less efficient, of similar efficiency or of higher efficiency than what is offered by the “best current equipment” approach.

A maximum efficiency scenario better reflecting its name would in this light be defined by making projections regarding the typical average efficiency improvements over the planning period, and then by insisting that the best technology at each instant in time is used for all new equipment introduced at that moment in time. While projections on future efficiency of individual pieces of equipment may be uncertain and sometimes wrong, it appears reasonable to assume that average efficiencies over groups of related equipment can be extrapolated more reliably.

2.3 Supply options

Basic energy supply is important in all scenarios, because the technologies for further conversion depend on the type of primary energy used (through factors such as physical form (gas, liquid or solid), energy quality, temporal and geographic patterns of provision). Further important considerations relate to reliability of supply, with issues such as resource depletion and stability of trading partners being crucial.

The present study is based on the premise that fossil fuels are a temporary solution due both to depletability and to their emission of pollutants and greenhouse gases. In the case of oil, the concern over resource depletion is large, with North Sea resources expected to fade out over the next decades, and substantial amounts being available only in the politically unstable Middle Eastern region. Even these substantial amounts may last only about half a century, especially if the new demands in rapidly developing countries such as China continue to rise (Sørensen, 2005, chapters 5 and 7). Also natural gas resources in Europe are expected to decline soon. There is substantial discussion of the reliability of global resource estimates, with a possible hope of discovering new gas fields in unexpected locations, but on the other hand, the reserves in Russia may suffer from political instabilities as much as the resources in the Middle East. Only for coal is the resource base substantial and the possibility of supply during more than 100 years a realistic proposition. However, coal emits more greenhouse gases per unit of energy than the other fossil fuels, and a growing consensus is emerging, according to which continued use of coal (with smaller contributions from other fossil fuels) is acceptable only if the CO_2 emissions can be sequestered or avoided, e.g. by transferring the energy content in coal to hydrogen before use. All this points to fossil fuels being of interest for future energy supply only if combined with a successful development of hydrogen technologies (Sørensen, 2005, chapter 5). Environmental and political impacts are further discussed below in sections 2.6 and 2.7.

The nuclear fuels currently used in some parts of the world do not emit greenhouse gases but have a number of other serious problems, related to infrequent but large accidents (causing global radioactive fallout such as in the Chernobyl accident), to radioactive waste accumulation (waste that has to be kept separate from the biosphere for periods much longer than the average life-time of countries or even civilisations), and finally to divergence of nuclear materials to belligerent nations or terrorist organisations capable of manufacturing nuclear bombs. Efforts to modify the nuclear technologies to avoid or reduce these problems have been ongoing for some time, but with slow progress. One fundamental problem is that known nuclear fuel reserves are no larger than those of oil, if they are to be used in once-through nuclear cycles, and a contribution from nuclear energy to the post-fossil era thus depends on successful development of breeder reactors without any of the mentioned problems. It is very doubtful if there is any chance of meeting these requirements, but if the R&D is undertaken and is successful, it likely again involves hydrogen as an intermediate energy carrier (Sørensen, 2005, chapter 5).

The most promising successors to current depletable and environmentally dubious fossil and nuclear fuels are the renewable energy technologies based on wind, direct solar conversion and biofuels, supplemented by existing hydropower. Currently, wind power and some biofuel technologies have direct costs similar to those of fossil fuels, but at least in the case of wind with substantial indirect economy benefits from reduced pollution as well as absence of greenhouse gas emissions. Furthermore, the prospect of rising energy prices due to global competition for the finite oil resources will make more renewable energy technologies economically attractive over the coming years. As regards resource size, coastal countries like Denmark have wind power resources capable of supplying all the electricity needs of all the demand scenarios considered. At high latitudes, the solar resources have time distributions poorly matching the variations in demand and are therefore not expected to gain a dominant role, although production of a storable intermediate fuel (such as hydrogen) during periods with high solar radiation is a possibility. At lower latitudes, solar power and heat could become a major energy supplier, if the costs develop favourably.

Biomass is a major energy source in countries such as Denmark due to the substantial agricultural production, furnishing lots of residue usage options. This can be supplemented by sustainable forestry residues. Current Danish food production greatly exceeds the Danish demand and is a key export article. Therefore, any new, dedicated energy crops would have to compete with food production, where the average price of final products is 5-10 times higher than current prices for the inherent energy content. This points to biomass residues as the basis for energy uses, rather than the primary harvested crops (e.g. sugar). If the biomass production resembles the current mix, then there will be about ten times as much residues as food products (measured in terms of energy content), and it is thus possible to derive about equal economic benefits from food products and residues converted into energy products, at current prices. Presently, this is insufficient to cover the additional cost of conversion to energy products, but again, the expected energy price increases can make it attractive in the relatively near future (Sørensen, 2004, 2005). Current use of biomass residues for direct combustion is unlikely to be an acceptable solution in a future unhappy with the pollution from fossil fuels. Particularly, the dispersed use of biomass in home furnaces currently gives rise to a much larger fraction of undesired emissions than the fraction of energy produced. A possible addition to the land-based biomass resources would be extensive aquaculture, e.g. on those offshore areas set aside for wind power installations.

2.4 Role of energy storage

Mismatch between energy supply and demand may be handled by a number of measures, of which energy storage is an obvious one in cases, where the primary energy production cannot be controlled, whether it is due to the fluctuations in solar or wind energy, or to built-in constraints in the system such as fixed platform gas production or bound heat-electricity ratios in combined power plants. A second possibility is demand management, where tasks that are not time-wise urgent can be postponed until it is favourable for the energy system to satisfy them. There would normally be limits to the length of displacement, and the final user should be able to see an economic advantage in subscribing to such a scheme. Some tasks have to be made on demand, and the demand management is therefore only a partial solution to variability of renewable sources, which includes periods of no supply at all, at least from local resources.

The amount of wind variability with distance of wind turbine dispersal has been studied, and although the power duration curve is flattened, the period of below-average supply remains nearly the same as for a single, well-placed turbine (Sørensen, 2004). In order to take advantage of variable wind regimes, wind turbine output should be combined (traded) over distances large enough to ensure passage of separate weather systems, which means 500 km or more. For solar panels, the day-to-night variation can only be smoothed by connecting the output from panels placed at different longitudes around the world, and the seasonal variation only by connecting across hemispheres (or preferably place solar panels near the Equator).

Similar considerations apply to many forms of demand management. For example, social habits make it difficult to disperse the period of hot meal cooking by more than 1-3 hours, but demand management across different longitude regions could do much better. This has actually been done for a number of decades in Russia, where the national electricity grid covers many longitudinal zones. Much more limited possibilities are offered by the chiefly North-South exchange of power in Western Europe. Also industry and commercial energy use has limited flexibility, due to conventional working hours and the need to adapt to the time where customers like or are able to shop. Lighting and electronic equipment such as computers or audio-visual devices show similar inflexibility (unless they are equipped with rechargeable battery modules), because their use is determined by the schedules of people. Only a few items such as dish or clothes washing machines and driers allow the desired flexibility of 3-30 hours of delay, being desirable as an alternative to short-term energy storage.

Active energy storage can be based on a large number of devices, which may broadly be divided according to capacities measured in terms of typical storage times: seconds to minutes for reasons of system stability (flywheels, capacitors), hours to days for optimal use of fuel-based power systems (pumped hydro, compressed air, batteries), weeks to months for weather-dependent energy production such as solar or wind power (seasonal water reservoirs, hydrogen, reversible phase-change or chemical reactions) (Sørensen, 2004). Seasonal water reservoirs are often the cheapest among these, but suitable reservoirs exist only in special regions (e.g. in Norway but not in Denmark), and cheapness assumes that the environmental costs of using such reservoirs are low and that the other country does not overcharge for this service. In scenarios for future energy systems based on renewable energy supply, the long-term storage options are particularly interesting, and one purpose of the present study is to explore the possible roles that hydrogen can fill in this connection. However, “long-term” is typically only a few weeks for wind power systems (see Sørensen et al., 2001; 2004), whereas solar heat or power has both a diurnal and a seasonal (6 month) component under high-latitude conditions. This is one of the reasons that wind is seen as more appropriate than solar energy for the North European energy system.

2.5 Role of trade (agreements or pool auction)

To the extent that transmission capacity is already in place or can be established at acceptable cost, exchange of power between different regions or countries would appear an ideal way of handling surpluses and deficits in a given system. However, import requires that there is surplus production capacity in the neighbouring regions/countries, and export that the adjacent production can be adjusted downwards. Historically, a certain surplus capacity was normally present in any electric utility system, but with privatisation of the production industry, a tendency to maintain the smallest possible limit of extra capacity has emerged, based on economic arguments incorporating the smallness of eventual penalties for being unable to satisfy demand during a (statistically) few hours a year. This policy has, e.g. in the United States of America, been blamed for major blackouts occurring in the Eastern states.

Currently, Denmark can avoid active energy storage and deal with fluctuating production by renewable energy sources (where Denmark has some 20-30% of electricity generated by wind) through trade with the neighbouring countries. If all the countries concerned has large shares of fluctuating sources in their power systems, the unconditional need for import and export adjustment would apply to all countries, and to a large extent surpluses would coincide in time and deficits develop simultaneously (due to the characteristics of e.g. wind systems discussed in the previous section). In such a system, only the remaining fuel-based units and the hydropower units could serve to adjust the production up or down, and ultimately, as renewable sources take over, the fuel-based back-up would have to be based on biofuels. Still, for a while one could maintain cheap fossil generators (gas turbines) for use in these situations, as long as the periods of using this option are short and the annual fuel use can be kept at insignificant levels.

In Scandinavia, the situation is better than in most other regions, regarding trade as an alternative to energy storage. The reason for this is the very large component of hydropower based on seasonal water stores. Particularly in Norway, water reservoirs may contain enough water to serve the average supply for nearly a year (except in years of exceptionally low precipitation), and the generating capacity is quite generous compared with the average production. The implication is that adjustments of say Danish wind power surpluses and deficits even in case of 100% coverage of Danish electricity supply with wind would produce minute variations in hydro reservoir filling relative to the case of no exchange (Sørensen, 1981, Meibom *et al.*, 1997; 1999). However, being aware of its very special endowment, Norway will likely try to maximise the economic revenues from delivering such services to neighbouring countries.

Continuing this line of reasoning, Norway has historically maintained electricity prices far below European averages, and the current liberalisation of the power market has shown an expected tendency to approach European price levels. This means that the use of electric power by the Norwegian consumer is unlikely to remain at the current level high above the consumption in neighbouring countries. It increasingly pays, as seen by the Norwegian customer, to invest in more efficient energy use, and the result is that the already installed Norwegian hydro energy capacity (which is unlikely to increase for environmental reasons) will in the future likely be considerably above the indigenous Norwegian consumption, leaving room for substantial exports to the European continent, provided that transmission lines have sufficient capacity.

This very special situation in the North of Europe will be an important consideration in discussing the region’s options for dealing with fluctuating energy sources. As hinted at, the Norwegian effort to reach market prices may also imply that the use of power trade as a method to handle the intermittency problem will may reach a price (unrelated to cost) which may be considerably higher than today. Assessing the likely future level of such prices is an important part of the balancing between the options of trade/exchange and active energy storage, where estimates of future price structures will be much more essential that just considering the current costs (whether for power exchange contracts or for Nordic power pool trading on various conditions related to warning times). Still, it is important to investigate the times of the day where wind surpluses and deficits are likely to occur, and compare them with diurnal variations in expected future power pool prices.

Other considerations are the seasonal trading price variations and at the next time scale, the effects of Norwegian dry or wet years as basis for the availability of hydropower. Also wind generation varies from year to year, but due to the time bracket of at most a few weeks for “repaying” the power loaned, the hydro system would not be particularly strained by such power exchange even during dry years, although the general price level may be higher. In this situation, a net export of power from Denmark to Norway (or to a lesser extent to Sweden) may by an economically interesting option, requiring a certain overcapacity of wind turbines to be installed.

2.6 Environmental aspects

One basic reason for moving away from fossil and nuclear fuel-based energy systems is to avoid the environmental problems associated with them, due to emissions, wastes, accidents, proliferation and in the case of carbon-containing fuels also climate impacts. While technological improvements can reduce the impacts associated with pollution from emissions, greenhouse gas emissions are better handled not by cleaning the flue gases, but by a basic transformation of the fuel before combustion or conversion, e.g. moving the energy from carbon to hydrogen. Large-scale application of such measures will in any case create large amounts of carbon-containing waste to be disposed of. Workable solutions to these problems are under study, but it is too early to decide which (if any) of the suggested technologies that may become environmentally acceptable. Removing CO_2 from the flue gases after conversion (such as electricity production) is considered less attractive due to high cost and a quite low efficiency, both in terms of energy balance and of the fraction of CO_2 actually captured (Kuemmel *et al.*, 1997; Sørensen *et al.*, 1999).

Among the renewable energy sources, direct solar- and wind-systems have very small impacts, mainly associated with the materials used in manufacturing the equipment – noise and visual impacts being manageable and temporary). Hydropower has severe environmental impacts if it involves the creation of reservoirs, altering the landscape and biosphere over areas that are quite large, e.g. in the Norwegian case. For this reason, global large-scale hydro expansion has nearly halted, and only small run-of-the-river hydro plants are constructed, with careful integration into the natural setting (Sørensen, 2004).

Most environmental concerns over renewable energy sources are associated with biomass use. Although biomass sources are usually taken as CO_2-neutral due to the balance between previous CO_2 intake during plant life and emission when used for energy, many biomass uses has severe environmental impacts during their utilisation for energy purposes. This is particularly true for combustion in small-scale furnaces, but also in large boilers where pre-treatment has often made the biomass fuel more uniform, there are emissions, particularly during start-up. Whether in developing and amateur or in industrial settings, the burning of biomass cannot be considered environmentally sustainable, and other ways of using the energy in biomass should be considered.

The fermentation routes offer ways of dealing with biomass residues and waste from households and have gained popularity as a viable method of waste treatment, but often without exports of surplus energy out of the plant. The net energy production by fermentation depends on the energy cost of collecting and transporting biomass residues to the biogas reactor site, and there is a clear compromise to be made between transportation cost and economy of scale for the fermentation plant (Kuemmel *et al.*, 1997).

Another route to gaseous biofuels is to gasify biomass residues (both lignin-containing wood scrap and also agricultural waste of moderate water content). The producer gas can be used directly in industrial furnaces, but distribution by pipeline to former natural gas customers, or use in the transportation sector, requires purification and/or reforming, if specific fuels such as hydrogen are desired. Pollution from the involved industrial processes is believed to be containable, and the transformation routes are thus preferable to direct combustion in boilers or furnaces.

A set of technologies estimated to gain an increasing and perhaps dominating role in biomass conversion is the production of liquid biofuels. These include ethanol, methanol and biodiesel, already produced in some countries and mixed into vehicle fuels. Most vehicle engines allow a certain amount (on the 10% level) of alcohols to be mixed into the gasoline fuel without requiring engine adjustments. Also, many diesel engines can operate on pure biodiesel fuel without modification. Current production of ethanol is based on sugar, while methanol is based on wood scrap. Somewhat more expensive catalytic production methods are being developed, which can use virtually any biomass residue for production of these fuels. The same is true for biodiesel, which today is mostly produced on the basis of grains and seeds. All these biofuels have associated air pollution when used in e.g. vehicles. This could be avoided by further reforming to hydrogen, but thereby loosing the advantage of a high energy-density liquid fuel similar to the ones used presently and thus with small infrastructure change requirements entailed (Sørensen, 2005).

2.7 Non-economic factors

By non-economic factors are meant all effects involving an impact on economy that is hard to quantify, at least in monetary terms. An important example is supply security. This highlights considerations such as the variety of suppliers or supply options, and the risk of disruption of supply, due for instance to natural disasters or political instability, conflicts or warfare.

The situation here is that for petroleum products, several of the North Sea deposits currently used by e.g. Denmark are expected to decline over a period less than the fifty year planning horizon of the present study. High-latitude finds in Norwegian or Greenland seas may extend that period. Most of the world's remaining oil deposits are in the Middle East, in countries of highly unstable situations, with dictatorial regimes challenged by religious fundamentalists and with high risk of internal conflicts or civil wars. At the same time, the strongly growing oil demand from countries such as China and India and the increasing imports by the USA due to decline in its own oil resources makes it impossible to satisfy global demand without production being continuously stepped up and more than doubling over the planning period considered. These facts would seem nearly impossible to reconcile, and steeply increasing prices are likely to be the first sign of the rising problem. The very nervous nature of the oil market will likely overlay the cost increase with fluctuations both up and down. For Europe, the interest in oil substitution should thus be a top priority. The USA could (in principle) stretch its own oil resources by increasing its energy use efficiency to at least the present European level, a possibility that would require a reversal of both political and consumer attitudes.

For natural gas, the European situation is similar to that of petroleum, with possible additional resources primarily in the North, but also in Russia (including the non-European part). Recent events have shown some signs of instability of Russian policy towards gas exports (notably to East European neighbours), but generally, Russia has been a stable supplier, at least in the past. Substitution options for natural gas uses are better than for oil in the transportation sector, but will not become available without effort (such as rapidly establishing a coal gasification program). Due to the pipeline type of supply, the final users are in a relatively inflexible situation, presently taken care of by having established large underground gas stores. Danish gas storage facilities can furnish at least two months of supply, deemed necessary in case of major ruptures in the undersea pipeline to the Danish North Sea platforms. Seen in the light of a major substitution, this period is still too small to supply proper supply security.

Finally, for coal, there is a geographically more attractive distribution of resources, but still doubts regarding the willingness to expand production, as would be needed if coal should take over some of the oil and gas markets (after suitable transformation). Because coal has a higher emission of greenhouse gases per unit of energy produced, the expanded use of coal is connected with aims to transform coal into hydrogen fuel before usage. This makes the future of coal highly connected to the successful development of hydrogen technologies, including the fuel cell technologies to be used in the transportation sector and possibly in a much wider range of stationary applications.

Most uranium resources are in Niger and in the unstable region of former Islamic Soviet republics, although resources relatively evenly distributed over the rest of the world can sustain a modest use of nuclear energy.

Renewable energy sources (except hydro and high-temperature geothermal) are much more evenly distributed over the regions of the world, with direct solar use having better prospects near the Equator (due to seasonal invariance), while wind energy is most abundant under the mid-latitude jet streams. Biomass production is relatively similar all the way from the Equator to latitudes of about 60 degrees, because the different solar radiation levels are compensated by oppositely varying levels of soil moisture and stability of nutrient supply. As a result, a suitably selected mix of renewable energy resources can supply all energy needs in nearly all parts of the world, provided that rural-to-city transmission and a level of international trade are maintained at about the same level as conducted today, but avoiding trade with the politically more unstable parts of the world (Sørensen and Meibom, 2004; Sørensen, 2004). Generally speaking, renewable energy sources have the least indirect impacts or impacts with uncertain or hidden economic costs.

3. SCENARIO CONSTRUCTION

In section 2 above, some precursor scenario ideas for the end-use demand and for the efficiency efforts in conversions were discussed. A full energy system scenario needs to add scenarios for choice of energy sources and for the assignments of energy carriers to different energy-dependent tasks performed in society. Previous studies for Denmark (Sørensen, 1975; Sørensen *et al.*, 2001) and for the World (Sørensen and Meibom, 2000; Sørensen 2004; 2005) assumed moderate activity increase combined with high energy efficiency to prove that any region in the world could satisfy demands with 100% renewable energy, with a different mix in different regions and with continued energy exchange and trade (Denmark being an export country). Below I give an account of the update in demand and supply scenarios used in the current investigation (Sørensen *et al.*, 2007).

3.1 Demand scenario construction

The demand scenarios are constructed using the bottom-up approach (Sørensen *et al.*, 1999; 2001; Sørensen, 2004). Actual human demands are for services and products, all of which may (or may not) involve conversion of energy. The ways to deliver any needed energy are discussed below in section 3.2. Here all the demands believed to have a relation to energy use are listed, with a core that is indisputable ("basic demands") and continuing to increasingly negotiable wishes and desires ("secondary demands"). Because there is no point in guessing in great detail what secondary demands that may prevail in future societies, the discussion is generally held at an aggregate level. This is considered a better way to characterise future choices because it is a way that does not depend on identifying the precise nature of new technologies and new consumer products.

Biologically acceptable surroundings

This basic demand requires access to indoor space with a temperature of about 20°C, in home and for indoor working. As in the previous work (Sørensen *et al.*, 1999; 2001; Sørensen, 2004), we use an assumed floor area of housing/work space to define this demand. In all scenarios, the value assumed is 60 m^2 per person, such as furnished by 40 m^2/cap. in the home and 20 m^2/cap. in work area. Ceiling height is taken at 2.3-2.6 m. The implied space is not the minimum for biological purposes, but include a generous secondary demand for a large indoors living space (160 m^2 for a family of four) offering space for relaxing and home activities. The work area may also seem generous compared with the current average of closer to 10 m^2/cap. in most office buildings, but it includes common space in hallways, canteens, etc. The energy implications of providing this space with suitable temperature and air exchange are detailed in section 3.2. We do not consider it necessary to provide ranges around the 60 m^2/cap., because this is already an average, and because contemporary family structure make larger areas difficult to manage without help, and smaller areas increasingly incompatible with typical activity patterns.

Food, health and security

The energy in food (some 120 W/cap. average) has been included in previous renewable energy scenarios, because of the dual role of biomass in providing both food and biofuels or simple heat by combustion. The general principle of providing food first and using residues for energy is well established. Only marginal land unsuited for food production is used for energy crops. This decision is applied also to countries such as Denmark with surplus agricultural land (relative to its own food needs), considering that export of food is necessary in order to satisfy demands in highly populated countries with insufficient agricultural land, and that Denmark has a long tradition for supporting such export industries. The present study thus does not deviate from the previous ones, Sørensen *et al*. (2001) for Denmark and Sørensen *et al*. (1999) for the neighbouring countries, with respect to food production and therefore just take over the numbers derived in these studies. For biofuels, new technology has been forthcoming, that suggests a different mix of biofuels to be produced in the present scenarios, as compared with the previous ones. The associated demands, particularly in the transportation sector, will be detailed below.

Food storage (refrigeration and cooling) and cooking is taken to imply an end-use energy demand of about 18 W/cap., as in the previous studies (Sørensen, 2004). Heat losses in freezers and refrigerators are added in section 3.2.

Energy use for health includes hot water for personal hygiene and household uses, taken as 50 litres/day/cap. heated to an average level 40 °C above the water supply temperature (an average 8 °C in Denmark), yielding an average energy demand of 97 W/cap. Clothes washing and drying plus dish washing is estimated at an average energy demand of 45 W/cap. (Sørensen *et al*., 1999). These numbers include energy spending requirements at the waterworks for purification and pumping. Health institutions (hospitals etc.) have heat requirements assumed to be included in the estimates given above, and their electricity use are assumed to be included in the activity energy use given below.

Security needs (police, military and related institutions) are assumed to be covered through space conditioning and activity energy requirements generally.

Human relations

In this category, electricity use for lighting and audio/visual/computing equipment in the home or in other social surroundings are included, but at different levels for the different demand scenarios. The range of 85-140 W/cap. was estimated in Sørensen *et al*. (1999), assuming a saturation in energy-demanding leisure activities, using the argument that these encourage individual relaxation (playing computer games, etc.) rather than a more desirable social interaction. This is clearly only one of several possible developments. In order to restrict the number of end-use demand scenarios from the five proposed in section 2.1, the proposal is here to use three variants, with energy demands for human relations gives as 100, 200 or 300 W/cap. The first one, corresponding to the one used in the previous study, reflects an energy-conscious implementation of desirable social interactions, the second being characterised by a larger expansion of activities in the area (making trips to energetic shows and spectacles, etc.), with the third one being an implementation of a little controlled scenario with human relations imbedded into very individualistic desires to show-off and compete (racing, offering communal car and boat trips, sporting events and competition involving energy-intensive equipment, and so on). For comparison, the current level of end-use electric energy in this sector is below 100 W/cap in Denmark (Sørensen *et al.*, 1999).

There are transportation energy demands associated with recreational travel and social visits. Typical values for Denmark are of the order of 10000 km/y/cap. (Sørensen *et al.*, 1999), composed of many short visits (some 100 km roundtrip travel distance) and a few medium and long distance trips, such as in the latter case taking a vacation in another continent with use of air travel. The spread in demand for non-work related travel is large, ranging from a few thousand kilometres to several tens of thousands. The population-averaged demand will for the three end-use demand scenarios be taken as 8000 km/y/cap., 16000 and 24000 km/y/cap. To this comes work-related travel and commuting, which will be dealt with below.

Human activities including derived ones

Human activities include the acquiring of knowledge as well as the social activities described above. However, other activities must be added to these, because an effort is required in order to supply basic needs for food and shelter, as well as for the educational and social endeavours. This means establishing production industries for agricultural cultivation and processing as well as for construction of equipment, buildings, roads and other infrastructure, that allows the necessary production and distribution of goods and services, which again imply needs for supplying means of transportation and equipment used by service providers. Furthermore, the chain of derived requirements continues with a demand for materials and energy, a demand that in the past has been catered to by mining and processing industries, but recently has been supplemented by industries for recycling and providing energy from renewable sources in addition to the traditional wood burning and hydro power plants.

The current net end-use energy used for these activities is somewhat less than 100 W/cap. (Sørensen *et al.*, 1999). The future energy requirement of the agricultural and construction sectors is unlikely to change dramatically, while that of manufacturing industry and services will depend on the direction of social organisation and preferences. Current trends in Denmark have been towards less heavy industry, but this is not necessarily the case for all the countries in the region. The current mineral-based resource industry has a high level of energy consumption, but also the recycling and renewable energy equipment industries are energy-intensive. The international goods manufacturing industry produces a number of products from furniture to computers, of which some are or can be made considerably less energy-intensive than the technology being replaced. However, the quantity of products increase, and new products appear on the market every day. These opposing trends may lead to an end-use energy demand lower than today, or a good deal higher. The scenario end-use energy for production of food and goods with the associated materials and equipment industry may then be taken to require 60, 120 or 180 W/cap.

To this comes transportation of materials and products. The current exemption of international transport from taxation has made it extremely cheap to use materials shipped from far away, and to build equipment from parts travelling around the globe, sometimes several times (e.g. parts being shipped from Europe to the Far East to have some other parts added, or wherever the cost of labour is lowest, and back again). Also the transportation distances of the final products to the customer have increased, as the point of production has become less relevant due to the low transportation energy costs. Without inexpensive fossil fuels, this pattern of production will become less desirable, and old virtues of nearness to the customer may again come into vogue. The uncertainty of how quickly this attitude will penetrate the market behaviour in a world with rapidly increasing demand for products, e.g. in the large Asian economic growth countries, makes it necessary to work with scenarios spanning a fairly large range of transportation energy demands. The scenarios are 3000 ton-km/y/cap. (close to the present level; cf. Sørensen *et al.*, 2001), 4000 and 5000 t km/y/cap.

Also the amount of business travel (for sales, industry management and knowledge transfer) has been greatly increasing during recent decades, despite the fact the technical options such as video conferencing has made it possible to essentially replace all business travel by near-zero energy alternatives. To this should be added commuting transport of employees, which has also been increasing due to abandoning the preference for settling in homes close to the place of work. A possible reduction in commuting needs could again technically be accomplished by making use of new communication technologies, which allow many types of work to be carried out from a home office. However, this also implies a change in attitude, after several generations of people have been brought up to value a strict division between work and leisure. The scenarios thus work with non-leisure transportation (of people) demands including commuting based on annual travelling distances of 10000 km/y/cap. (current level equal to current transportation demand for social relations; cf. Sørensen *et al.*, 2001), 40000 and 70000 km/y/cap. This should include transportation work for shopping and for services, which in the low energy-demand scenario would take advantage of bicycle use (assuming nearness of shopping facilities), but in the high energy-demand scenarios would assume a centralisation of shopping and service facilities making use of cars necessary.

One could consider differentiating end-use energy needs between the countries and regions included in the study, such as applying larger transportation needs in sparsely populated areas. However, the principle of not going into too high levels of details when predicting possible usage patterns fifty years into the future has spurred the decision not to work with any regional differentiation of energy demands.

3.2 Scenarios for energy delivery to end-users

In section 2.2, some scenario thoughts on the energy conversion chains leading from primary energy sources to the end-user were presented. The detailed description of conversion losses depends on the way the entire energy system is put together and thus must be discussed for each combined scenario. Of particular importance is the fraction of energy having to go through storage cycles with the associated losses. The future scenarios based on renewable energy will have different types of losses as compared with those of the current system. Losses connected with transformation of fuels will occur for biofuels and for hydrogen, whereas the losses in converting wind energy into electric energy by wind turbines is not usually included in the modelling, although it does of course influence the economic viability of wind turbines. Instead, one usually in this type of systems assessment consider wind energy as delivered at a specific production cost.

The following subsections estimate the energy that has to be supplied to the end-user in order to provide the demanded energy service. Other energy losses between primary energy and delivery to end-user will be discussed for each overall scenario. This is facilitated by assuming that the three scenarios for attitudes towards conversion efficiency discussed in section 2.2 will simply follow the end-use scenarios (now also reduced to three), so that the highest efficiency go together with the lowest end-use demand, the middle efficiency together with the middle end-use demand, and the laisser-faire conversion efficiency together with the high demand growth/run away demand scenario. These three demand-conversion scenarios will be described below under the names "highest efficiency scenario", "improved efficiency scenario" (because the middle scenario assumes a continued efficiency improvement trend with modest legislative intervention, as it has materialised in the past) and finally the "unregulated-efficiency scenario", named such because it assumed not only absence of new legislation aimed at improving efficiency, but also a measure of deregulating areas presently covered by legislation (such as progressive automobile taxation linked to efficiency).

3.2.1 Highest-efficiency scenario

Biologically acceptable surroundings
In our previous work (Sørensen *et al.*, 1999; 2001; Sørensen, 2004), a fixed relationship between indoor temperature T and space heating or cooling requirement P (for power) was assumed:

$$P = c \times \Delta T \text{ with } c_{\text{based on assumption A}} = 36 \text{ W/cap/°C}.$$

The "assumption A" used was that the best current technology would be the average future one, with "future" being year 2050 and the actual year where this value corresponded to the best technology was around 1980, based on detached houses with 25-30 cm mineral wool insulation, double-layered glazing and high tightness requiring forced (and thus controlled) ventilation. Current best technology buildings (in Denmark) have at least as good insulation, but with better control of cool bridges, and better energy glazing (low-conductance gas between panes), estimated to lead to a value ("assumption B") of

$$c_{\text{based on assumption B}} = 24 \text{ W/cap/°C}.$$

The methodology suggested for the highest-efficiency scenario (section 2.2) was to assume a further technology improvement to take place and, in the highest-efficiency scenario, become implemented by 2060. For this scenario, we shall therefore assume a further improvement ("assumption C") to

$$c_{\text{based on assumption C}} = 18 \text{ W/cap/°C}.$$

The use of this coefficient is to require a delivery of space heating and cooling at the rates of

$$P_{\text{heating}} = 18 \times d \times (16\text{°C} - T),$$

$$P_{\text{cooling}} = 18 \times d \times (T - 24\text{°C}),$$

as it is assumed that the dependence of the comfort temperature zone on outdoor temperature exhibits a ±4°C interval due to the flexible influence of indoor activities, as influenced by body heat and clothing. The factor d is the population density, people per unit area (cap/m^2) and P thus in W.

Figures 1 and 2 show seasonal variations in temperature and calculated space heating and cooling energy requirement for the geographical region studied. Temperatures used here are monthly averages from satellite observations (Leemans and Cramers, 1998; Sørensen *et al.*, 1999). The more detailed Danish study (Sørensen et al., 2001) uses hourly temperatures to obtain a more accurate value for the space heating requirements. Based on the average data, one finds that except for Southern Germany, there is only an insignificant requirement for space cooling in this geographical region, which does not show in this type of Figures, because periods of cooling need are usually much shorter than the month selected for averaging. However, space heating is important and increasingly so when moving towards the North (latitude effect) and the East (continental effect). The population in 2060 is nearly the same as in 2000, for the countries considered. Sørensen *et al.* (2001) give a detailed model for Denmark of population development to 2050. The total population is constant or slightly diminishing, if strict immigration policies prevail, and there is a modest movement away from city centres, contrary to the situation in developing countries. The actual populations assumed by 2060 are as in that study, and outside Denmark as in Sørensen *et al.*, (1999). The population densities *d* are depicted in Figures 3.

Food, health and security

Food energy, energy for food storage and hot water for personal hygiene and for indoor cleaning are basically the same as at the end-use levels, with differences showing only in the conversion steps leading to the end-user. However, there may be slight variations between the end-use scenarios due to emerging technology and to changes in habits. The latter would be difficult to predict, having to do with e.g. gastronomic preferences being linked to food preparation times and temperatures as well as to food choices implying different cooking requirements. For instance, it takes lower energy at the end-user to sustain a diet on sushi than on artichokes, and it takes more energy to sustain a diet on stews than on rare steaks. Also for hygiene, there are significant energy implications of shifting from bathtub use to shower use, and even more by using the low water-usage showering cabins recently appearing on the market. For cleaning, water usage is also a key energy-determining factor, as is the type of chemical agents employed. The same is true for clothes washing, where simply stated one has a choice of using low temperatures and stronger detergents or higher temperatures and simpler soaps. In this case, one may see a balancing issue involving environmental impacts from detergents ending up in the sewer systems versus energy use for water heating. The tendency over the last century has been towards using lower temperatures and more chemical aids for washing, but in recent decades, alternative chemical agents have been introduced with less environmentally adverse effects and still allowing lower washing temperatures to be used.

We shall leave the energy use in this sector identical for all scenarios, except for a differentiation in hot water usage, where the sum of hot water for hygiene and clothes washing was 142 W/cap. in the old study (Sørensen *et al.*, 2001). Here we shall use an average of 100 W/cap. for the high-efficiency scenario, 142 W/cap. for the intermediate scenario and 200 W/cap. for the unregulated-efficiency scenario, taking the new technology on-board in the first case, and in the second case increasing hot water use by for example more use of heated swimming pools.

Human relations and activities

Following section 3.2, relations and leisure activities at the end-user translate to 100 W/cap. electricity use and 8000 km/y/cap. travel (and some heat energy for heating venues of leisure activities, assumed incorporated into the building heat use), while the indirect activities for food and equipment production, distribution and sale, as well as for building and infrastructure construction and consequently materials provision, were estimated for the most efficient scenario to comprise some 60 W/cap. of mainly high-quality energy (electric or mechanical energy), plus 3000 ton-km/y/cap. of goods transportation plus 10000 km/y/cap. of work-related passenger transportation. The transportation figures translate into 400 W/cap. average power use for person transport and 300 W/cap. for freight transportation.

Passenger transportation is based on the current state-of-the art vehicle (3 litre of diesel fuel per 100 km) with an average occupancy of 1.5 persons on both leisure and business trips. Today, air transport is about twice as energy intensive per passenger as transport by road vehicles, but since the estimate pertains to a future situation, the high-efficiency can technically be reached. In any case, the end-use demand scenario does not include conversion losses and only use the vehicle example above as a proxy for the technical minimum energy use for the given task, which is used as a proxy for end-use demand in cases where no clear physical efficiency limit exists. Similarly, the proxy used for end-use requirements for freight transport is 9 litres of diesel fuel per 100 ton-km. The endse demands include international transport of passengers and freight, which particularly in the latter case is a major contributor.

3.2.2 Scenario with some efficiency-emphasis

Biologically acceptable surroundings

The demand is as for the maximum-efficiency scenario described above in section 3.2.1, except that the average 2060 building standard only corresponds to the best in 2005,

$$c_{\text{based on assumption B}} = 24 \text{ W/cap/°C}.$$

This scenario reflects a possible outcome of a policy like the current one of improving building energy codes with respect to energy at regular intervals, but with fairly modest steps taken. Graphically, the demand is like the one shown in Figures 1 to 4, because only the overall magnitude is changed, not the geographical distribution.

Food, health and security

Following the discussion in sections 3.2 and 3.2.1, we use average end-user energy requirements of 120 W/cap. for food, 18 W/cap. for food storage, and 142 W/cap. for hygiene-related tasks, again assuming small contributions for water supply, institutions and security (police, military) as included.

Human relations and activities

Again following the assumptions made in section 3.2 and 3.2.1, the end-use demands for human relations, leisure and all upstream construction, manufacture and materials supply are 200 (electricity) + 120 (agriculture and industry) + 1244 (passenger transport) + 400 (freight transport) = 1964 W/cap. The high transportation demand involves globalisation of the business activities as well as an extrapolation of numbers of vacation trips to other continents.

3.2.3 Unregulated-efficiency scenario

Biologically acceptable surroundings

The demand is as for the maximum-efficiency scenario described above in section 3.2.1, except that the average 2060 building standard only corresponds to the best in 1980,

$$c_{\text{based on assumption A}} = 36 \text{ W/cap/°C}.$$

Due to the long life of many buildings, this scenario is still quite likely in case of no progressive improvement policy for building energy standards. The best 1980-standard is still three times higher than the average 2000 building standard (Sørensen *et al.*, 2001).

Food, health and security

Again following the discussion in sections 3.2 and 3.2.1, we use average end-user energy requirements of 120 W/cap. for food, 18 W/cap. for food storage, and 200 W/cap. for hygiene-related tasks, again assuming small contributions for water supply, institutions and security (police, military) as included.

Human relations and activities

According to assumptions, the end-use demands in the unregulated scenario for human relations, leisure and all upstream construction, manufacture and materials supply are 300 (electricity) + 180 (agriculture and industry) + 2089 (passenger transport) + 500 (freight transport) = 3069 W/cap. Needless to say, a significantly increased fraction of people's time will in this scenario be used for transportation, particular work-related. It is one criticism against such a scenario, that the business economy may decline if more paid time is spent unproductively on travel, but at least when public transportation is used, at least some of the travel time may be used productively. For freight, the figure reflects a life-cycle of products with components travelling back and forth between continents to become processed at the lowest possible labour cost, and to become ultimately disposed of in the region where this can be done cheapest. Clearly, this scenario only works in case the cost of energy remains low compared to that of labour.

3.3 Choice of primary energy sources

The general situation for fossil, nuclear and renewable supply options was briefly discussed in section 2.3. The present scenario work is exploring the options for 100% or near-100% coverage by renewable energy sources, as a continuation of the efforts required by and performed as a result of the official Danish energy planning over the last 25 years. The maximum energy yield from renewable sources such as wind power, biofuels and solar energy has been investigated and is estimated in several previous studies (Sørensen, Kuemmel and Meibom, 1999; Sørensen and Meibom, 2000; Sørensen *et al*., 2001; Sørensen, 2004). The numerical values will be discussed here only in connection with the individual scenarios in which they are used. Scenarios employing other types of primary sources than renewable ones have been discussed in Sørensen (2005).

3.4 Selecting intermediary energy carriers

Due to the intermittency of renewable energy sources such as wind and solar energy, the system must contain compensating carriers of energy, ready to step in when winds are low or when it is dark. The most obvious such energy carrier is biofuel, because it is already a part of the proposed energy system. The question is, to which extent there is enough of it to fill the gaps between demand and production at the relevant times, and if the conversions to and from the desired energy forms can be performed without excessive losses. Investigations of the viability of biofuels to serve this purpose will be addressed in connection with one of the scenarios (see section 3.5.2). Hydrogen is another suggested energy carrier, but one that requires substantial infrastructure modifications, depending on its penetration into the different energy sectors. The two scenarios described in sections 3.4.1 and 3.4.2 corresponds to expectations of either successful development of hydrogen technologies in all sector applications, or a more limited success in the introduction of hydrogen for a limited number of specialised applications, notably associated with the energy storage cycles that may be employed to deal with the variability of some of the renewable energy sources.

The choice of intermediate energy carriers and system layout (e.g. more centralised or more decentralised) has implications for the efficiency options regarding the conversion chain between primary energy supply and end-user. These issues will be dealt with as part of the construction of each scenario on the system level.

3.4.1 Scenario with successful development of hydrogen technologies

In this scenario, it is assumed that fuel cells, the key technologies for employment of hydrogen for both transportation and stationary applications, are successfully developed to both economic and technical viability. Technical viability comprises performance (where the goal is 50-65% conversion efficiency from hydrogen to electric power and near 100% for the reverse reaction), long lifetime (durability of fuel cell stacks rising from the present goal of 5 years to around 20 years, like that of the equipment into which fuel cells are to be integrated) and low environmental impacts during manufacture and use. The economic goals include a competitive price relative to present or future alternatives (such as diesel engines, gas turbines and so on) capable of delivering energy in the desired form and mode, albeit not necessarily using hydrogen as their fuel. Current fuel cell prices are an order of magnitude too high, and the lifetime an order of magnitude to short. If one does not achieve a 20-year fuel cell durability but only 5 years (similar to that of technology-similar advanced batteries), the break-even fuel cell cost is diminished by a factor of 4. The viability issue may be eased by insisting on including all life-cycle costs, which usually is to the favour of hydrogen (as of renewable sources) and to the disfavour of fossil fuels and to some extent biofuels.

In this *successful hydrogen technology scenario*, surpluses of variable renewable energy electricity production that cannot be used more profitably in other ways are converted into hydrogen, centrally or decentrally. The decentralised version most likely requires successful commercial development of small-scale reversible fuel cells for building integration. Some of this hydrogen would have to be re-converted into electricity in order to cover periods with deficit in renewable power production. However, when feasible, conversion losses are minimised if the hydrogen can be used as such. This could be in vehicles using fuels cells to produce power for electric motors, or in direct hydrogen use for industrial process energy.

The centralised version of this scenario has pipeline or other distribution of centrally produced hydrogen to the sites where hydrogen is distributed. For example, surplus wind power may be converted to hydrogen near the wind turbine sites, or at central collection points, which could conveniently be located where the hydrogen storage facilities are (salt intrusion or aquifer storage types as those used today for natural gas). In the latter case, hydrogen transmission pipelines would transport the hydrogen to automobile and other vehicle filling stations, as well as to industrial users. Where existing natural gas lines can be upgraded to hydrogen quality, supply to individual-building owners of fuel cell units could also take place. Alternatively, if the building-integrated fuel cells are reversible, the input could be confined to electric power line transfer of electricity, both for direct use and for hydrogen production and filling into vehicles parked at the building. One possibility is to totally dispose of central hydrogen storage, if building-integrated storage types would become technically and economically feasible (Sørensen *et al.*, 2001). The advantage of the decentralised fuel cell placement is that the waste heat can be used to cover the building's heat requirements. This is possible despite the high power efficiency (and hence lower waste heat generation) of fuel cells, provided that the building heating needs are reduced by improved insulation standards. Hot water needs would have to be covered in any case, which is totally within the capability of fuel cells rated to cover the electricity needs of the building. If there is a deficit of waste heat for space heating during winter, this may be covered by electric heating, preferably through heat pumps, as in the 2001 scenario. Precise matching between hydrogen stored in buildings and the electric power demands during low-wind conditions may not be feasible for each building, but this does not matter due to the electric grid connection between buildings, as demonstrated by time-simulations in Sørensen *et al.* (2001), however only for the middle demand scenario.

In the present work, hydrogen storage is weighed against international power exchange. This implies, that the market price of power sold in a given hour will determine if export is economically advantageous to producing hydrogen for storage. Similarly, the import power price will determine whether to draw from the hydrogen store (i.e. to re-generate electricity with the entailed additional energy loss) or to cover the demand by imported electricity. In more sophisticated versions of this balancing, the degree of filling in the hydrogen stores could be considered and held up against the expected cost development on the import-export market over a period of time, in order to determine, if it might pay to use energy from the stores or to hold it back for more profitable usage later. Clearly, this type of calculation is time-consuming as it requires forward calculation at each time step, and it will only be done for selected periods in order to illustrate the nature of this particular dispatch problem.

If the re-generation of electric power during periods of insufficient renewable energy supply is performed centrally, the fuel cell technology utilised is likely that of high-temperature fuel cells, due to their superior conversion efficiency, while low-temperature fuel cells are the obvious choice for building and vehicle applications, where establishment of operating temperatures of the order of 800°C is considered inconvenient by most independent hydrogen scientists.

3.4.2 Scenario assuming failure in development of fuel cell technologies

The *no-fuel cell scenario* emerges if the technical or cost break-even targets of fuel cells (low- or high-temperature) cannot be met. The need to make up for fluctuating renewable energy sources still exist, but must now be solved either by biofuels or by hydrogen in a pure energy storage function.

The biofuel option involves converting biofuel to electricity, whenever fluctuating renewable sources are insufficient and import options are unavailable or more expensive than biofuel conversion. The will be a conflict between these uses of biofuels and the use as a vehicle fuel, which is difficult to substitute. An assessment will be made of whether the biomass resources are sufficient to sustain both functions. Surplus electricity would still have to be exported, as conversion into biofuels is not an option.

Such problems may be dealt with by conversion into hydrogen for storage. Without viable fuel cell technology the conversion of electricity into hydrogen for storage would have to be by conventional (alkaline) electrolysis. The regeneration of electric power in periods of insufficient direct supply will in this case have to be made in conventional units such as gas turbines (but now fuelled by hydrogen). The efficiency will be lower than if viable fuel cell technology were available, but not unacceptably so. In this scenario, biofuels and hydrogen would both be available for uses in the transportation sector, but hydrogen would serve the important task of filling supply-demand gaps in power production.

3.5 Constructing combined energy system scenarios

In this section, we combine the demand, storage, conversion and supply scenarios into complete system scenarios. These are labelled according to the technology characteristics of the alternatives discussed in section 3.4, i.e. successful development of fuel cell technologies, hydrogen used only for storage, and dealing with fluctuating production mainly through international power exchange.

3.5.1 Complete renewable energy-hydrogen scenario

A completely renewable energy scenario with use of hydrogen as a major energy carrier and storable energy form will be constructed for the following combinations of subsystem scenarios:

I. Highest-efficiency demand and conversion scenarios – successful fuel cell scenario
II. Improved efficiency demand and conversion scenarios – successful fuel cell scenario
III. Unregulated demand and conversion efficiency scenarios – successful fuel cell scenario

From the earlier work, we know that scenario I and probably II can be realised. For scenario III with much higher demands on renewable resources the aim is to investigate if such a scenario is at all possible.

A discussion will be made of the possibilities for decentralisation based upon reversible fuel cell technology. The preliminary investigation of this option in Sørensen *et al.*, (2001) can be further discussed at present due to the advancing commercial efforts to develop precisely the solutions envisaged in the 2001-scenario.

3.5.2 Renewable energy plus limited hydrogen energy for storage scenario

The restriction of hydrogen to storage uses with either re-generation of electricity and possibly minor industrial direct uses of hydrogen makes the central question for these scenarios one of whether international power exchange plus the use of biofuels in the transportation sector can sustain the demand scenarios considered. Again, this will be investigated for three scenarios corresponding to the ones listed in section 3.5.1, but without fuel cells:

IV. Highest-efficiency demand and conversion scenarios – no fuel cells; hydrogen storage
V. Improved efficiency demand and conversion scenarios – no fuel cells; hydrogen storage
VI. Unregulated demand and conversion efficiency scenarios – no fuel cells; hydrogen storage

As in section 3.5.1, the viability of scenarios is questionable, and probably even more so in the scenarios considered in this section, not having available the high-efficiency fuel cells or the convenient two-way conversion options offered by the reversible fuel cells.

3.5.3 Renewable energy scenario with trade replacing storage

In these scenarios, international power exchange is used whenever economical to avoid using the (lossy) storage cycle. The neighbouring countries, with which power is exchanged, are assumed to have gone through a transition to renewable energy sources like Denmark, although not necessarily with the same mix of renewable energy resources (in Norway, more hydro energy, in Sweden and Finland, more forestry-based biomass, and in Germany, both wind and photovoltaic energy).

This type of scenarios might be interesting both in case of successful fuel cell development and in case of failure. It does not mean that hydrogen storage should be completely avoided, but it might be expected that the storage demand will be less than in the section 3.5.2 scenarios. However, this is by no means certain, as the maximum storage demand could well turn out to be unaltered, because the time of such storage demand may coincide with a moment where trade rules are unfavourable or where the neighbouring countries do not have any electricity surplus to sell. This is particular likely if similar energy sources are employed in the collaborating countries, because e.g. wind deficits over demand would likely happen simultaneously throughout the region.

In practice, we will run all scenarios including an option for power exchange, and thus the 6 scenarios described in sections 3.5.1 and 3.5.2 will be performed for a geographical area extended from Denmark to neighbouring countries. Without the import/export possibility, the 6 scenarios could have been simulated for Denmark in isolation. However, there is a question regarding the rules of trade between the countries. Current power exchange consist of a part governed by fixed contracts, and another part traded on what is called the Nordic Power Pool, a bidding and exchange system allowing competitive trade in a number of categories, ranging from forward options over 24-hour market bidding to a short-term spot market operated by a power balancing agent charged with maintaining the stability of the system under conditions of technical problems, failure of parties to fulfil contractual agreements, or unexpected demand variations. The tools to take care of these tasks include a list of additional bids from power producers willing to supply additional quantities of power to the spot market. Furthermore, a renewable energy-based system would like to add fluctuations in power production to the list of problems to be attended to by the balancing agent, and one would likely want to modify the auction rules, e.g. by altering the period of time for which bidding is required and hence for which reliable production forecasts have to be available.

In an earlier project, the frequency of incorrect forecasts in a 100% wind-based Danish system was estimated (Meibom *et al*, 1997; 1999). The wind power average production forecasts were found highly reliable for periods of a few hours, they still have reasonably high accuracy for 24-hour forecasts (based on either meteorology or non-linear trend forecasting), but then deteriorates quickly as the period of weather front passage times (typically some 3-7 days) is approached. For the present trade rules requiring 36-hours forecast, we found that about 25% of the bids were in error, but only 5% to such an extent that it caused significant economic penalties with the rules of the current pool system. The present study will explore the effect of introducing trading rules more favourable to renewable energy systems, such as they are already implemented in some parts of the world (e.g. allowing bids and decisions on bids to be made continuously). Thus, while the simulations outlined in section 3.5.1 and 3.5.2 will be made with current pool rules deciding whether power exchange of hydrogen storage is to be invoked, we will make an additional set of simulations with new rules designed to benefit renewable energy systems (in all the trading countries) rather than conventional fuel-based ones:

VII. Highest-efficiency demand and conversion scenarios – fuel cells; new pool trading rules
VIII. Unregulated demand and conversion efficiency scenarios – fuel cells; new pool trading rules
IX. Highest-efficiency demand and conversion scenarios – no fuel cells; new pool trading rules
X. Unregulated demand and conversion efficiency scenarios – no fuel cells; new pool trading rules

An adjacent article is carrying through the simulation of a middle variant of the spread of scenarios described above (Sørensen, 2007).

4. RENEWABLE RESOURCE MAPPING

An appraisal of renewable energy resources may be found in Sørensen (2004). For off-shore wind, a new method of assessing the potential has been developed. It will be described below. Solar, hydro and biomass assessment is essentially unchanged, except that off-shore biomass production is an additional potential source considered here. It too will be described below.

4.1 Wind energy

Wind energy is the dominating renewable energy form in the future Danish energy system and is also expected to play a significant role in other countries with a high wind ocean coastline. In Sørensen *et al.* (2001), the data used for simulation of the future Danish wind system was scaled up from current production, for which hourly data were available. The scaling was done separately for on-shore and off-shore wind, based on two year-2000 time series, each of which merged from the separate time series published by the East- and West-Danish power utilities. Because the wind conditions are better and also more stable over water, the two time series had somewhat different characteristics. Added to this, there is the difference originating from the fact that most land-based turbines are constructed to give maximum energy over the year, whereas the current Danish off-shore turbines use blade profiles yielding less than maximum energy over the year, but in compensation have considerably more productive hours over the year. This is already the case due to the more persistent winds over sea, but was emphasised by the manufacturers having employed power curves peaking at lower wind speeds than would have been dictated by a maximum energy optimisation (Sørensen, 2004). Apart from this, the off-shore wind data was very suited for extrapolation to a large penetration of off-shore wind, because they were already based on turbines with hub heights of 50-70 meters. Because the data are from actual production figures over a year with some new wind turbine construction being commissioned and also decommissioning of old machines, there is some question regarding the precise validity of using the data as a proxy for future demand over a year.

For the on-shore data, one could further object that because they are a mixture of output from older and newer turbines, the data would contain the effects of some very small wind turbines built over the past 30 years, turbines that would experience winds in much lower heights than contemporary and future, larger turbines. The assumption in the scenario was, that the total number of land-based turbines would remain as it is today, but that older machines would gradually be replaced by new ones of 2-4 MW unit size. Still, the extrapolation of current production data is likely to be fairly reliable, because the older machines, despite large numbers, contribute fairly modestly to the total production, which is then dominated by modern turbines much more similar to the ones envisaged for the future situation. In any case, any increase in the overall Danish number of turbines was assumed to involve off-shore wind parks, so the off-shore contribution to the hourly time series would in the scenario future be much more important than the on-shore extrapolations.

The scenarios developed for the present project assume that neighbouring countries, with which Denmark exchanges power, expand their renewable resource utilisation including wind energy, and data for future wind production in all these countries are therefore required. One of the key questions asked is, if the lulls and peaks in wind power production occur during the same period in all countries, in which case wind power exchange would not be able to contribute to smoothing the effects of the variability in each region. It is well known, that passage of weather front systems, and thereby also wind power production, is similar for regions of linear dimensions of the order of 500 km (Sørensen, 2004). Because the distance between e.g. Denmark and the Northern parts of Scandinavia is more like 1500 km, one would expect that some levelling could be accomplished by export and import between these regions. Furthermore, the neighbouring countries would not necessarily have wind as a dominating renewable energy source (as Denmark is supposed to have in the scenario future), but would be able to offer power smoothing based on hydro and perhaps other renewable sources such as biomass. These possibilities will be investigated, and therefore a certain amount of wind power will be assumed for each of the neighbouring countries, necessitating the construction of time series of wind power production throughout the region of Scandinavia and Germany. However, the methods presented below are applicable for any part of the World.

For another previous study (preliminary report in Meibom *et al.*, 2003), wind data for the Nordic countries were collected by Holttinen (2003). For Denmark, she also used total production data from the electric utilities (however, it seems, omitting the available off-shore data), while for the other Nordic countries, time series from a very limited number of operating turbines were used. In Norway and Finland, these were all located at coastal sites, while for Sweden, also two inland sites at the far North were included. For two additional Finnish locations, meteorological data were used to estimate potential wind turbine output. The data for these few sites with existing wind turbines were then extrapolated to much higher levels of wind energy use in the countries involved. One may question if this is a fair representation of possible future wind energy use. In Denmark, coastal sites are specifically excluded from wind turbine erection due to environmental legislation. Similar legislation may not be in place in the other Nordic countries, but if expansion of wind power should materialise, it is likely that similar restrictions on these recreationally important sites would be imposed. The inland sites in Norway, Sweden and Finland are all characterised by fairly low winds, due to shadowing from the Norwegian mountain ranges and due to the high roughness created by the forest-covered areas in Sweden and Finland (Sørensen, 2004). It would therefore seem more realistic to assume, that any substantial use of wind energy in these countries will become based upon off-shore locations, where the wind conditions are much more favourable.

These considerations have spurred the present project to find alternative sources of wind energy data particularly suited for estimating off-shore potentials. Two potential methods appear to be available. One is the wind atlas method, where limited data on geostrophic winds at a few latitude-longitude points are combined with surface roughness data to predict the production of wind turbines of a given hub height (Mortensen *et al.*, 1993). This method is mainly aimed at estimating monthly or annual production from a wind turbine erected at a proposed location, which is not sufficient for the current project. The other potential method is to depart from the reanalysis of global measured wind data, using circulation models to improve consistency in areas of few measuring stations (Kalnay *et al.*, 1996), and using the model calculations to assess height variations up to the top of the atmosphere. In order to explore short-term fluctuations, additional satellite measurements from suitable instruments can be used. The reanalysis data have until recently only been available at a very course spatial resolution (some 250 km) and time resolution (one month). Such data were previously used to represent gross geographical variations in potential wind production, using an interpolation between the two lowest atmospheric pressure layers to represent data at a height of roughly 70 meters (Sørensen, 2004). Recent efforts have lowered the resolution and have added new high-resolution satellite scatterometer-data over sea areas and blended the two kinds of data using novel reanalysis methods to obtain a time resolution of 6 hours and a spatial resolution of 0.5° (56 km latitudinal width multiplied by the cosine to the latitude angle for longitudinal width). The aim of these efforts has been to study ocean-atmosphere interactions (Chelton *et al.*, 2004), and it is by no means obvious that they could be used to estimate wind power production. Because the satellite passes over a particular latitude-longitude location only a few times a day, the idea is to overlay the previous gross reanalysis data with the high-resolution satellite data, and to extrapolate these to areas between the trails of satellite passage, so that the final mixed dataset contains the high-frequency behaviour everywhere (at least over water), but with correct time sequences only for the (moving) locations of the satellite over its trajectory. This new type of data would seem particular interesting for off-shore wind estimation, as the ship and buoy data available is very scarce.

It may seem a daring project to attempt to use these data for short-term wind energy calculations aimed at studying energy storage requirements, and the approach was adopted only after conducting a pilot study for on- and off-shore locations in Denmark and the Netherlands during a year with known wind power production at a number of sites, and comparing these actual data with the satellite data analysis, ideally for the same period and the same sites (Sørensen, 2006). Figures 5 and 6 shows the results of such a comparison, for a location at 11.5°E longitude, 55.0°N latitude and compared to measurements at Vindeby off-shore wind farm (Sørensen, 2004). It was not possible to obtain data for the same years as those covered by the off-shore scatterometer and on-shore reanalysis data, so only the overall impression of temporal variations can be derived. A more precise evaluation was possible for sites in the Netherlands, where data for the exact same period in year 2000 could be compared. These are presented in Figures 7 to 9. It is seen, that the frequency of variations in power produced is very well reproduced, although minor deviations between calculated and measured data exists during the periods where the satellite was not passing over the Netherlands area.

For one off-shore site, there is measured data at a height appropriate for modern wind turbines. This allows a comparison between model and data not requiring the use of wind profile scaling for the measured data but only for the blended scatterometer-reanalysis derived wind production. The result of this comparison is shown in Figure 7. The implication is that the sea surface scatterometer data corresponds to an effective height of about 3 meter over the average water surface.

Figure 8 shows a similar comparison for Ijmuiden on the Western shore of Holland. The Dutch data are here measured at low height (18.5 m), and the question of extrapolation to wind turbine hub height (assumed to be 60-70 m) has to be studied. A scaling factor is determined by standard methods, assuming a profile corresponding to the roughness of the local surface (which is measured at all the Dutch locations). This scaling factor was found to lie in a narrow region of 1.3-1.4 for the near-shore and off-shore sites studied. Theoretically, the scaling factor depends on both stability of the air and on surface roughness (see Fig. 10, from Sørensen, 2004), and the scaling factors used correspond to typical values for a neutral atmosphere and a mesoscale (rather than strictly local) roughness length.

Figure 9 makes the comparison for an interior location, on the border of Holland and Germany. Here the blended data derive entirely from reanalysis, and since no normalisation has been performed, the effective height may not be the same as for the scatterometer data over water. Because the reanalysis is supposed to reproduce 10 meter measured data at selected stations, one would expect the standard model of scaling to depart from this height. However, this is not true. Because the Dutch data include measurements of roughness, the scaling of measured data can be extended from off-shore to on-shore sites using the same neutral scaling law. Because of the higher roughness over land, the scaling factors get larger, in addition to varying from place to place. Trying to fit monthly wind production means derived from the reanalysis to the Dutch data, it becomes evident that the best scaling factor for the reanalysis data is about unity. This is surprising, but in accord with the questions regarding the interpretation of the reanalysis data asked, e.g. by Milliff *et al.* (1999) and by Chelton and Freilich (2004). The point is that even the new circulation model calculation with a mesh of some 50 km does not have a spatial accuracy of more that 4-6 times this dimension, and one should therefore not be surprised that the effects of local roughness is lost. On the other hand, the behaviour at larger heights (the circulation models uses some 100 levels vertically through the atmosphere) is much more likely to be realistic, and the resolution of the problem may simply be to regards the lowest level results as being more representative for altitudes of some 40-80 meters above ground, i.e. exactly where the wind turbine hubs would typically be placed (cf. Sørensen, 2006).

Fig. 11 shows the wind turbine potential production map for Northern Europe obtained for a scaling. As mentioned, this scaling is giving the best agreement with measurements for off-shore locations, but on land the proper scaling varies on scales smaller than that of the map, and actual values could deviate by some 30% (or of course more in case of particular obstacles to wind flow, such as cities or other structures).

4.2 Biofuels

The biofuel assessment is based on a biomass net production model (Melillo *et al*., 1993) adapted to assess energy values (Sørensen, 2004). Figure 12 shows the net biomass production for the North European region. The agricultural residues are used to produce ethanol or bio-diesels at an assumed conversion efficiency of 45%, while the forestry residues are used for methanol production at an assumed efficiency of 50%. New in the present study is the consideration of aquaculture. Figure 13 shows the fraction of the grid cells used in the geographical coverage, that contain water surfaces. These comprise waterways and lakes inland, as well as off-shore waters to a distance of about 20 km from the shore. Because the Nordic countries have long coastlines, there is considerable potential for off-shore aquaculture. In contrast to inland waterway aquaculture, this might be dedicated energy production areas, assumed to be environmentally protected from interfering with the biology of open ocean waters. Identification of the most suited plants or algae for ocean farming aimed at fuel production has not been done (despite some work on hydrogen production from algae, cf. Sørensen, 2005), so this is an option lying some years (decades) ahead.

5. APPLICATION OF THE SCENARIO DATA

An example of using the data described in the preceding section for simulation of an entire future energy system is given in an accompanying article (Sørensen, 2007).

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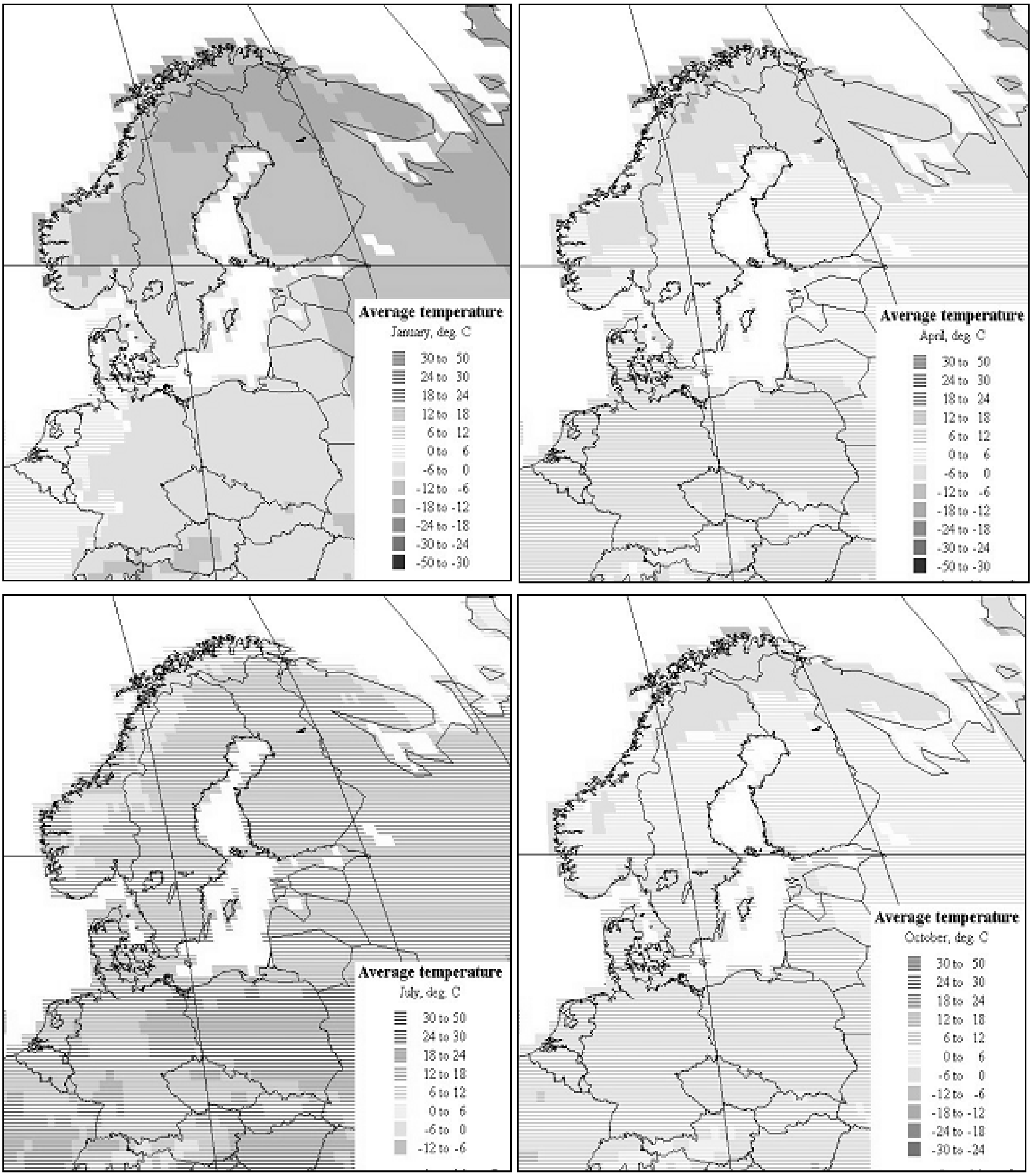


Figure 1. Average temperatures in January, April, July and October (based on data from Leemanns and Cramer, 1998).

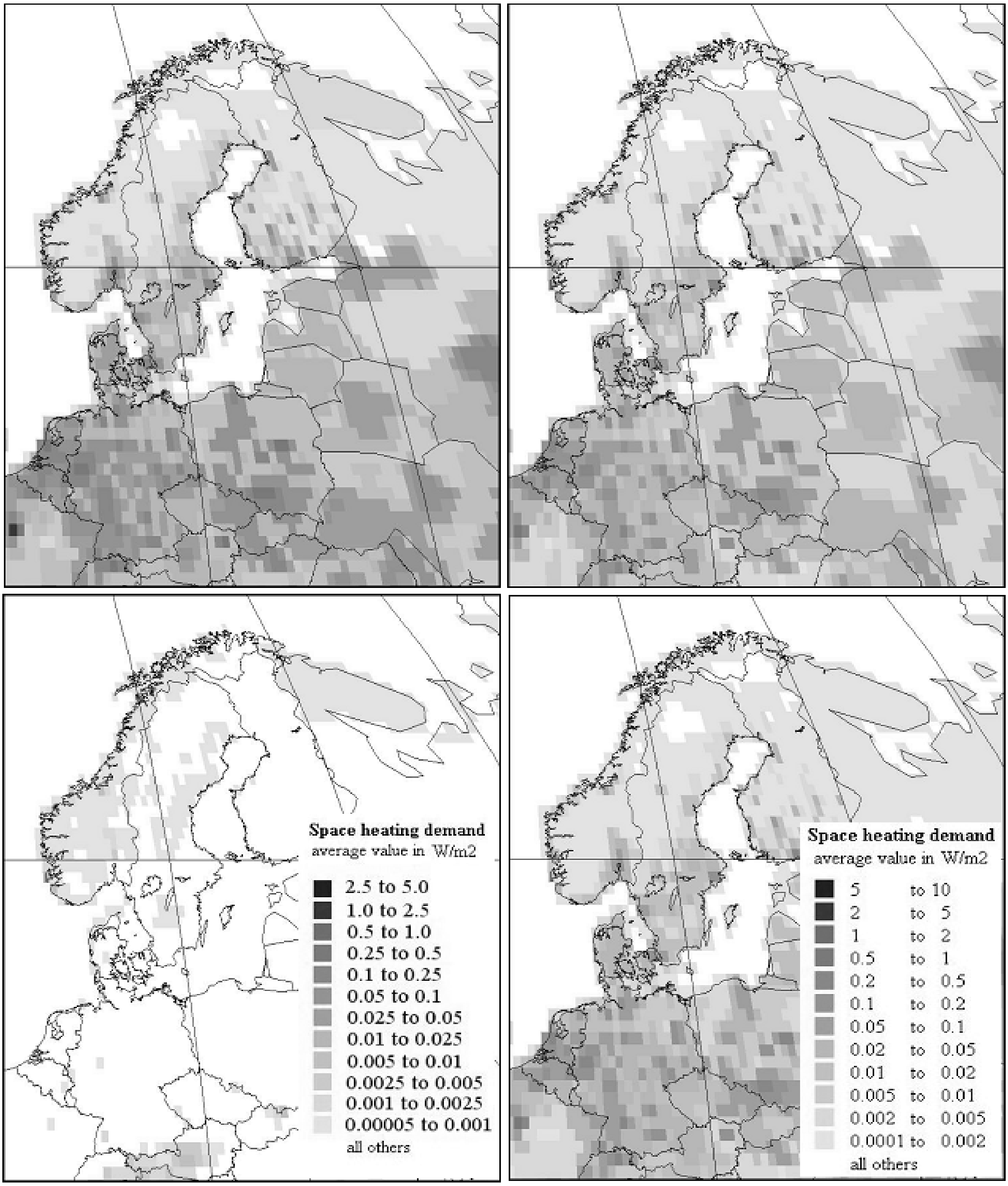


Figure 2. Average end-use space heating demand in January, April (top: left, right), July and October (bottom: left, right), for highest-efficiency scenario (left-hand scale for all four maps) or the unregulated-efficiency scenario (right-hand scale for all four maps).

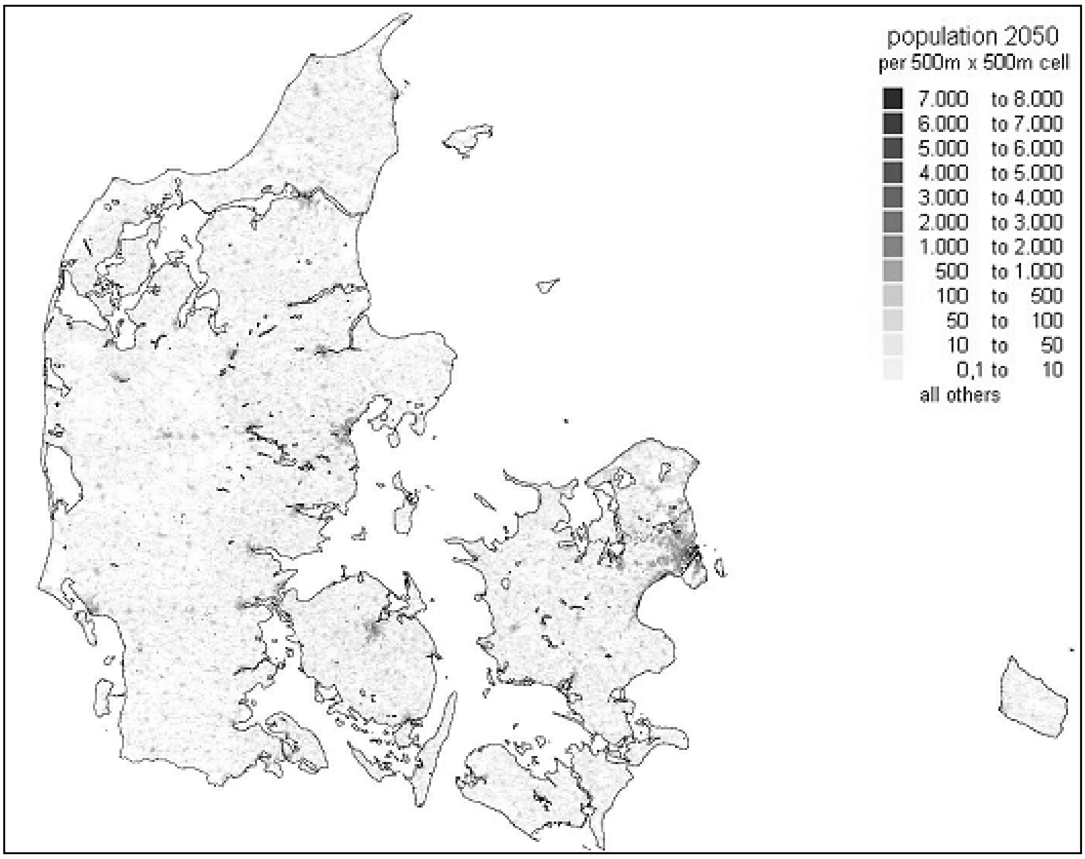
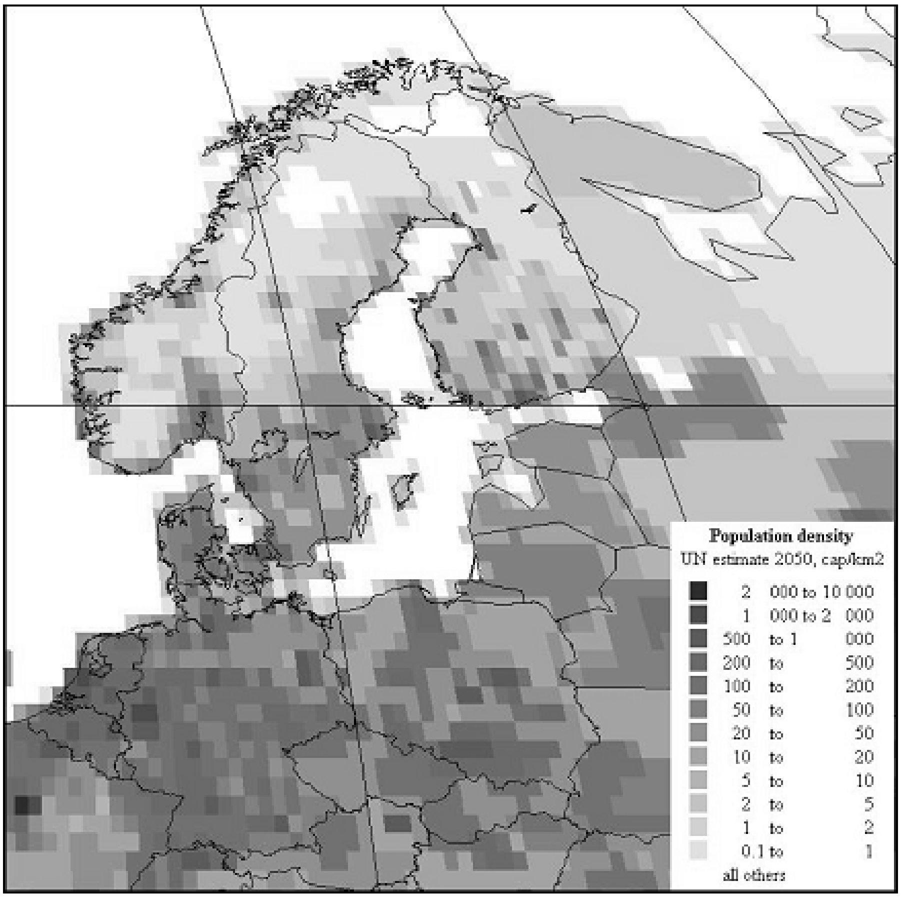


Figure 3. Above (a) : Danish population density assumed in 2060 (number of people per 500 m × 500 m unit cell; Sørensen et al., 2001). Below (b): North European population density assumed in 2060 (number of people per km^2; Sørensen *et al.*, 1999).



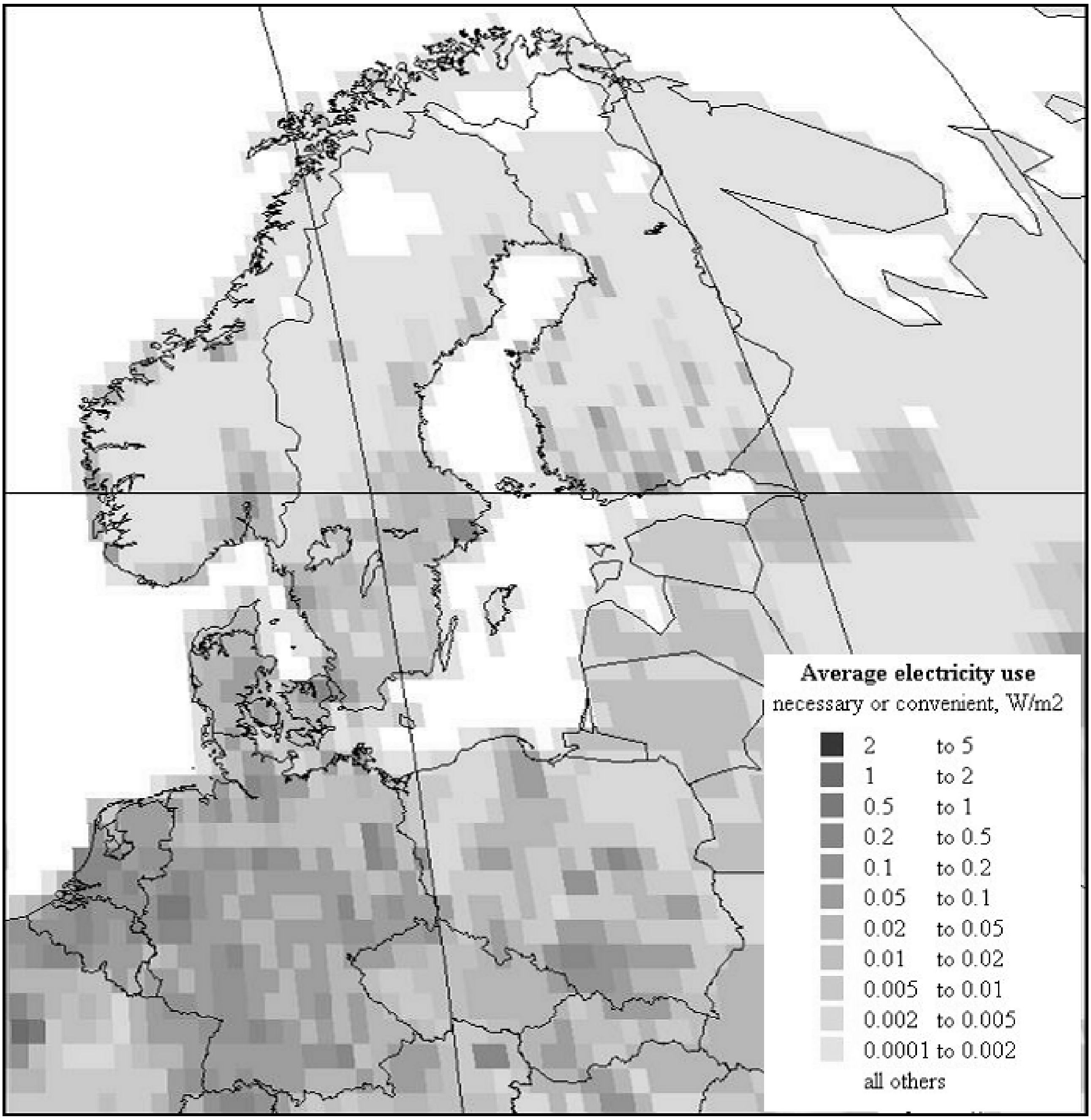
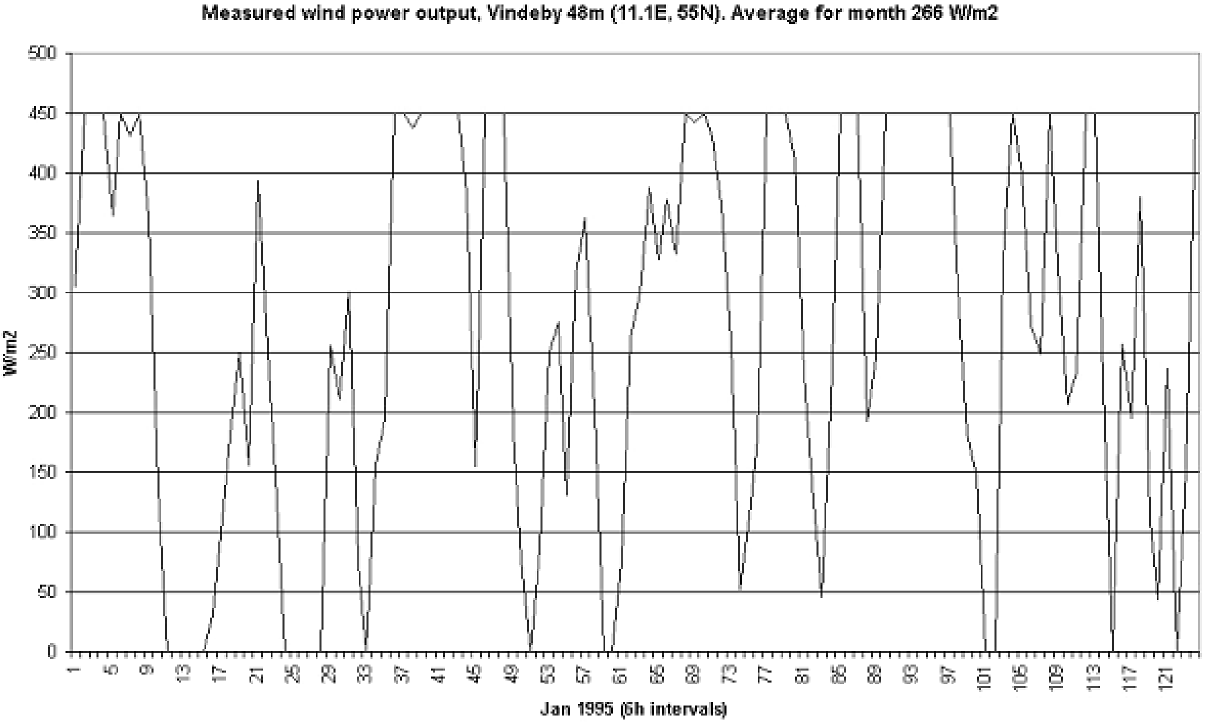


Figure 4. End-use electricity demand in 2060 for the highest-efficiency scenario. Included are both unsubstitutional electricity and electricity used for convenience (e.g. for dishwashers, industrial furnaces).



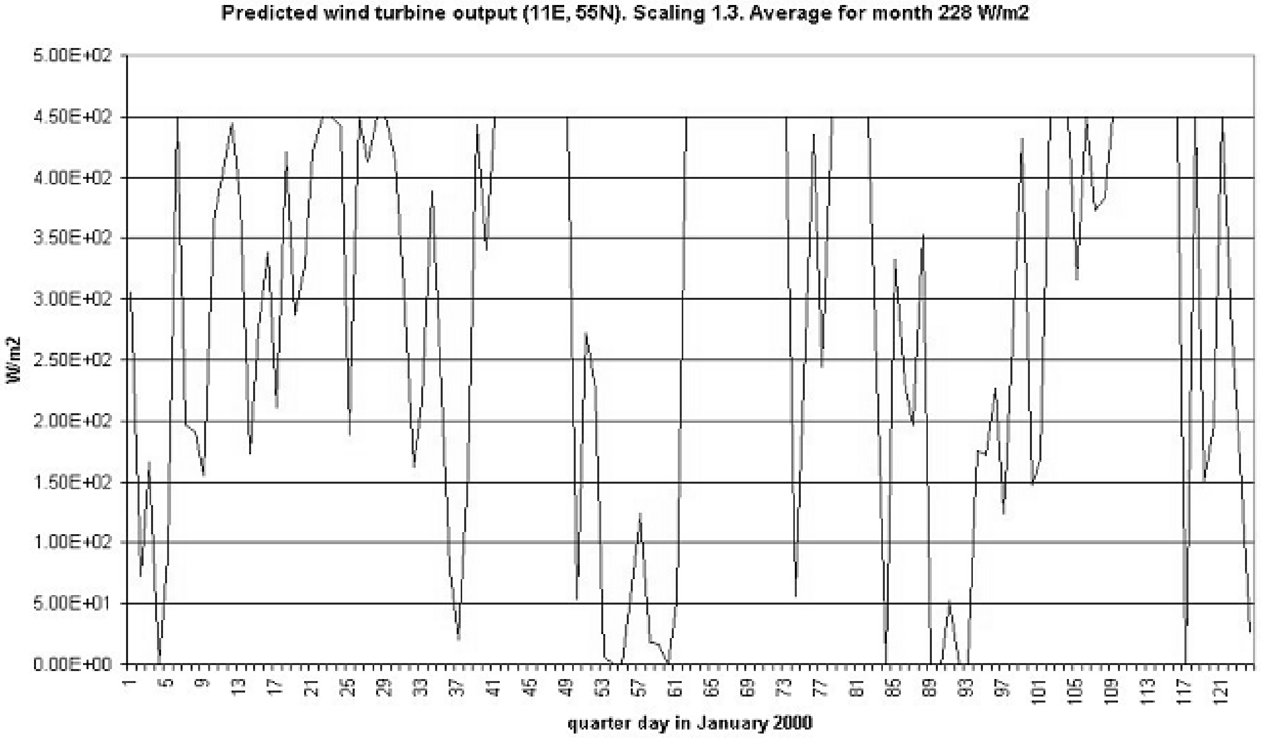
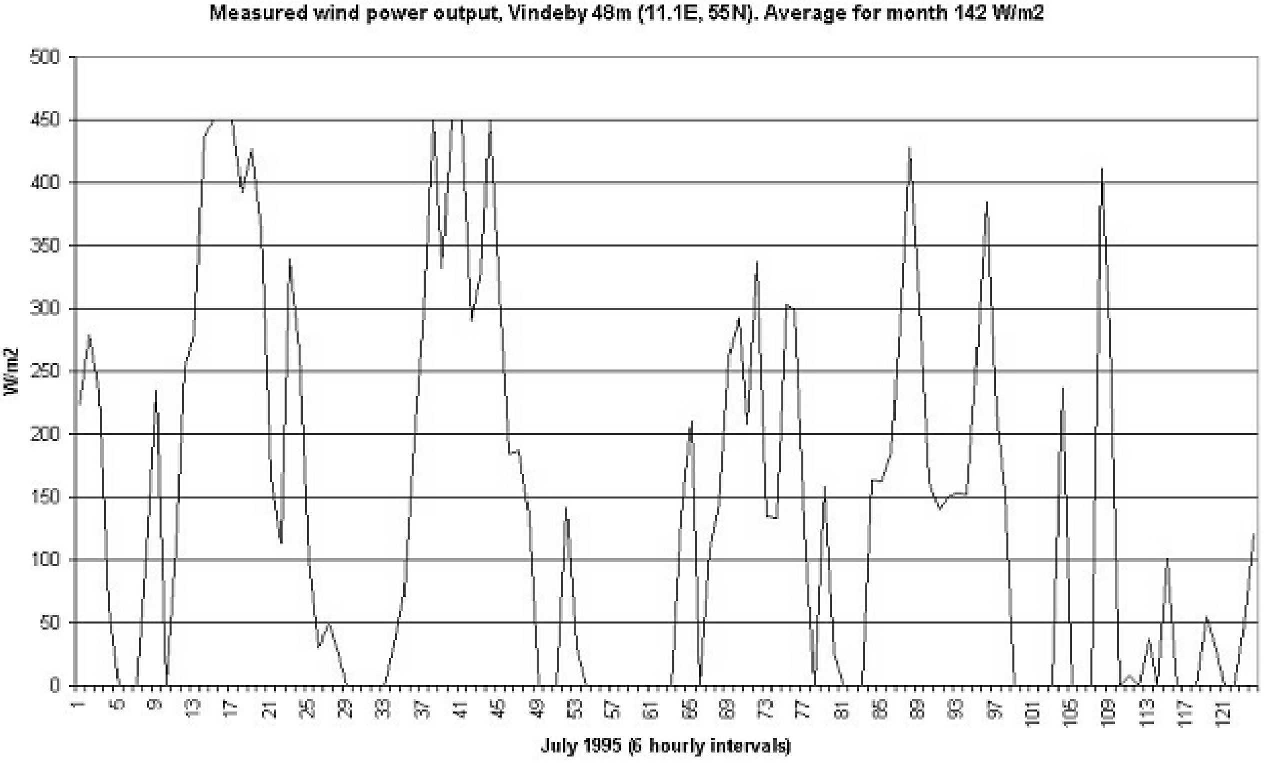


Figure 5. Measured time series of wind power output at the off-shore Danish location Vindeby during January 1995 (top) and corresponding power calculated from scatterometer blended data for January 2000 (bottom). The time resolution is 6 hours (Sørensen, 2006).



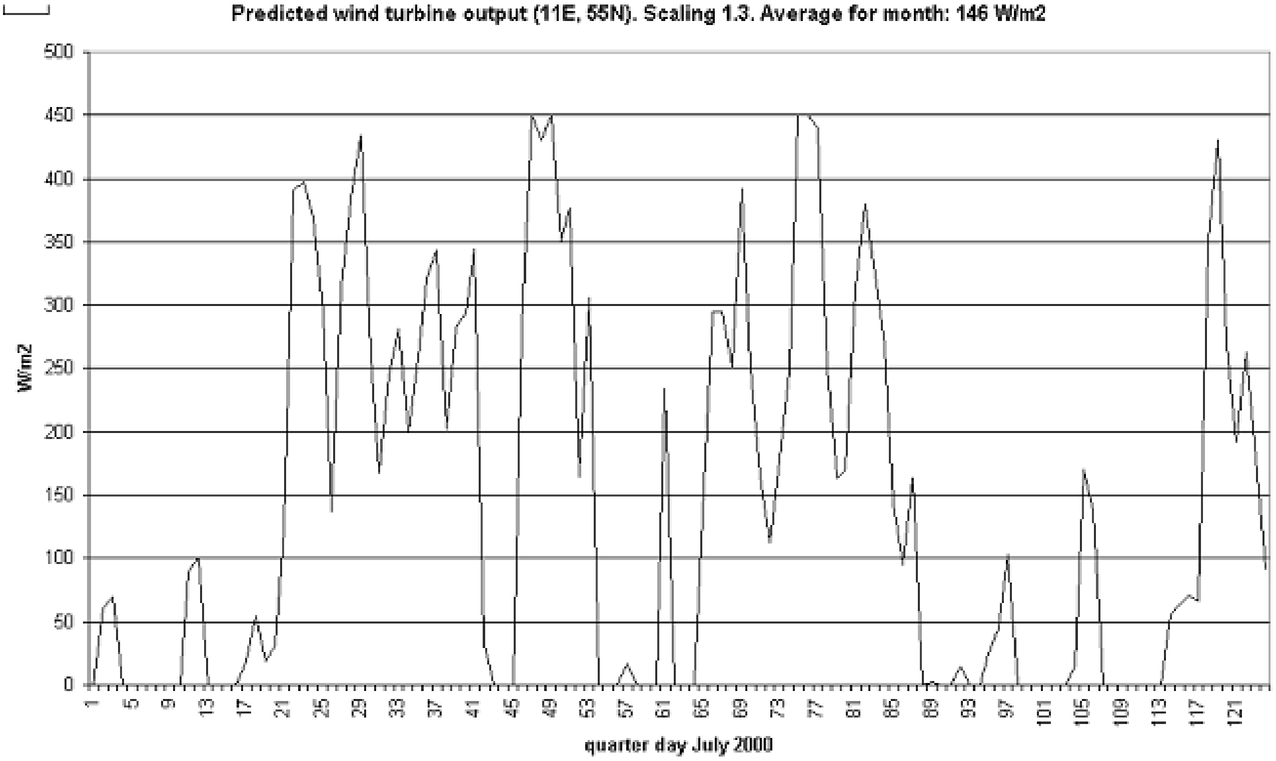
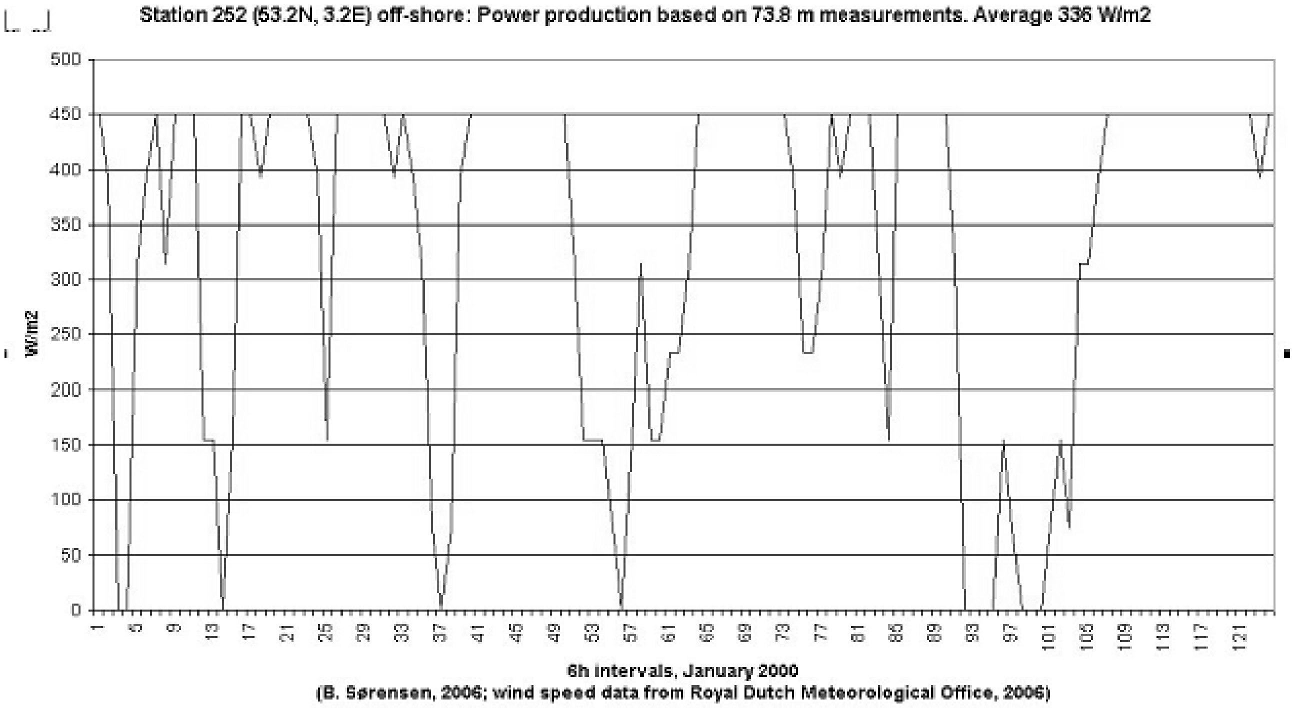


Figure 6. Measured time series of wind power output at the off-shore Danish location Vindeby during July 1995 (top) and corresponding power calculated from scatterometer blended data for July 2000 (bottom). The time resolution is 6 hours (Sørensen, 2006).



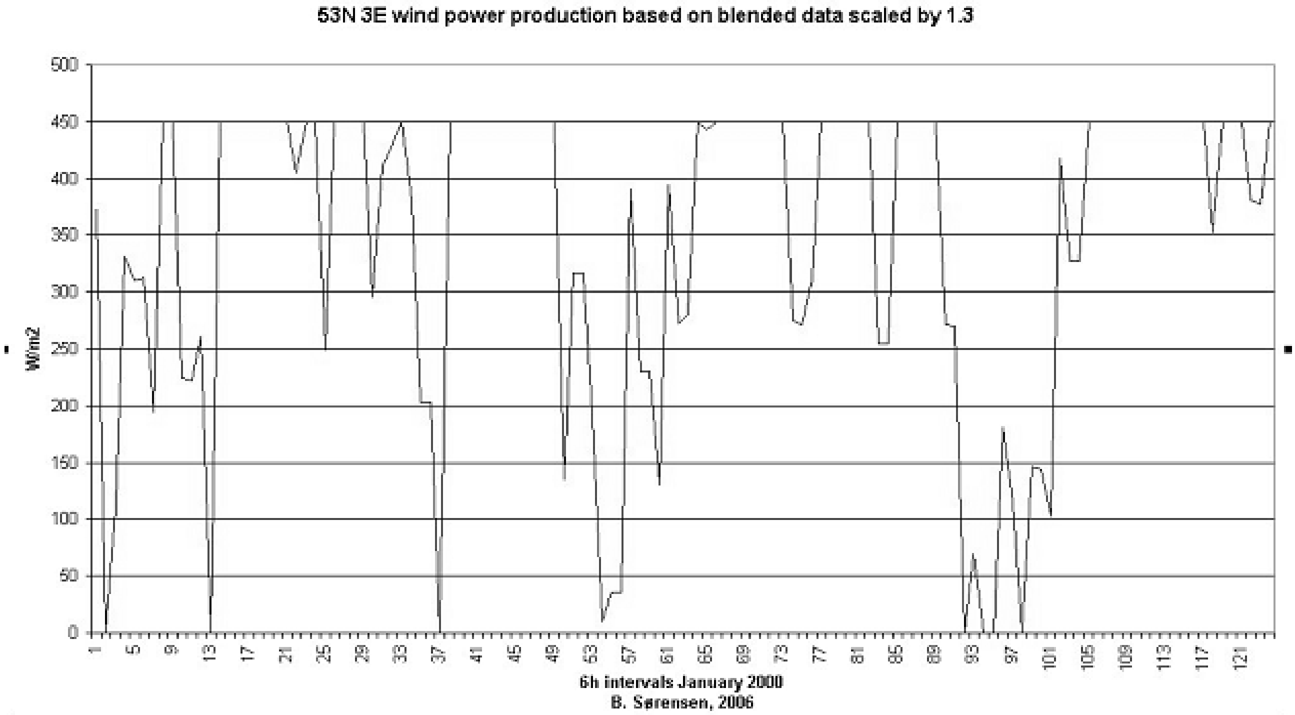
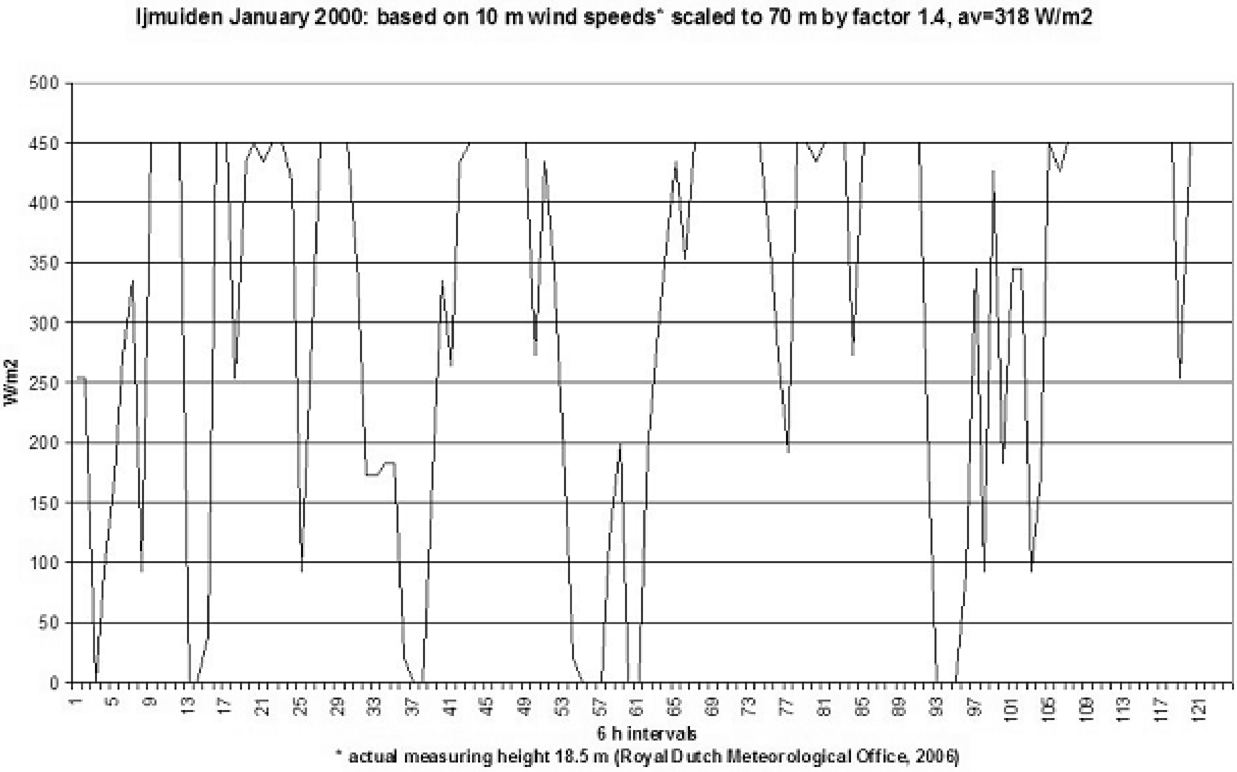


Figure 7. Measured time series of wind power output at the off-shore Dutch location Station XX during January 2000 (top; KNMI 2006) and corresponding power calculated from scatterometer blended data for (bottom). The time resolution is 6 hours (Sørensen, 2006).



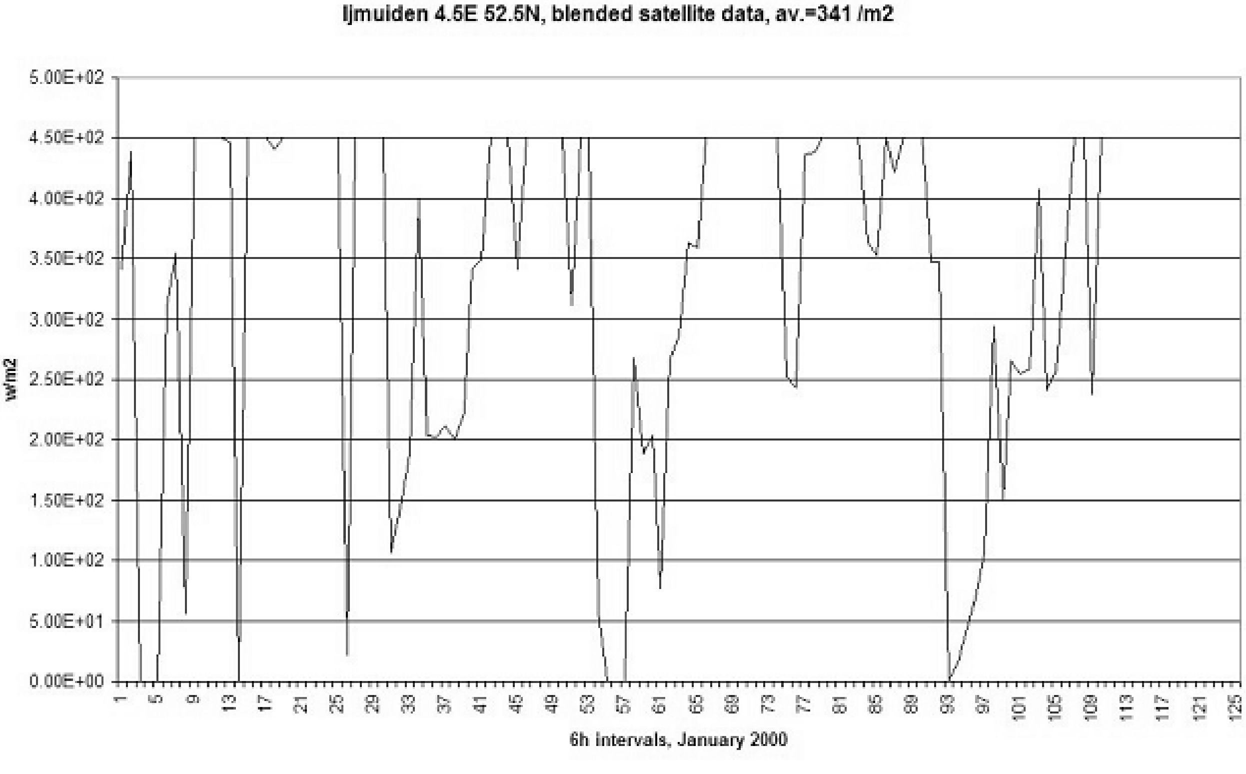
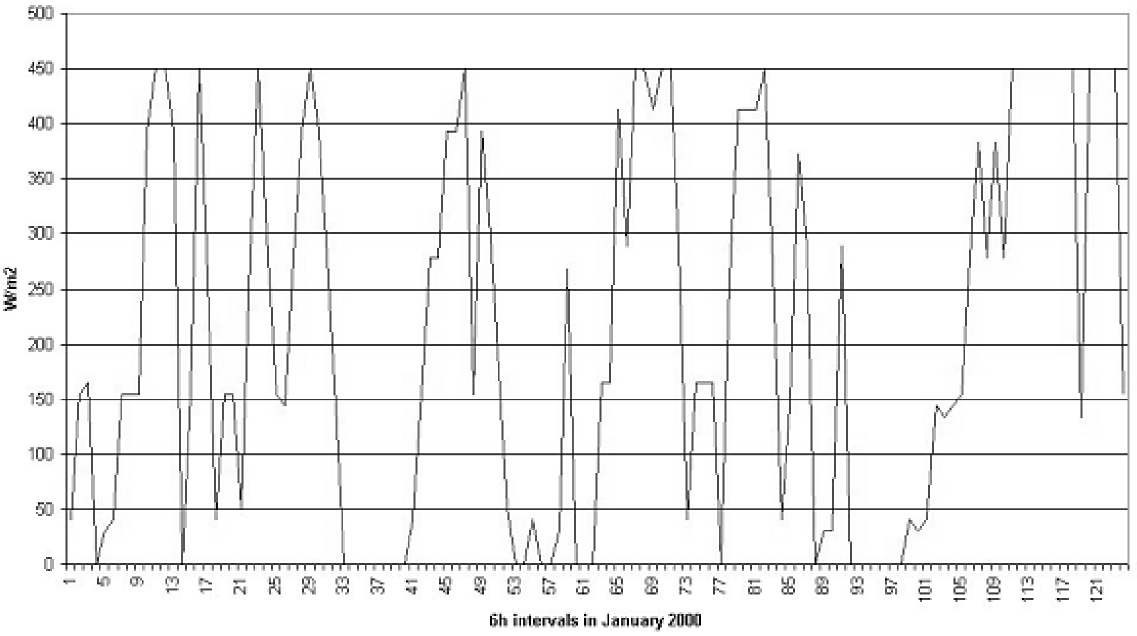


Figure 8. Measured time series of wind power output at the Dutch location Ijmuiden during January 2000 (top; KNMI 2006) and corresponding power calculated from scatterometer blended data for January 2000 (bottom, scaling 1.0). The time resolution is 6 hours (Sørensen, 2006).

Twente wind power production based on measured speeds at 10 m scaled to 70 m by 1.61 (av. = 209 W/m2)



Twente (7.0E, 52.5N) based on blended data (scaling 1.0). Av.=193 W/m2

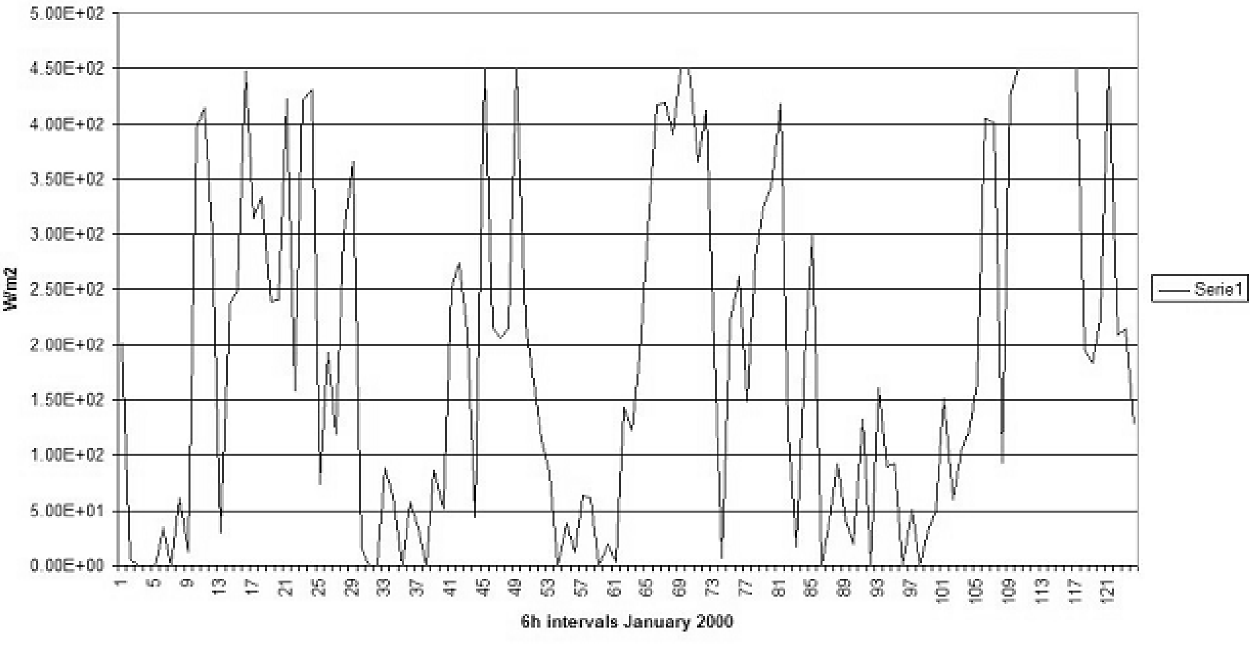


Figure 9. Measured time series of wind power output at the Dutch location Twente during January 2000 (top; KNMI 2006) and corresponding power calculated from scatterometer blended data for January 2000 (bottom). The time resolution is 6 hours (Sørensen, 2006).

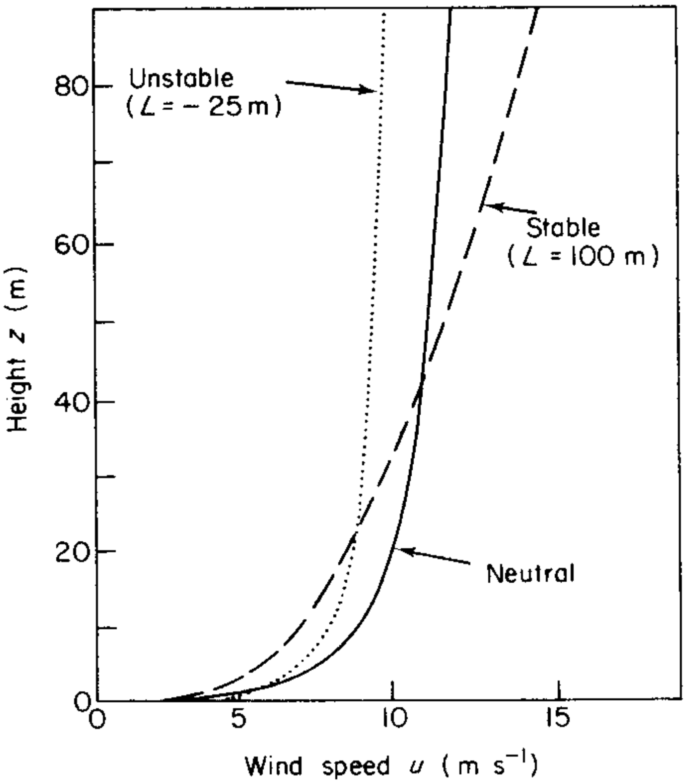


Figure 10. Wind speed profiles for three types of atmospheric stability. The parameter *L* used to describe the non-neutral curves is called the Monin-Obukhov length (from Sørensen, 2004).

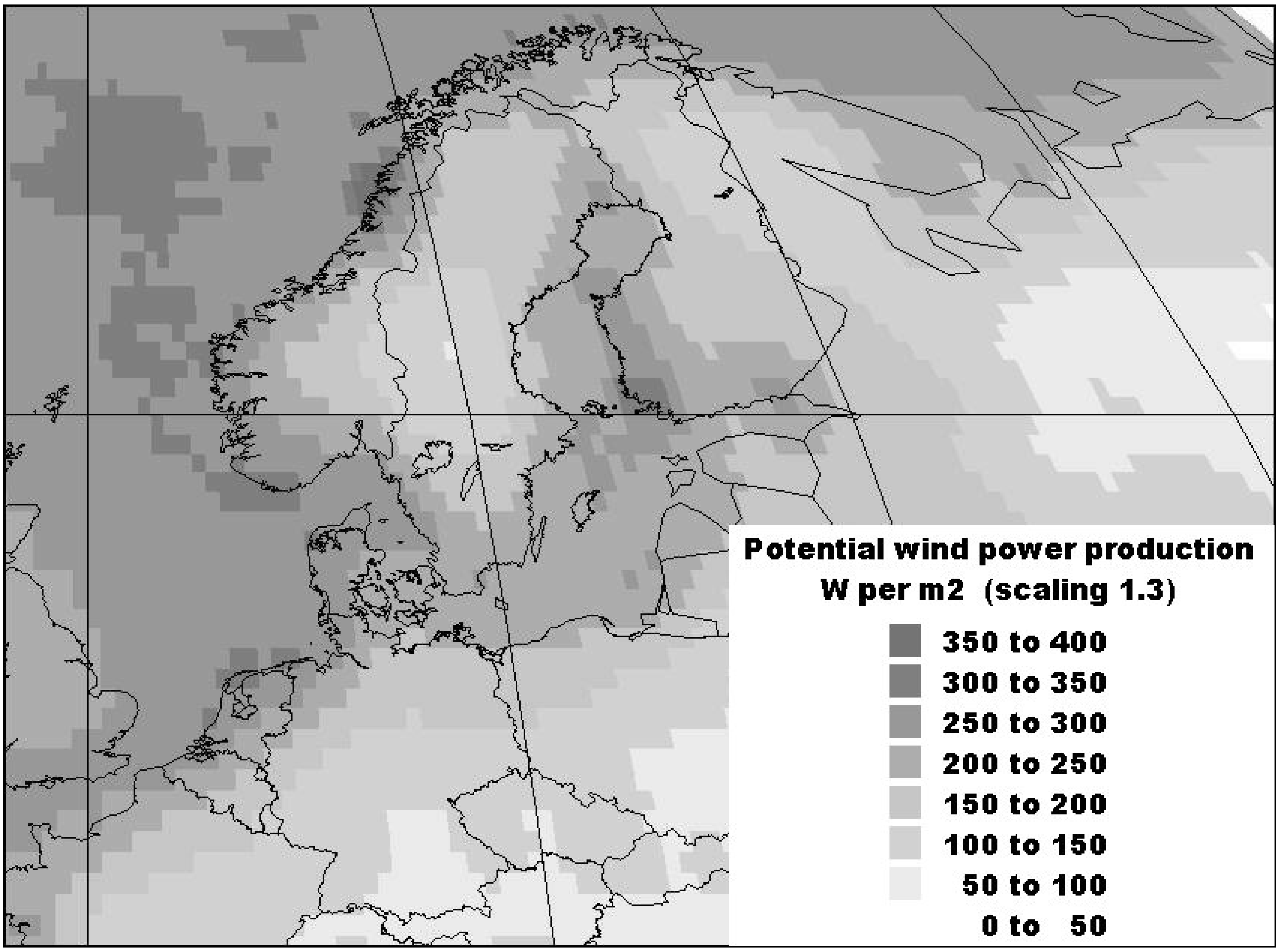


Figure 11. Map of wind resources in Northern Europe, based on blended data model with a scaling factor of 1.3 and a power conversion curve typical of current wind turbines (Sørensen, 2006). The unit is annual average watts per m^2 of swept turbine area

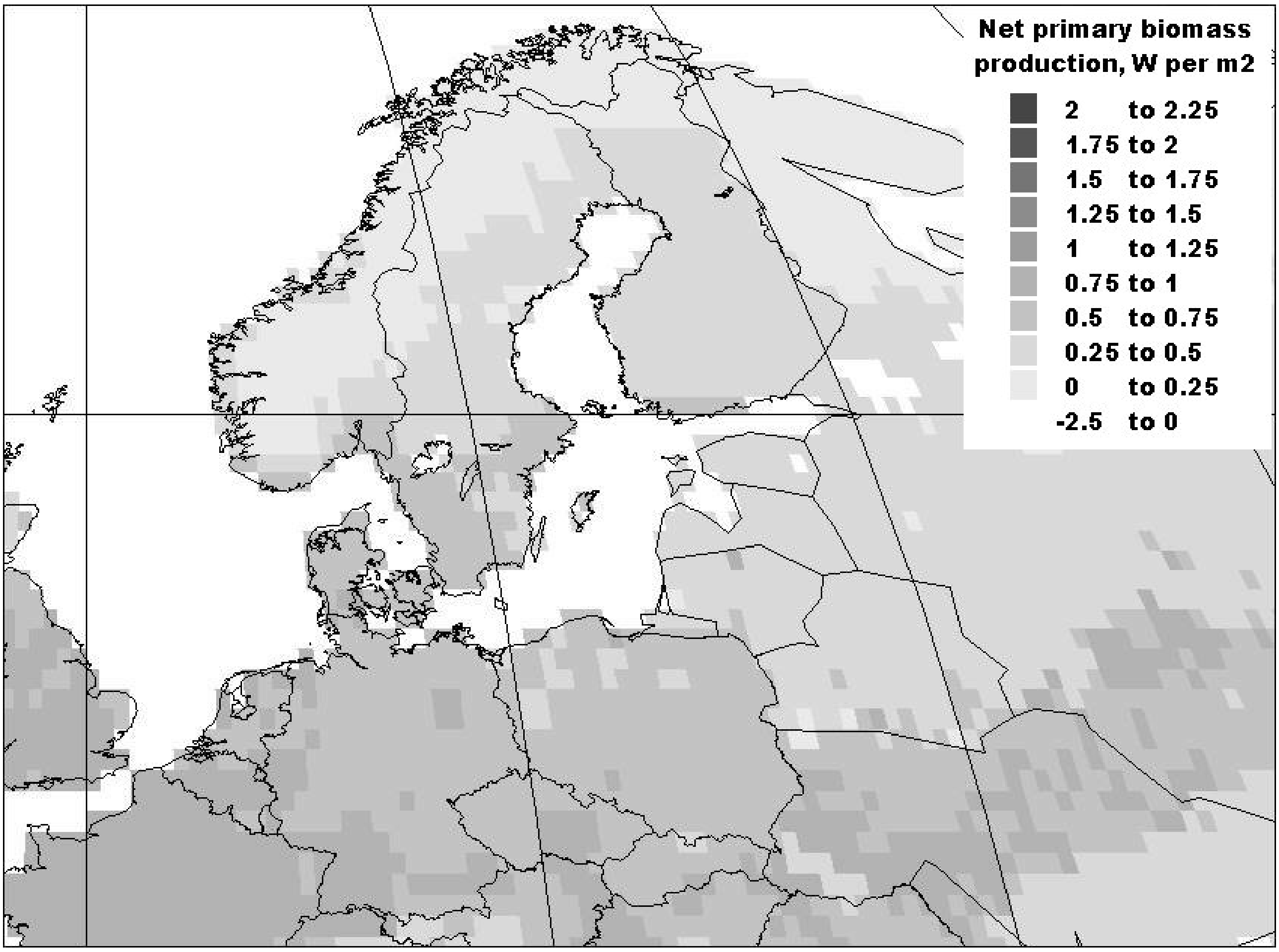


Figure 12. Potential net biomass production in Northern Europe, based on the model described in Sørensen (2004). The unit is W per m^2 of land.

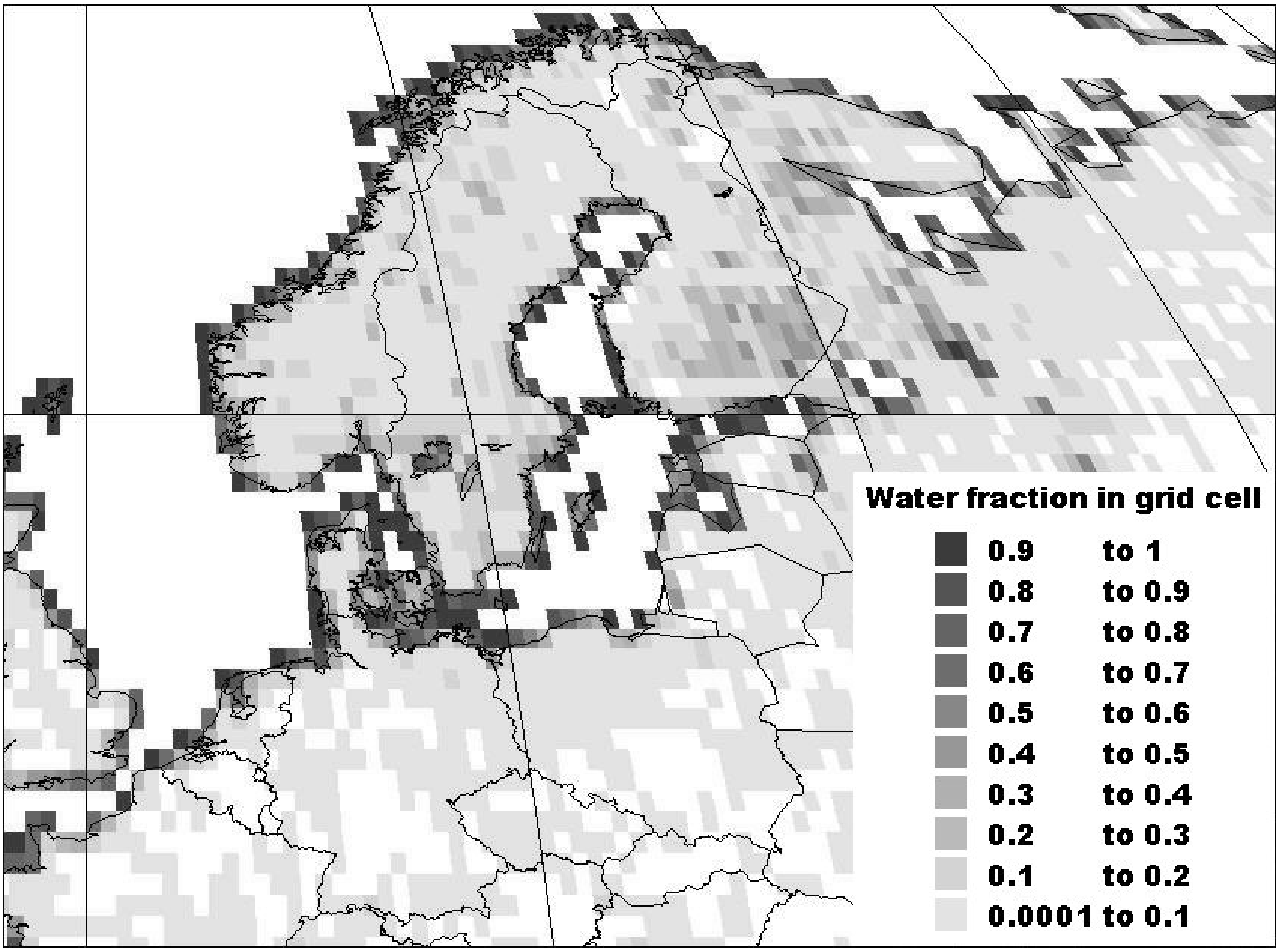


Figure 13. The water fraction of each cell in the model geographical grid. Inland values contain lakes, rivers and other streams, while off-shore values basically indicate the areas of up to 20 km from the coastline, which potentially could be utilised for aquaculture.

Chapter 3. A renewable energy and hydrogen scenario for northern Europe: Supply-demand matching simulation studies *

SUMMARY

A scenario based entirely on renewable energy with possible use of hydrogen as an energy carrier is constructed for a group of North-European countries. Temporal simulation of the demand-supply matching is carried out for various system configurations. The role of hydrogen technologies for energy storage and fuel cell applications is studied and applied to both stationary energy use and transportation sectors. As an alternative, biofuels may take the role of hydrogen both as a storable fuel and for direct use in the transportation sector. It is shown that there is scope for considerable amounts of energy trade between the countries, due to the different endowment of different countries with particular renewable energy sources, and to the particular benefit that intermittent energy sources such as wind and solar can derive from exchange of power. The establishment of a smoothly functioning renewable energy supply system is demonstrated with use of the seasonal reservoir-based hydro components in the northern parts of the region. The outcome of the competition between biofuels and hydrogen in the transportation sector is dependent on development of viable fuel cells and on efficient technologies for converting biomass residues to fuels.

KEY WORDS: scenario technique, energy modelling, simulation, renewable energy

1. INTRODUCTION

The first study suggesting that all energy needs in society could be derived from renewable resources was put forward several decades ago by Sørensen (1975). That study also constituted the first use of the scenario technique to the energy sector, and was one of the first demonstrations of the role that hydrogen can play as an energy carrier and storage medium. Other suggestions of an important role for hydrogen in future energy systems were put forward during the early 1970ies, e.g. by Marchetti (1973), Bockris (1972) and Veziroglu (1975), but mostly based on supply from non-renewable resources such as nuclear energy.

The development of the energy scenario method has gone through a sequence of increasingly well-founded and detailed models of the functionality and consistency of the energy systems found worthy of study. In particular, the procurement of realistic data on future availability of various energy sources and the mapping of technology progress towards higher energy conversion efficiency have advanced considerably. Some recent studies are described in Nielsen and Sørensen, (1998), Sørensen and Meibom (2000), and in Sørensen (2004, 2005). The present study is connected to an ongoing project on the relationship between hydrogen and energy trade (Sørensen *et al.*, 2007), aimed at studying the roles of energy trade and large-scale hydrogen storage in an all renewable energy-hydrogen energy system for Denmark and the neighbouring countries with which energy trade is already established (Norway, Sweden, Finland and Germany).

- Contribution from RUC to the Comparative Assessment project, published by Bent Sørensen in the International Journal of Energy Research, 2007. E-mail contact: boson@ruc.dk, website: http://energy.ruc.dk

A number of energy demand scenarios has been formulated, as described in the adjacent article (Sørensen, 2007a). For the present study, the middle scenario (described in section 3.2.2 of Sørensen, 2007a) is used, as regards the year 2060 status of implementing efficiency improvements and particularly with respect to the development of human activities in the countries concerned. The energy demand assumed in 2060 for the five countries involved are shown in Figures 1-5, reflecting variations between countries due to different intensity of industry and different climatic conditions affecting building heat losses. It is assumed that the much larger demand differences existing today will decline in a future where energy transmission and trade has eliminated the large energy price variations of the historical energy system. The liberalisation of transmission and exchange business environments has already achieved a considerable move towards consistent pricing.

The primary renewable energy sources are wind power (on- and off-shore) for regions with a fairly open coastline, hydropower for regions with suitable mountains and biofuels for the regions with either agricultural or forestry production. Only residues from cultivation activities are considered for energy purposes, in order not to interfere with food production or alter forest coverage. However, aquaculture in near-shore locations is also considered, as this is seen as an important potential source for additional biofuels in the future. Whether a competition with food production over such off-shore areas will emerge depends on the global population growth, but even so, one could again restrict the energy use of biomass to the residues from aquaculture food production. Finally, solar energy used for electricity or heat production is considered for the southern part of the region under study (i.e. Germany), because further north, the seasonal mismatch between solar radiation and energy demand (especially for space heating) is likely to make solar solutions remain too expensive. Small contributions to solar hot-water production in summer and other sources such as geothermal have been omitted because their contribution is likely to remain small, even 50 years into the future.

Table 1. Potential renewable energy supply available for use in the North-European countries considered (unit PJ/y). PVT is combined photovoltaic and thermal collectors.

Country:	DK	N	S	SF	D
Wind on-shore	64	167	201	147	157
Wind off-shore	358	974	579	391	177
Biofuels from agriculture	241	51	111	49	1993
Biofuels from forestry	58	523	1670	1180	892
Biofuels from aquaculture	153	223	320	205	108
Hydro	-	510	263	49	27
Solar PVT electricity	-	-	-	-	129
Solar PVT heat	-	-	-	-	275

The energy sources that could be employed in a sustainable way and with acceptable social and environmental impacts are summarised in Table 1. The wind potential on land is derived from re-analysis data ensuring measurement consistency by use of global circulation modelling (Kalney *et al.*, 1996), and assuming a wind turbine density similar to the one presently existing in Denmark, but using contemporary multi-megawatt units. The wind potential off-shore is estimated from satellite scatterometer data (Chelton *et al.*, 2004; Sørensen, 2007b), and the area fractions of near-shore waters employed are similar to those already set aside for wind power purposes in Danish waters. Biomass potentials are estimated from global vegetation growth models (Melillo *et al.*, 1993; Sørensen, 2004). The hydro figures are the current actual production (NORDEL, 2005), as no expansion is foreseen, and finally, the solar radiation and collector model used for Germany is described in Sørensen (2004). It assumes photovoltaic collectors with an average efficiency of 14%

to be installed on about a quarter of all suitable south-facing building roofs and upper facades, but with removal of useful thermal heat from the same collectors at an average efficiency of 36%. The combined heat and power panels are denoted “PVT collectors”.

2. ENERGY CONVERSION, STORAGE AND TRANSMISSION

Because of the likely high proportion of electricity in the primary energy mix of the scenarios to be constructed, as caused by the large identified resources involving wind and hydro in the countries modelled, it is envisaged that electricity will cover not only demands specifically requiring this form of energy (called “dedicated electricity”), but also other demands such as industrial process heat, space heating and hot water needs in private and commercial buildings. This requires energy conversion, which is assumed to be by use of electric furnaces for high-temperature heat and use of heat pumps for low-temperature heat, taking advantage of a high COP of 3 to 4.5 (the coefficient of performance, COP, is the energy ratio of heat output to electricity input). Due to the intermittency of wind power, also conversion to and from a storable energy form is considered, although a competing option might be to use power import and export to cope with fluctuations, provided that there are surpluses or unsatisfied demands in the neighbouring system, whenever the need for import or export arises.

There is clearly a strong dependence of these issues on the precise nature of the wind variability. The time-series shown in the adjacent article (Sørensen, 2007a) indicate that seasonal variations on average are similar to those of demand, and that deficits are compensated by later surpluses on a time scale of a few weeks. This is then the required storage period, if storage is used to cope with the intermittency. Another way to view the variability of wind is to construct power output duration curves, showing how large a percentage of time the power exceeds a given value. For a single wind turbine erected in a given climatic regime, there is usually a fraction of time (typically 20-30%, cf. Sørensen, 2004) where no power is generated. For the combined production of a geographical region there is a smoothing effect of the wind variability over the distance of turbine dispersal. For a small-size country such as Denmark (some 500 km width) this leads to power curves such as the ones shown in Figure 6, representing all on-shore or all off-shore sites. It is seen that now there is always some output, but it goes to zero when availability all hours of the year is required. The maximum output, on the other hand, is around twice the average. The precise value depends strongly on turbine construction (blade profiles and procedures for handling high-wind situations, e.g. by shutting down the turbine above say 25 m/s winds, cf. Sørensen, 2004).

In Figure 7, power duration curves for off-shore wind power production are shown for all five countries studied. As expected, the German duration curve is very similar to the Danish one, because German coastlines are all in the North (facing Baltic Sea and North Sea). The Norwegian duration curve is quite different, with many more hours of high output. In fact, 20% of the average power is available more than 99% of the year, 50% of the average power is available 95% of the year. The reason is of course that there is excellent wind production potential all along the Norwegian West-coast, covering a latitude span from 58°N to 71°N or some 1500 km. This means that climatic differences in circulation patterns are large enough to produce substantially different wind regimes in the North and in the South, and hence smoothing of combined turbine power output. Typical sizes of weather front systems is of the order of 500 km (see e.g. Sørensen, 2004). For Sweden and Finland, the situation is intermediate between that of Norway and Denmark. Although the distance between Northern and Southern parts of these countries is also large, the wind conditions are favourable only on exposed coasts facing the Baltic Sea to the West or the South, and for Sweden the small coastline towards the Kattegat and Skagerak North Sea inlets. The interesting implication of these features is, that if the energy systems of these countries use high proportions of wind power, both for some non-time-urgent tasks such as hydrogen production and for direct coverage of power needs, then the fraction of dedicated electricity use may be low enough that is can be covered at all times, even without energy storage and with power trade only inside the region.

Biomass harvests often take place at specific times during the year, although collection of forest management wastes is more flexible. However, it is considered that the biomass residues used in the scenarios can either themselves be stored, or the biofuels obtained after conversion can. All the conversions lead to fuels (liquid fuels such as ethanol, methanol and biodiesels or gaseous fuels such as methane or hydrogen) that are storable in ways similar to present oil and natural gas storage. The reason for accepting a loss of around 50% of the energy by conversion to fuels is the specific needs of the transportation sector, together with the obvious lack of need for more electricity than can be derived from wind and hydro resources in the region, in all the countries considered except possibly Germany (see below). Any heat demand can be covered either by the losses in conversion, in those cases where district heating lines are available from the earlier non-renewable energy system (Germany, Denmark and Southern Sweden and Finland), or by heat pumps using the excessively available electricity, in cases where heat of fairly low temperature is required. High-temperature heat may be created by electric furnaces (based on wind if available or hydro) or by biomass furnaces (and in these case without much energy loss).

One alternative to biofuels in the transportation sector is fuels generated from electricity, of which hydrogen (by alkaline or proton-moving membrane fuel cell (PEM) electrolysis) is a clear possibility, having conversion losses expected to become lower than the current 20-30% (for large installations) and possibly as low as 5% (Sørensen, 2005). A further alternative is to use electric vehicles based on batteries, with a round-trip efficiency of around 75% but a serious weight penalty (lead or metal hydride batteries) and/or cost penalty (lithium-ion batteries). Most likely, pure electric battery-vehicles will only be serving special markets (such as city delivery and public transport), while battery-biofuel or battery-fuel cell hybrid vehicles offer quite attractive compromises between weight and cost. They will require environmental attention, primarily in terms of particle and NO_x emission control devices (Sørensen, 2006a, 2006b).

The energy storage options considered for handling the intermittency of particularly wind energy are hydro reservoir water storage and geological storage of hydrogen or other compressed gases (such as air). Hydro stores are abundant in the Northern countries, with reservoirs allowing seasonal smoothing of power generation. Peak water-inflow is in early summer, when snow covering the catch areas melts. Reservoir fillings have been monitored over several decades and show important variations between years, in addition to the seasonal behaviour illustrated in Figure 8. The inflow is derived from historical data (NORDEL, 2005) by adding power production to the signed increase in reservoir filling (translated into energy units).

The Nordic countries are characterised by generous access to renewable energy: Large amounts of hydropower in Norway and Sweden, large amounts of wood scrap from forestry operations in Sweden and Finland (to be converted to e.g. methanol in the scenarios) and large amounts of wind energy along coastal sites in all of the four countries (plus the 5th Nordic country, Iceland, which is not included here because it has no grid connections to the other countries). It is therefore not surprising, that the simulations show that these countries can be self-sufficient in energy supply from such renewable sources. The intermittency of wind energy turns out not to be so large, that any substantial trade of electric power between the Nordic countries is called for. The reasons are first the difference in wind regimes discussed in connection with Figure 7, and second the establishment of a level of wind exploitation considerably greater that that required by dedicated electricity demands. The latter choice implies that a part of the wind power generated does not have time-urgent uses but may be converted (e.g. to hydrogen) at variable rates, leaving a base-production of wind power sufficient to cover the time-urgent demands.

In Figure 9, the on- and off-shore wind power production of each country is shown, relative to the total land area of the country. Measured in this way, Denmark has the highest wind potential. Representing the totals relative to the country's population, the situation is as shown in Figure 10a. This is a relevant indication, as power usage is roughly proportional to population size. It is now seen, that Norway has a very large wind resource, the three other Nordic countries a substantial resource, but Germany only a very modest one. Except for Germany, the highest potential is off-shore, even if the placement of wind turbines is limited to the off-shore fraction of grid squares with an size of something like 25 km × 50 km (cf. the discussion in Sørensen, 2007a). The exploitation of potential wind sites inland is very modest, assuming that the area swept by turbine rotors is only 0.01% of the land area for all countries except Denmark, where it is 0.02%. Due to the fairly large grid size used, a large number of mixed grid land-sea cells in Denmark are classified as off-shore (the criterion used is a water fraction above 20%, cf. Fig. 13 in Sørensen, 2007a). Including the on-shore fraction of these, the Danish on-shore average wind production becomes 2027 MW, a reasonable estimate corresponding to the use of only sites already having a wind turbine today, but replacing the smaller turbines with units of at least 2 MW. The current average Danish production is about 830 MW. The larger turbines will have different production profiles (cf. Figure 9, top) from today's, because of the larger hub height and presumably modified power curve. The power curve assumed for all turbines in the current study is shown in Figure 10b.

For off-shore grid cells considered for wind power production, the turbine swept area is for all countries taken as equal to 0.01% of the (horizontal) grid-cell area. For mixed on- and off-shore grid cells, the water- and non-water fractions are used to assign wind production. It is interesting to note (see Figure 9, top), that the selected turbine characteristics imply a peak shaving in high-wind situations for Denmark that is absent in e.g. Norway. The reason for this behaviour of the total on-land production of each country is that Denmark is small enough to have fairly homogeneous high-wind episodes (exhibiting peak-shaving), while for Norway, the wind regime differences between North and South is large enough to conceal the peak shaving of one fraction having high winds, because there will be other regions without high winds during the particular hour looked at. The estimated off-shore production potential for Denmark (Figure 9, bottom, and Figure 10a, top) agrees well with estimates of the potential power production from areas already set aside for off-shore wind parks (cf. Danish Power Utilities, 1997; Sørensen, 2005, p. 325).

Transmission costs will necessarily be larger in a future system using all the above-mentioned options. Partly, there is increased transmission between regions (or countries), if trade is used to handle supply-demand mismatch, and between stores and load-centres, if energy storage is taking over the intermittency handling, and partly there is additional transmission between the new power production locations (such as off-shore wind parks) and the locations of electricity uses (including the sites of conversion facilities for hydrogen production, whether done centrally or decentralised). Although quite substantial, these costs are still a minor fraction of the total costs of the proposed energy system (Sørensen, 2004).

3. SIMULATION METHOD

A number of one-year time simulations were made for possible future energy systems combining the data series (using a 6 hour time step) for supply and demand as discussed above, and with use of different sets of conversion devices with different orders of priority. The simulation year is taken as 2060 in order to be able to assume that the present system has been largely phased out in an orderly fashion, i.e. without premature retiring of equipment. One set of simulations assumes half the transportation activities to use fuel cell-battery hybrid vehicles and the other half Diesel or Otto engines in vehicles of high basic efficiency. Hydrogen is stored in underground caverns such as aquifers or salt dome intrusions and piped to filling stations (Sørensen, 2005; 2006). Power transmission lines within and between the countries are assumed upgraded as necessary. Biofuels can be used at arbitrary pace, while solar and wind energy must be used or converted as produced.

The energy form initially produced is either electricity, liquid fuels or heat. A priority schedule then first allocates bound or available production to simultaneous demands, then consider using stored energy for unsatisfied demands and finally consider energy transformation from one form to another, so that additional demands may be covered. Hydropower in the Nordic countries is reservoir-based and can be regulated. For this reason, it is given second priority after wind and photovoltaics for covering time-urgent loads. Heat is divided into low-temperature (under 90°C) and high-temperature (over 90°C) heat, the latter being supplied by converting electricity or fuels and the former by associated heat from power-producing fuel cells or other power plants or boilers, and else by heat pumps using electric power at a coefficient of performance around 4 (using soil or water streams as low-temperature reservoirs). Hydrogen is produced by fuel cells in reverse mode of operation, or by electrolysers (which are also fuels cells, but of alkali type as opposed to the membrane types currently appearing most promising for automotive purposes).

A separate set of simulations have been made, assuming that viable fuel cells will not become available, putting more strain on the biofuels for use in the transportation sector. Hydrogen can still be used for storage, but due to the large amounts of hydropower based on seasonal reservoirs in the region, this turns out to be unnecessary in the Nordic countries.

The simulations are first performed for each country alone, identifying export potentials and import requirements, both in the form of a time series. A second round of simulations is then performed, using the identified surpluses as import options for those countries with unsatisfied demands. In some cases this involves choosing between different options for trade between the countries.

4. SIMULATION RESULTS FOR EACH COUNTRY IN ISOLATION

Figures 11-15 show some uses of electric power produced in the countries involved, for a scenario with use of fuel cells and geological hydrogen storage, but before considering trade between the countries. Because all the identified renewable energy sources are assumed exploited, there is a large surplus of energy in the Nordic countries, making them able to benefit from an important export trade of both power and fuels to the European continent, should they elect to do so.

Except for Germany, the number of hours where wind cannot cover the direct electricity demand is quite low. The same is true for coverage of heat demands by electric furnaces (high-temperature heat) and by heat pumps (low-temperature heat). The hours of deficit are in all cases covered by conventional combined heat and power plants or, as a secondary priority, separate power and heat plants using biofuels. The availability of biofuels (associated with residues from a large agricultural sector in Denmark and Germany, and residues mainly from forestry in the other three countries, supplemented by aquaculture if necessary) allows all needs in the transportation sector to be covered. Alternatively, hydrogen may be generated from excess wind (and here the occasional deficits do not matter, since hydrogen may be stored in the underground caverns) and used in the transportation sector, leaving more biofuels to be exported to countries with less abundant renewable energy supply. For Denmark, this is shown in the lower part of Figure 11. All the Nordic countries have large amounts of wind power and biofuels potentially available for export. The scenario initially assumes that half of the energy for transportation is assumed derived from hydrogen, and Figures 16 and 17 show the role of a moderate size store placed in Denmark and Finland, respectively, each with an assumed capacity of 1.37 PJ, which is quite modest. In Denmark, the hydrogen store is capable of smoothing the wind power deficits during the months of March and April, while in Finland, hardly any smoothing is required. For the remaining Nordic countries, the situation is as in Finland. The role of the hydrogen store is thus basically to insure against unusually long periods without wind energy for producing hydrogen for vehicles. Hydrogen production from biomass is not included in the present scenarios.

Sweden, Finland and particularly Norway have a large electricity production based on (already existing) hydro. Figure 18 shows the build-up of a large exportable potential power export from Norway during the simulation year, due in part to the high wind power production coupled with the priority given to wind turbines (once built) in covering supply. The curves for Sweden and Finland are similar, although the total export potential is smaller, especially for Finland.

The situation for Germany is particularly interesting, as the renewable resources are here considerably more modest than for the Nordic countries: very little hydro, suitable wind power locations only at the northern coasts (Baltic and North Sea), and some solar energy derivable from building-integrated panels. Biofuels are more abundant, based primarily on residues from a sizeable agricultural sector, and there are some forestry residues, while aquaculture is limited by the small coastline (although inland waterways may be used to some extent). Figure 15 indicated the need for generating more electricity than can be provided by hydro, wind and photovoltaic power, and tentatively attributed this to conversion from biomass. However, the required amount of biomass makes the total amount of biofuels available within Germany insufficient for also covering the needs of the transportation sector, and in section 5 below follows a discussion of different import options for covering this German deficit in meeting demand with indigenous renewable resources.

It was from the start clear that it would be difficult to secure enough renewable energy for a German population more than four times as large as that of the Nordic countries combined, on a land area considerably smaller. Yet, the simulation behind this section's results shows that for the given choice of priorities in assigning coverage, demand for electricity and heat for both space conditioning and processes can indeed be covered, but as stated then only a part of the demand for transportation energy.

Figures 19-21 show the disposition of hydrogen and biofuels for Denmark, Norway and Germany. Sweden and Finland is similar to Norway. The Nordic countries satisfy 50% of their transportation needs by hydrogen used in fuel cell vehicles (probably as hydrogen-battery hybrids) and the other 50% by biofuels. There is scope for changing the relative contributions, e.g. if fuel cell costs do not come down sufficiently or if the environmental effects remaining in combustion of biofuels are not accepted by future societies. Denmark has to use a small amount of biofuels for industrial process heat, while the other Nordic countries can do with electric furnaces based on wind and hydro. For Germany, it is not possible to satisfy the transportation sector needs by indigenous energy resources, and the isolated country scenario lumps the deficit as a need for fuel imports. In this case, as seen in Figure 21, there is not sufficient wind-based hydrogen to supply 50% of the transportation energy.

The 2060 scenarios cover low-temperature heat (such as for space heating, hot water and industry) by a combination of excess heat from energy conversions (e.g. in fuel cells), assumed to be distributed through existing district heating lines, locally produced heat produced from environmental heat and electric power in heat pumps, and if any further demand exists then by direct combustion of biofuels. The situation is similar in the countries looked at, so only the Danish low-temperature heat provision is illustrated, in Figure 22.

In Figures 23-26, the surpluses available for export from the Nordic countries are shown. A large potential export of as well biofuels, intermittent wind power or hydro energy is available. Figure 27 sees these as import options for Germany, which needs to import energy.

The additional potential for energy exports from the Nordic countries may go to other continental European countries, e.g. via the transmission lines to Germany, or alternatively, the expansion of renewable energy production equipment may be halted at a lower level. The potential export amounts shown in Figures 23-27, particularly for electric power, are so large that extended transmission over larger distances may appear too costly. For biofuels, the large export potential may be reduced, either if the cost of converting not grains and sugar but residues to fuels appear too high, or for sustainability reasons, if future farming becomes entirely ecological and if the recycling of nutrients to the fields turn out to be more difficult than anticipated. In this connection, the energy requirements for transportation of residues from and back to the fields, forests or aquaculture locations are important factors influencing the decision (as well as the location of biofuel conversion facilities, cf. Sørensen, 2004).

5. SIMULATION RESULTS WITH ENERGY TRADE BETWEEN COUNTRIES

Having established the large energy export potentials of the Nordic countries and the substantial import need of Germany, a second set of simulations were performed, putting the Nordic surpluses or some of them at the disposal of the German energy system and rerunning the German model with these available import options given in terms of time series of electric power or biofuels offered.

The outcome is illustrated in Figures 28-31. Figure 28 shows the new optimisation of power and fuel disposition in the presence of the new import options. The lower part of Figure 28 shows how production of hydrogen based on imported (and intermittent) power is taking a decisive role in covering the demands both in the transportation sector and for some of the heat and dedicated electricity demands (Figures 29 and 30). As a consequence, the use of biofuels in conventional power and heat plants is diminished, and there is an apparent sequence of periods with sufficient German biomass and periods with import needs (Figure 31). However, as biofuels can be stored, the net result is self-sufficiency in fuels. That electricity is imported rather than biofuels is a result of the priorities built into the model, where uncontrollable energy production from already installed capacity has preference over controllable production. The average electricity surplus from the Nordic countries combined is some 2700 PJ/y, and it is seen that Germany needs to import nearly all of this to achieve the hydrogen production required. An implication of this is a reinforcement of power transmission lines several places in the system, but still entailing an expense considerably lower than that of establishing a hydrogen pipeline system to accomplish the same level of trade.

6. ALTERNATIVE SCENARIOS AND DISCUSSION

Provided that the development of biomass-to-biofuel conversion technologies is successful and allows the full potential identified here to be exploited at a reasonable cost (compared to the hydrogen/fuel cell alternative) and without unacceptable environmental impacts, then one may shift the priorities and cover the German deficit by imported biofuels rather than imported electricity. Transport of biofuels is less costly than power transmission and there is no intermittency that increases the cost of further conversion because the installed conversion capacity cannot be used at all times. Figure 32-35 shows the results of an alternative simulation run for Germany, with only biofuel imports. These fuels now take over many of the roles attributed to hydrogen in Figures 28-31. Electricity deficits are covered by combined heat and power plants (Figure 32). They are assumed fuelled by biofuels rather than by raw biomass (such as straw or wood scrap), because biofuels have considerably higher energy densities and hence lower transport costs. However, if these cost gains are not considered capable of off-setting the conversion losses associated with the biomass-to-biofuel conversion (some 50%), German imports could be of raw biomass residues. Figure 33 shows the reduction in use of electricity (compared to Figure 28 bottom panel) when no electricity import options are available. The coverage of low-temperature heat is shown in Figure 34, and Figure 35 indicates the total requirement for biofuel imports in the fuel-import only scenario.

Several other scenario variants have been subjected to simulation. One assumed that Norway does not develop its wind potential. Reasons could be that the delicate placement of turbines along the Western shoreline would meet with economic or environmental resistance. Economic problems could arise from the fact that rapidly increasing water depths could make the foundation work for the wind turbines too expensive, forcing the turbines closer to the shore or up on the rock-covered islands and shores. This could lead to lack of acceptance for reasons of disturbing the visual environment. The objection is less convincing than the strong protests launched earlier against the establishment of hydro reservoirs, because while the latter constitute irreversible changes of the ecosystems involved, a wind turbine can be removed at any time, leaving the ecosystem and visual environment exactly as before the turbine was built. Further reasons for perhaps not seeing the Norwegians use their exceptional wind potential could be the transmission costs from turbines to load centres, which would in many cases have to cross difficult terrain and probably require avoidance of overhead lines, again for visual environmental reasons. In any case, the result of not expanding Norwegian wind is negative only for Germany, which (in the scenario behind Figure 31) would have to import more biofuels to make up for the missing electric power. As shown above, there is scope for avoiding all power imports, but most likely, the import of electricity from the countries already electrically connected with Germany (i.e. Denmark and Sweden) would be seen as beneficially, at least in the event that fuel cell technology becomes viable for the transportation sector.

In summary, it has been shown that a high level of renewable energy exploitation could provide substantial economic benefits for endowed countries such as the Nordic ones, as well as stable energy supply benefits for deficit countries like Germany, and that additionally, the storage/backup problem associated with the intermittency of wind and solar energy will actually be diminished by a higher level of exploitation, particularly if it stretches as far, geographically, as from Germany to North Cape.

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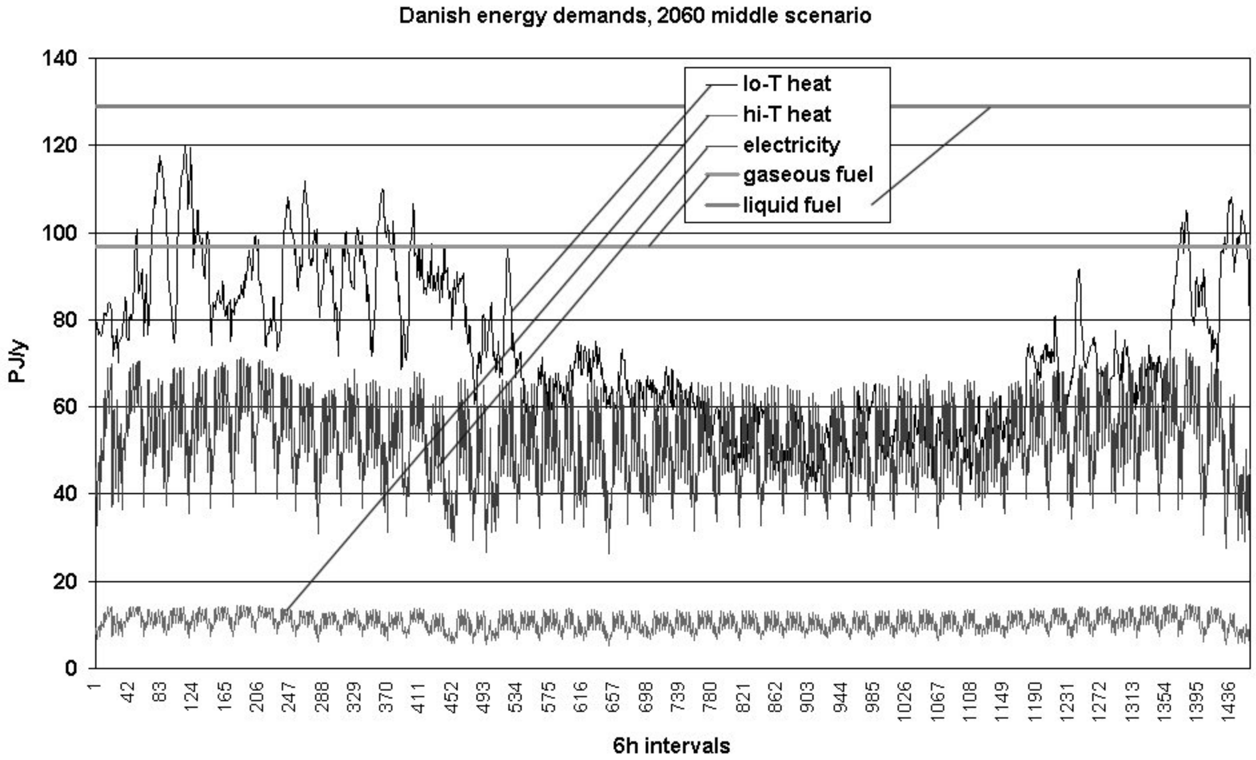


Figure 1. Energy demands for Denmark used in the 2060 scenario. The electricity usage shown is dedicated electricity, implying that further electricity may also be used to cover other needs, if convenient. The energy delivered for transportation is divided equally between fuel cell vehicles using hydrogen ("gaseous fuel") and biofuel vehicles (using "liquid fuel" such as biodiesel, ethanol or methanol), but the demand is different due to different engine efficiencies.

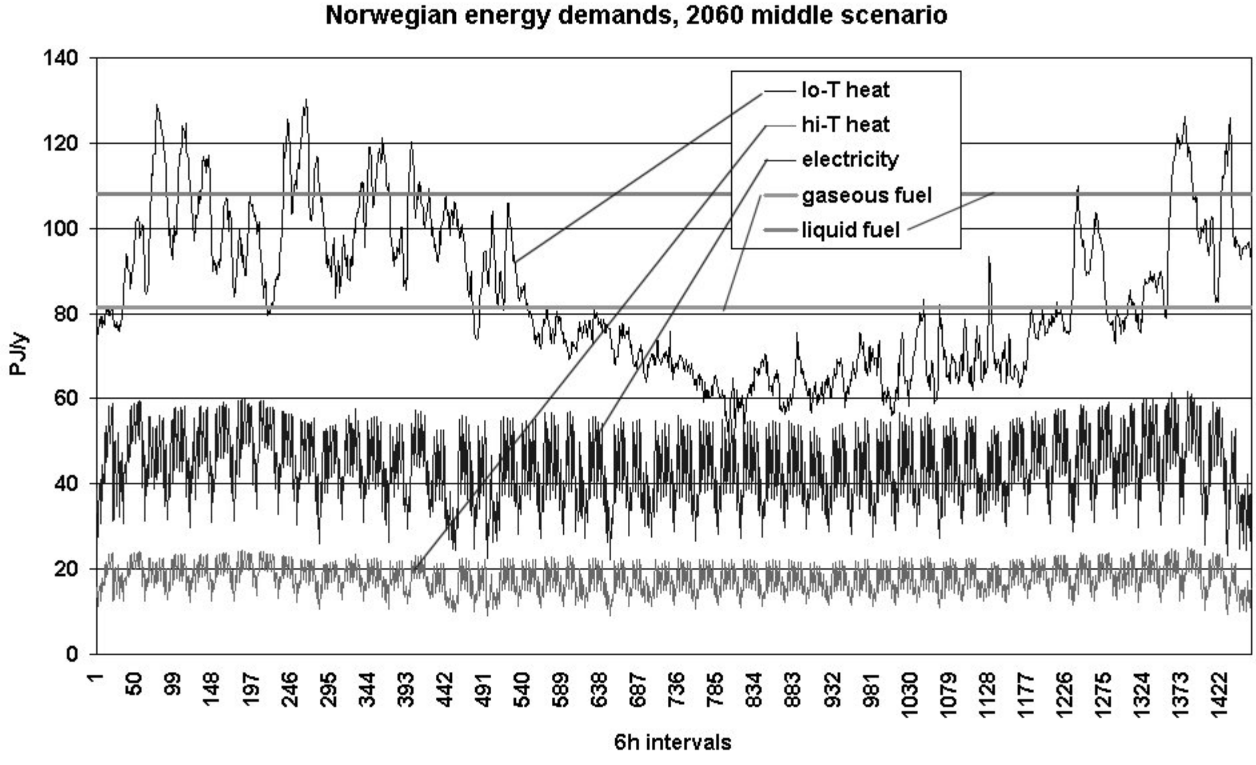


Figure 2. Energy demands for Norway used in the 2060 scenario. See remarks in caption to Figure 1.

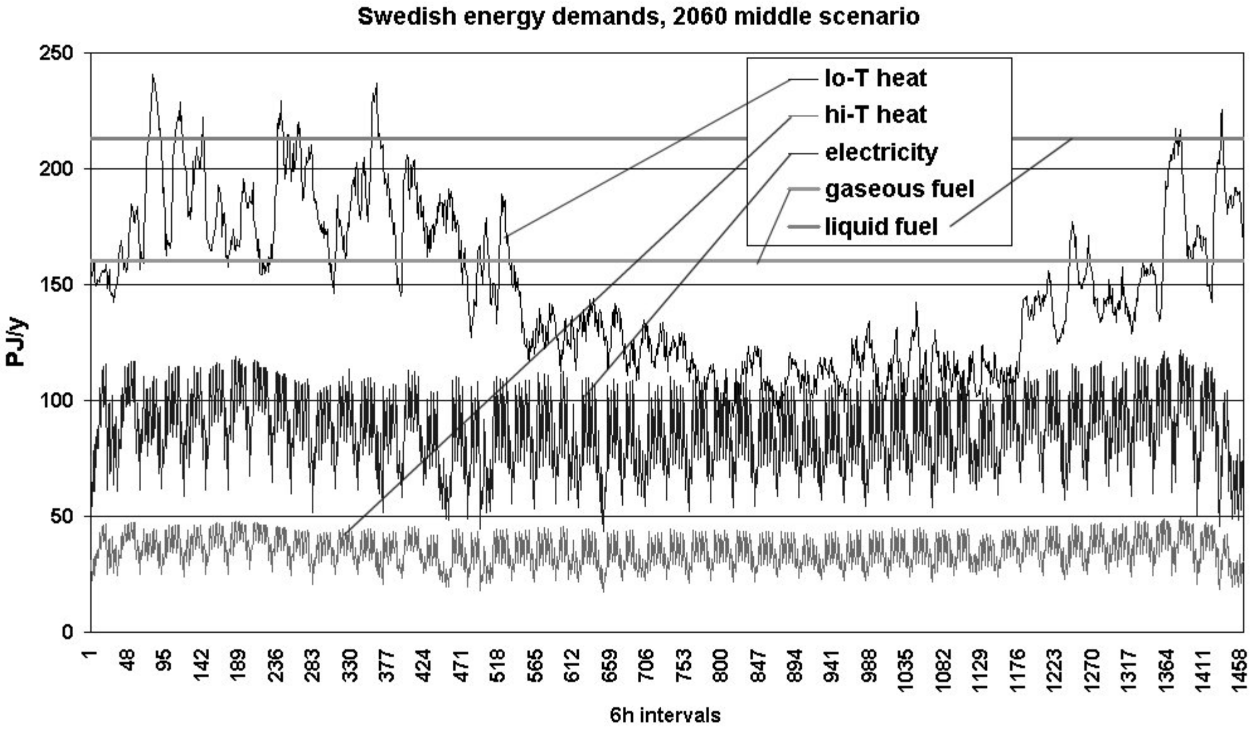


Figure 3. Energy demands for Sweden used in the 2060 scenario. See remarks in caption to Figure 1.

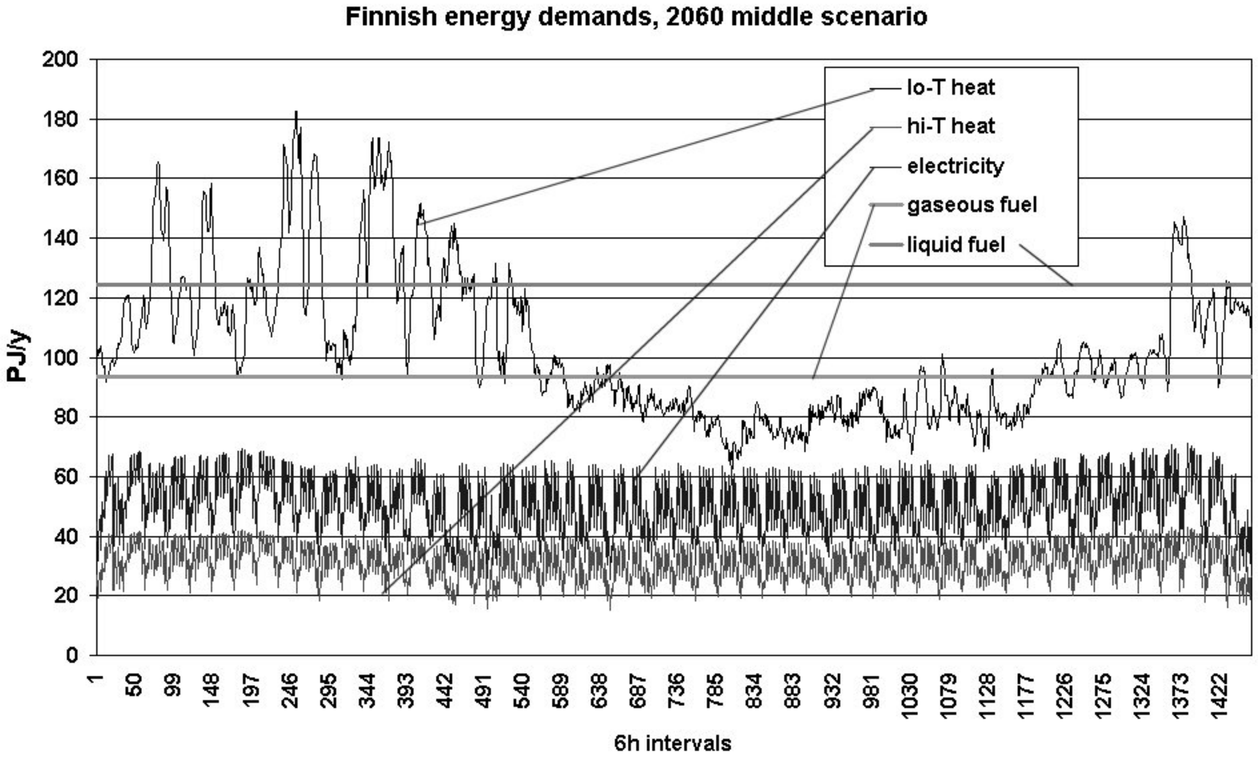


Figure 4. Energy demands for Finland used in the 2060 scenario. See remarks in caption to Figure 1.

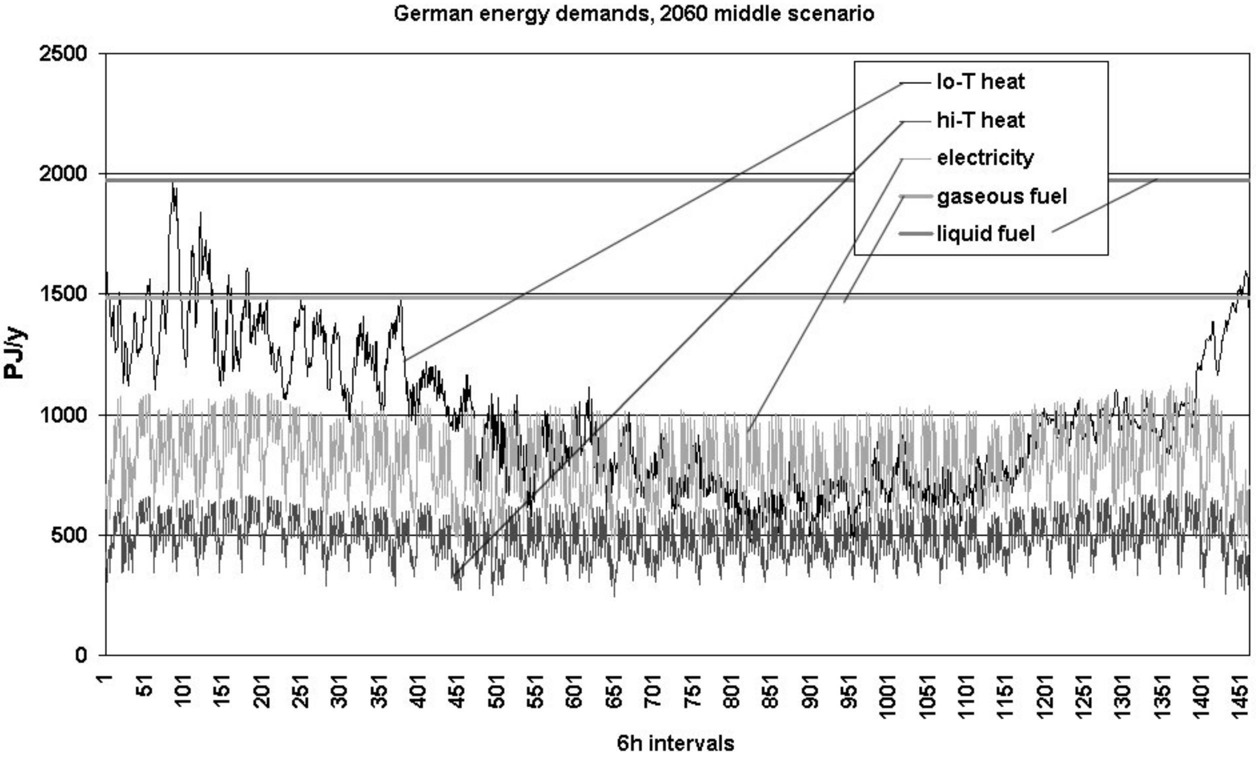


Figure 5. Energy demands for Germany used in the 2060 scenario. See remarks in caption to Figure 1.

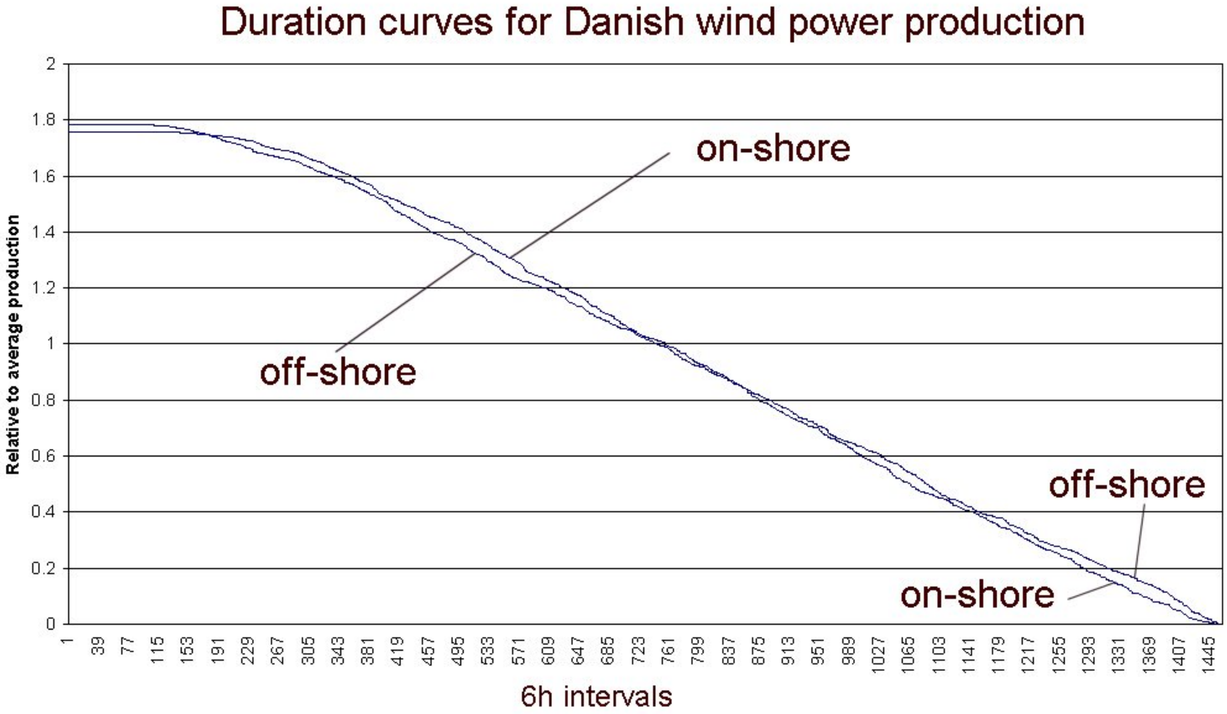


Figure 6. Power duration curves for Danish power output of all on-shore and all off-shore wind turbines considered in the scenarios. The off-shore wind production is only slightly more persistent than that on land, for the identical turbine power curves (power output as function of wind speed, see Figure 10b) assumed for the 2060 technology. This is in contrast to the current situation, where use of annual-production optimised turbines on land but not off-shore reduces the number of production hours for land-based turbines and in return gives a maximum production of more three times the average (cf. Sørensen, 2004).

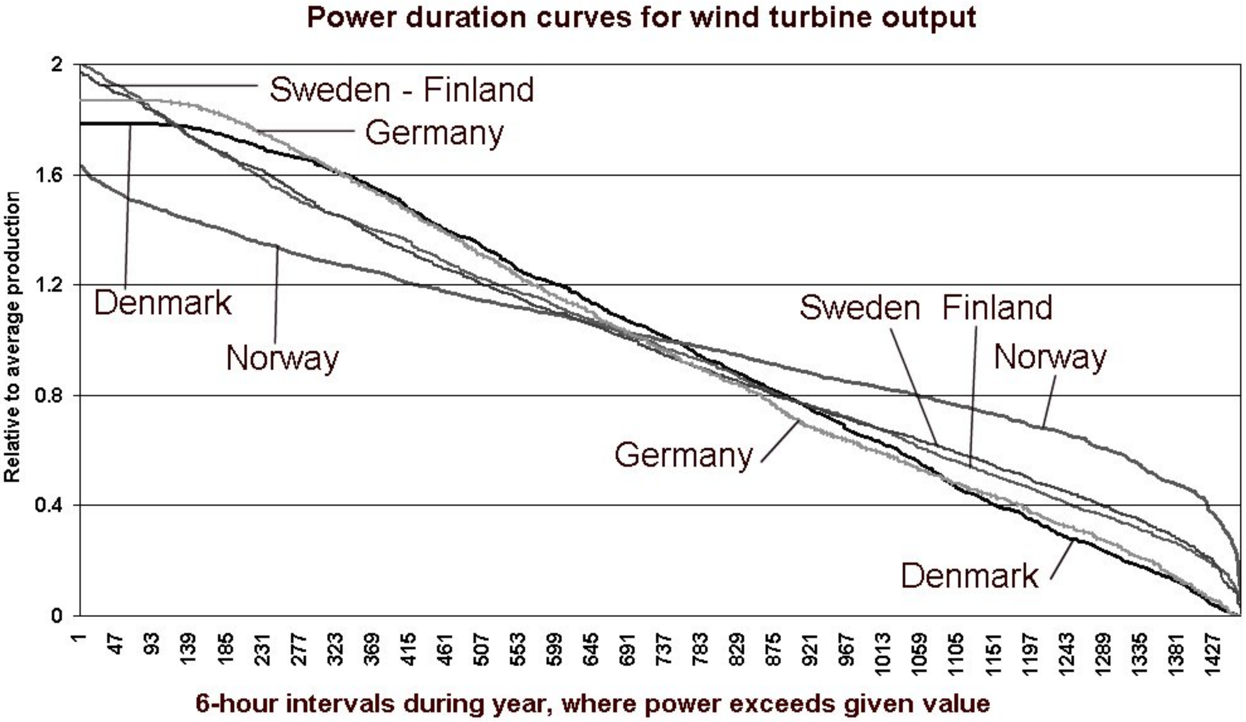
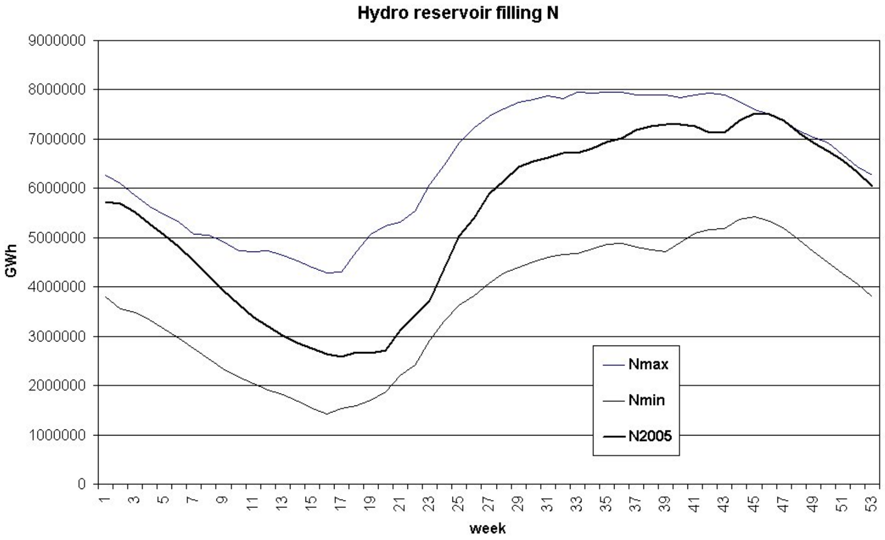
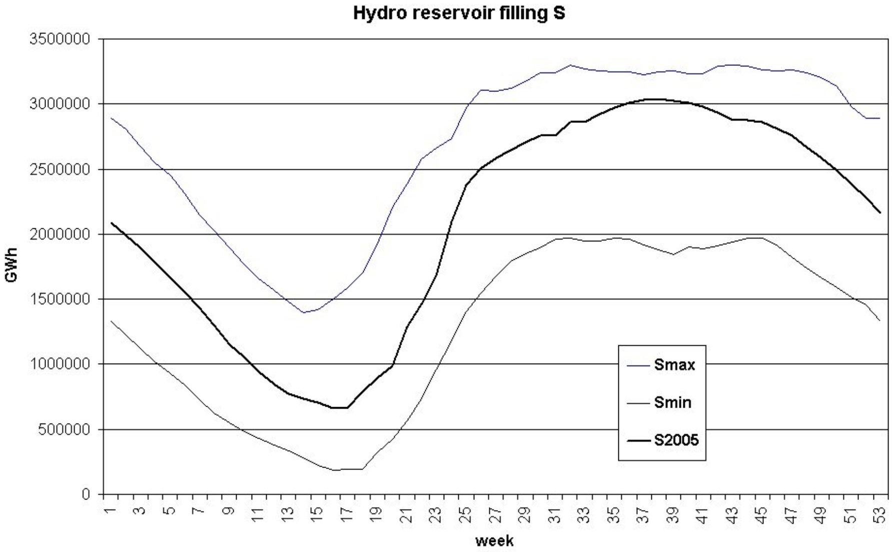


Figure 7. Power output duration curves for all off-shore wind turbines in the 2060 scenarios of the five countries studied. See text for a discussion of differences between the curves.





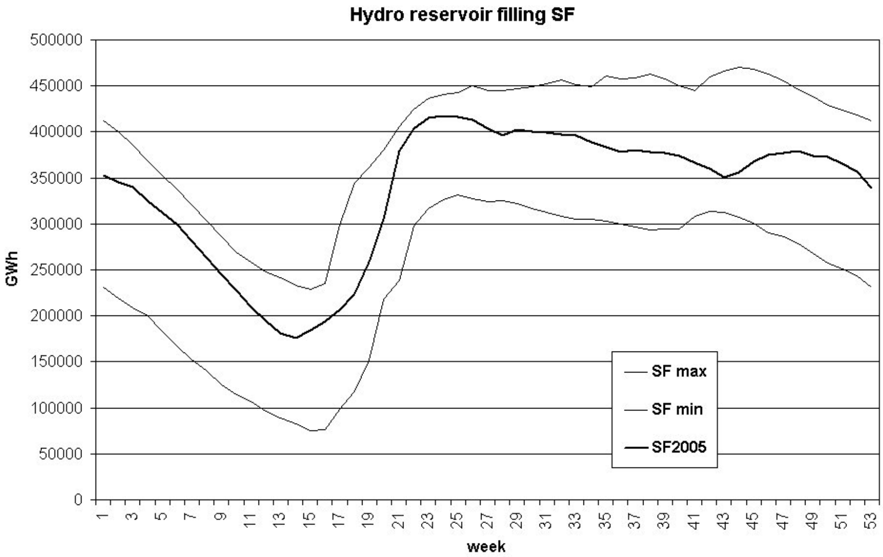


Figure 8. Current filling of Nordic hydro reservoirs, through the year 2005 and indicating the minimum and maximum filling for each week in the wear, over the past decades. Based on data from NORDEL (2005).

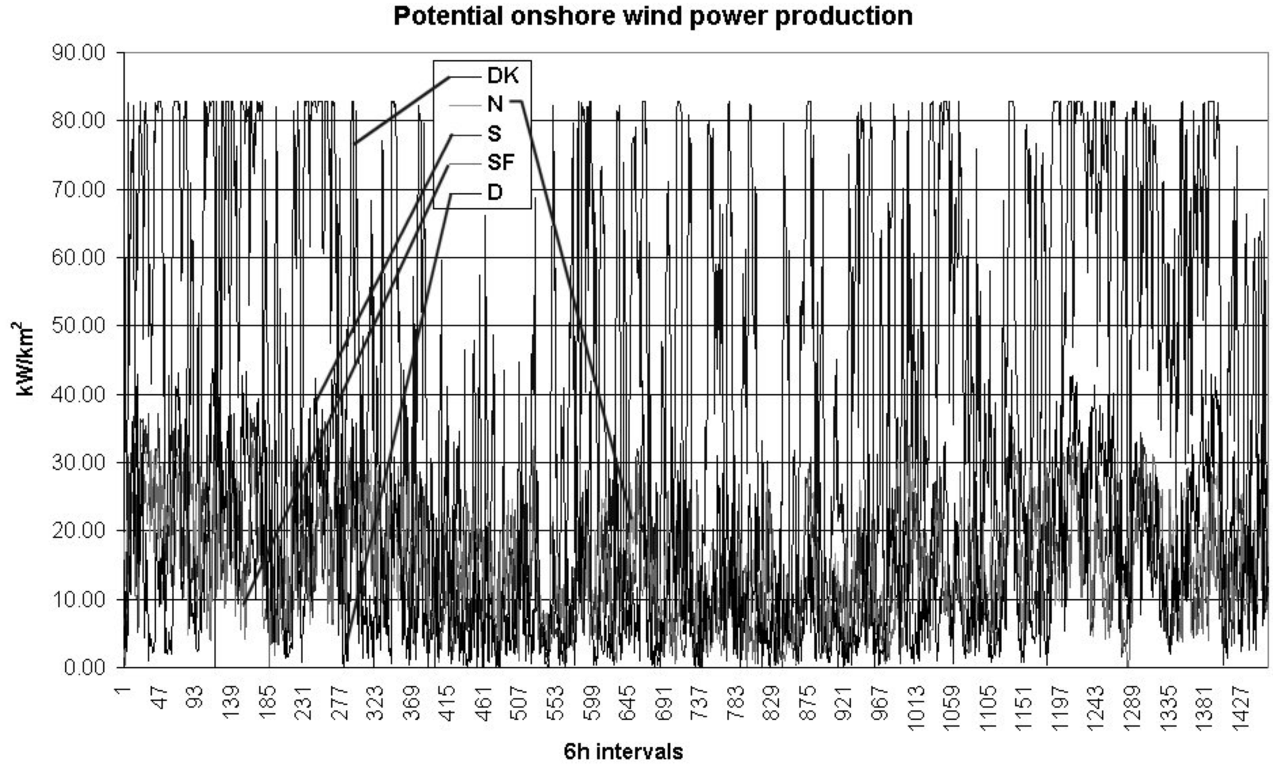
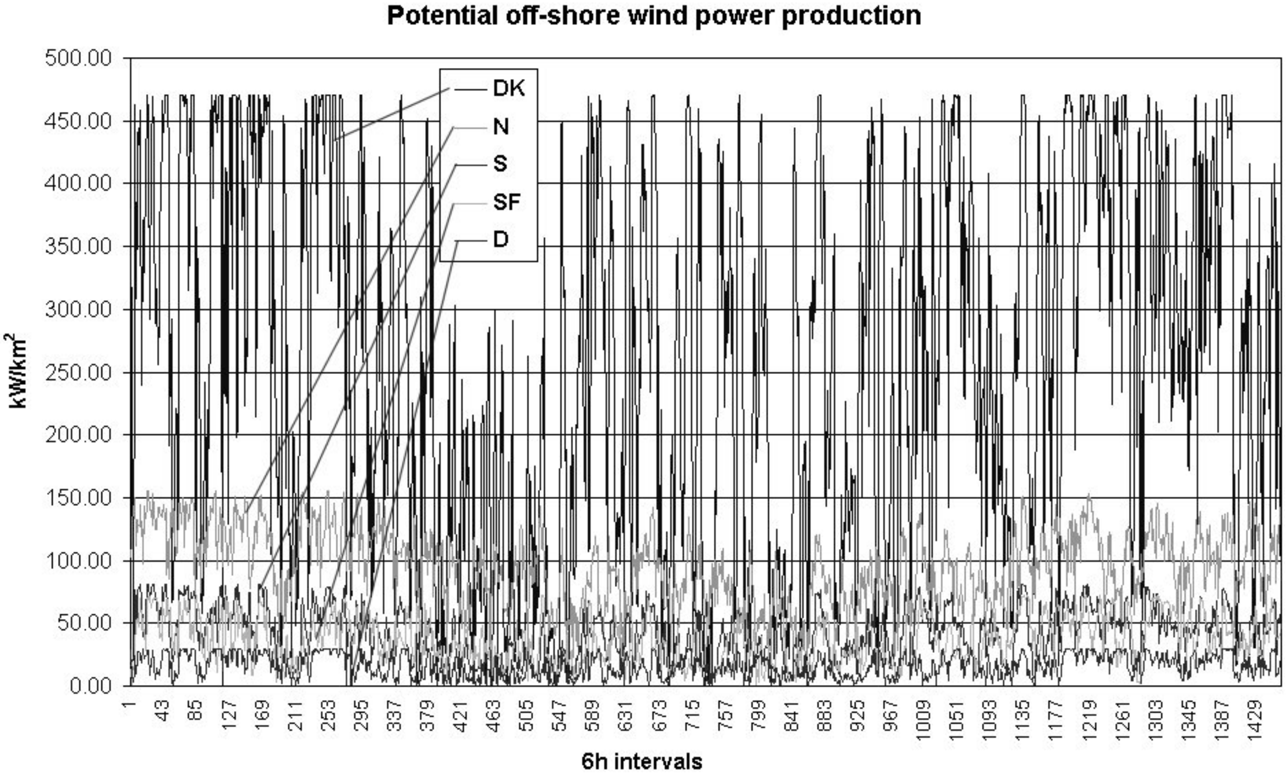


Figure 9. Wind power production from the sites selected for suitability, environmental acceptance and non-conflict with other area uses, in the countries studied. The unit kW/km^2 is total power production divided by the country's total land area (i.e. not just the areas with wind turbines). The total production on land areas are shown above and the total production off-shore is depicted below. The off-shore locations are near-shore, as shown in Fig. 11 of the adjacent article (Sørensen, 2007a).



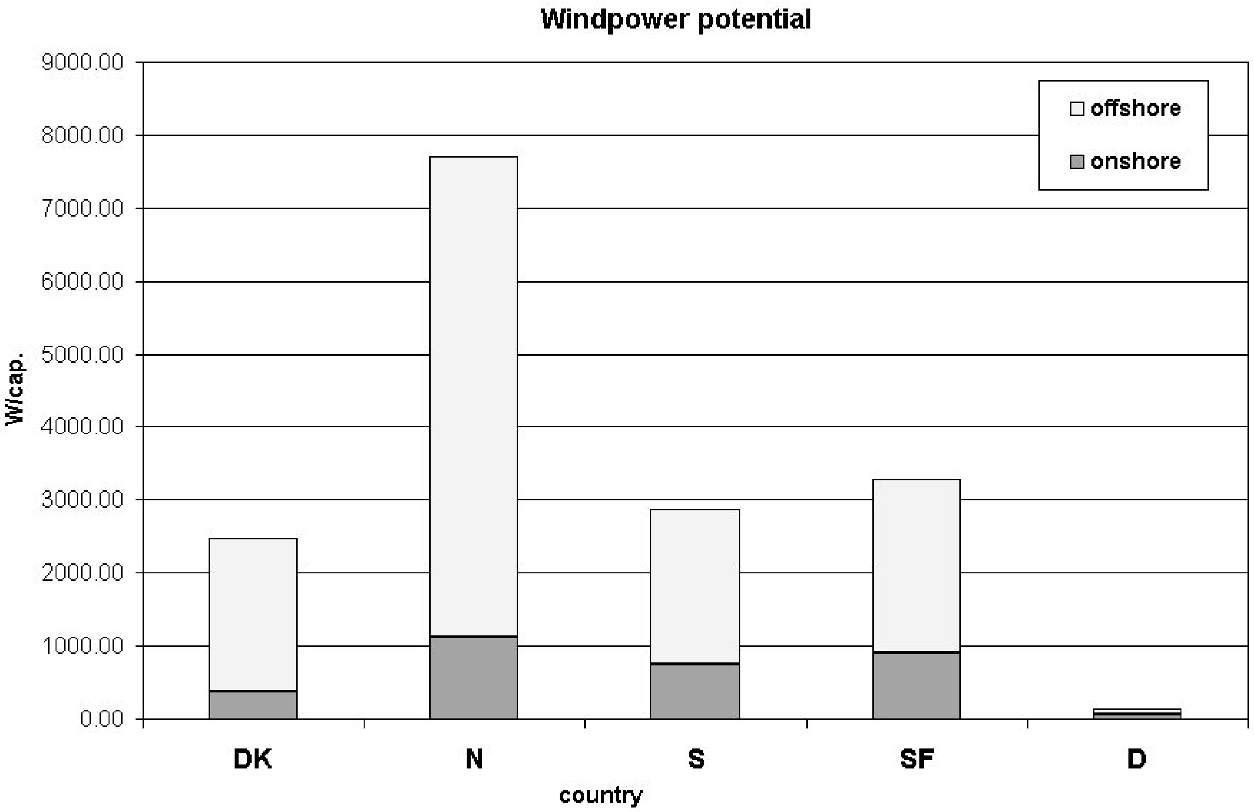
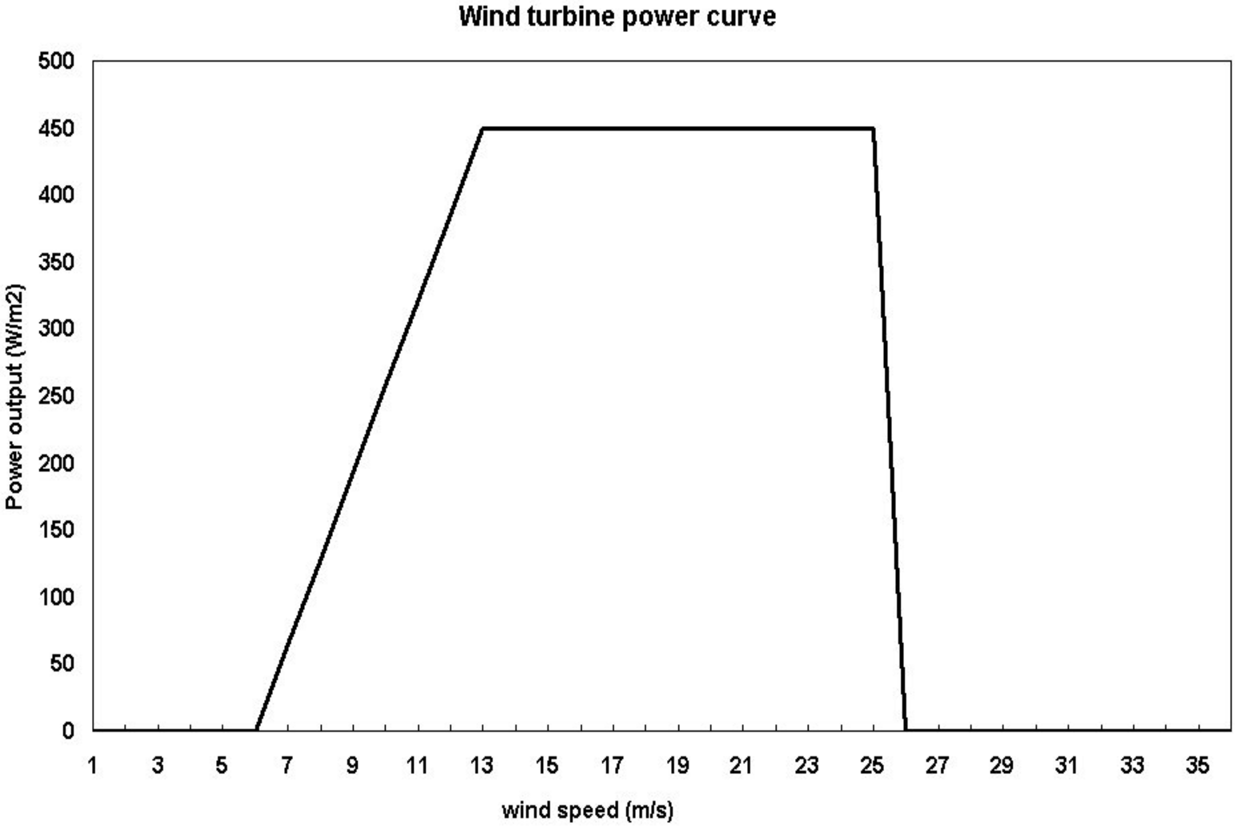


Figure 10. *a:* The total potential for average wind power production in the five countries studied, divided by population and given as W/cap., with on- and off-shore contributions indicated. *b:* Power curve assumed for all turbines in this study.



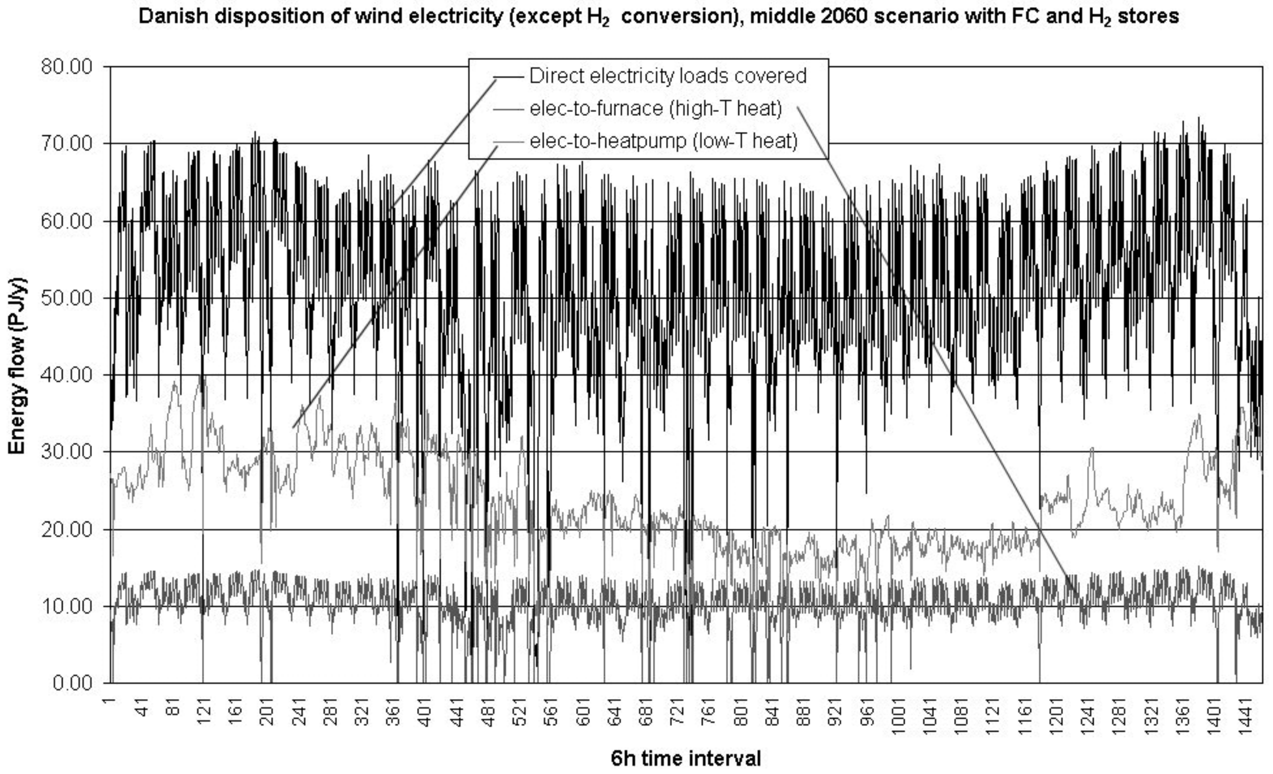
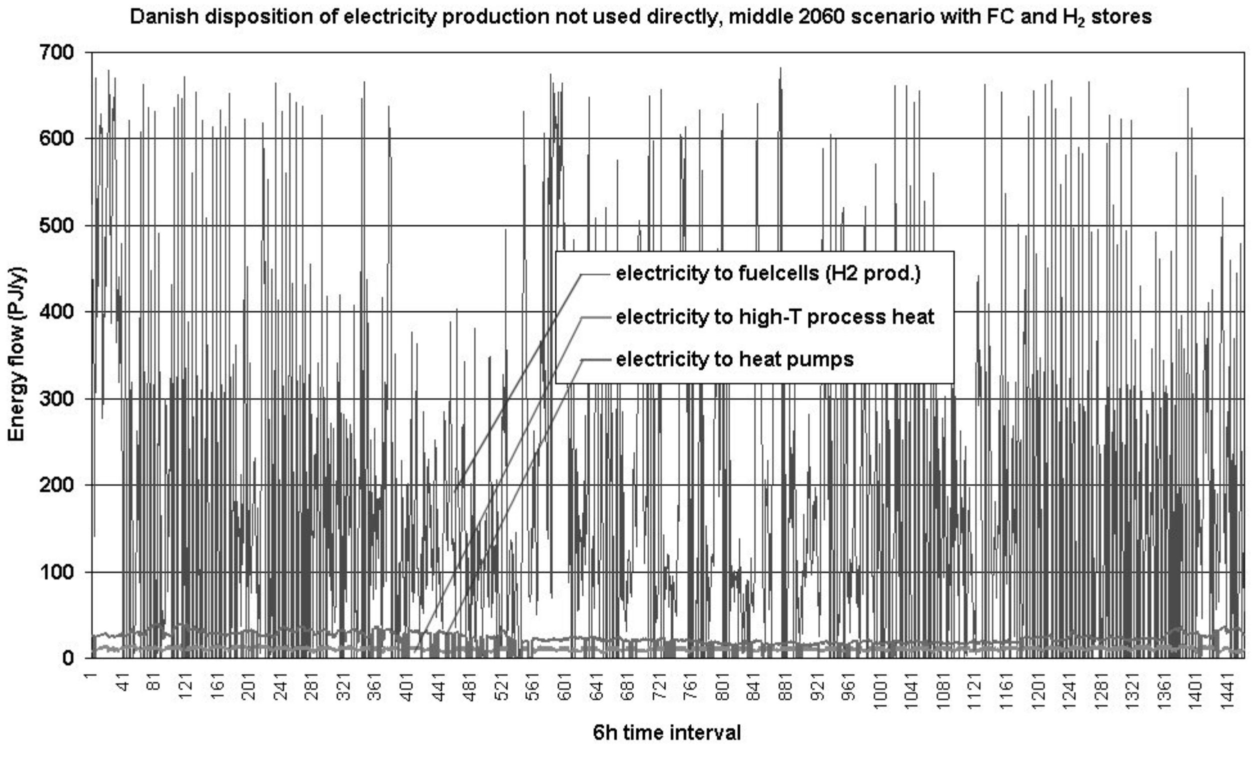


Figure 11. Disposition of wind power generated in the 2060 scenario for Denmark. Above are direct uses for dedicated power demands, for generating high-temperature process heat and for operating heat pumps. Below is shown the wind power used for hydrogen production (163 PJ/y), with the two other indirect uses indicated at bottom, in order to show their small size compared to hydrogen production (assumed to be by fuel cells in reverse operation).



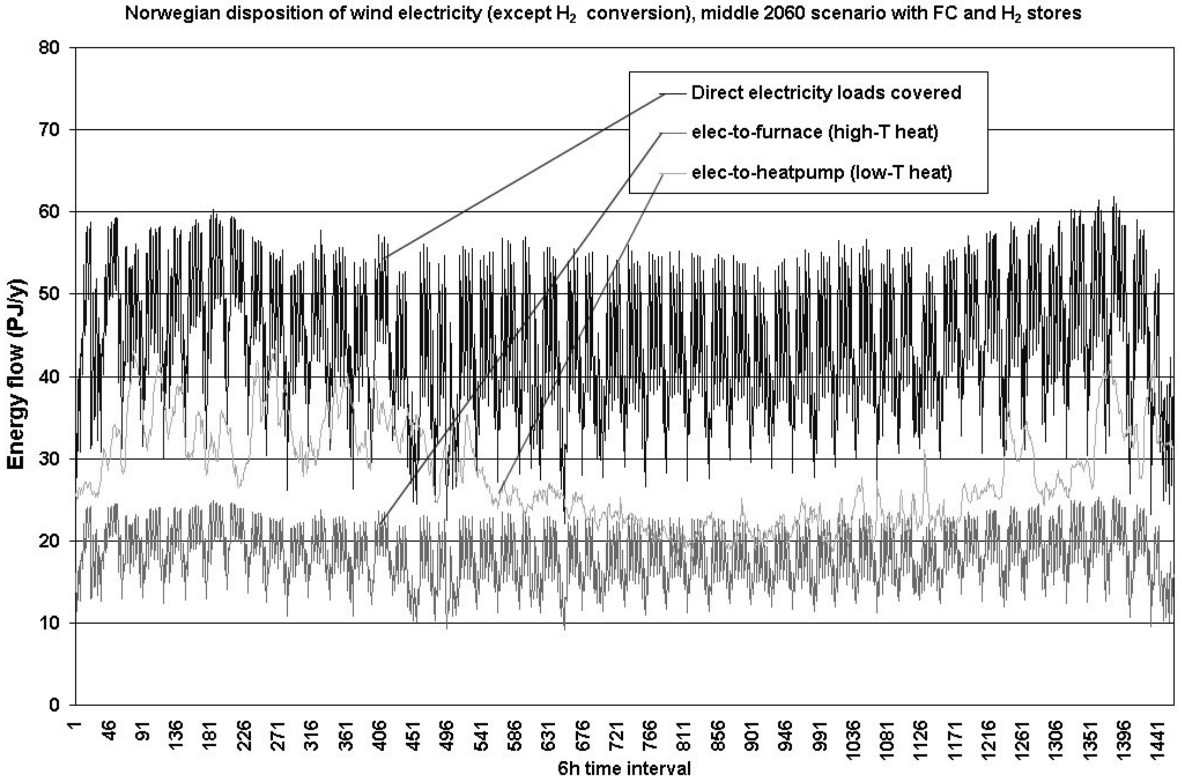


Figure 12. Disposition of wind power generated in the 2060 scenario for Norway. Due to the fact that the wind power duration curve is always substantially above zero (see Figure 7), loads may be covered by wind at nearly all times, although in practice, hydro power will also be used, leaving in all cases substantial amounts of power for export.

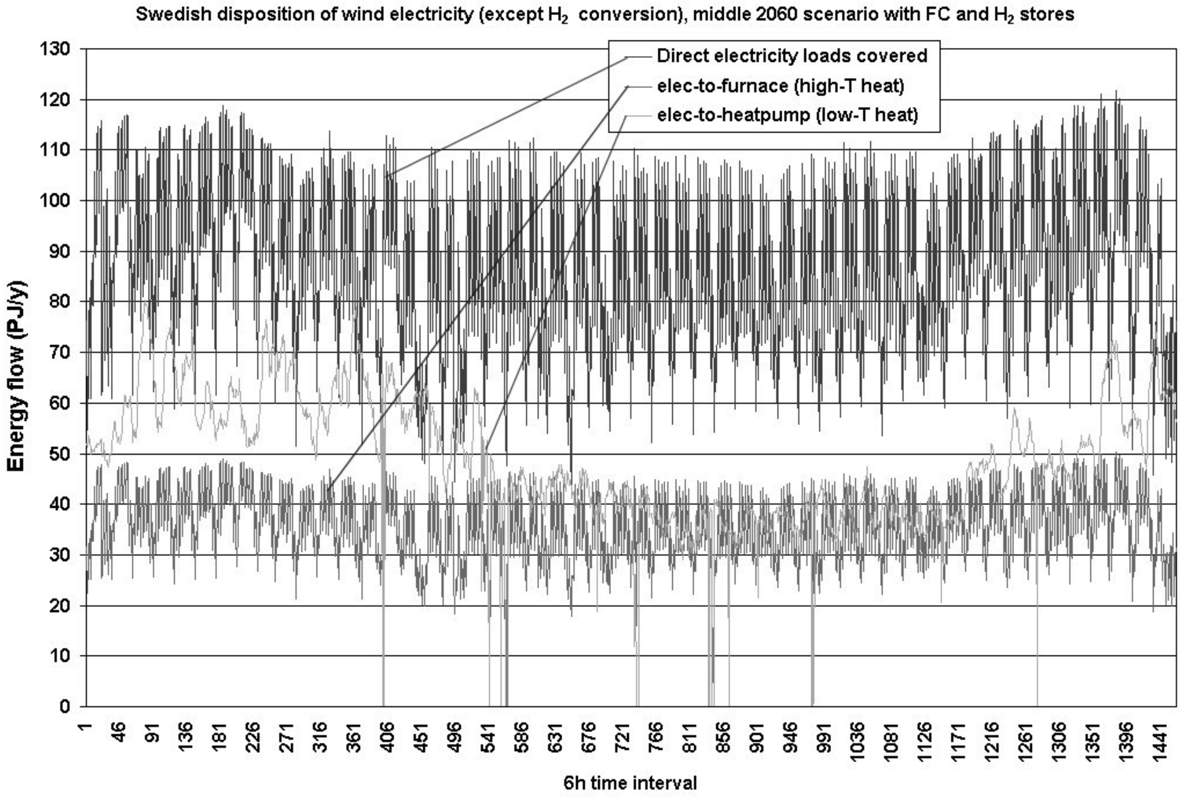


Figure 13. Disposition of wind power generated in the 2060 scenario for Sweden.

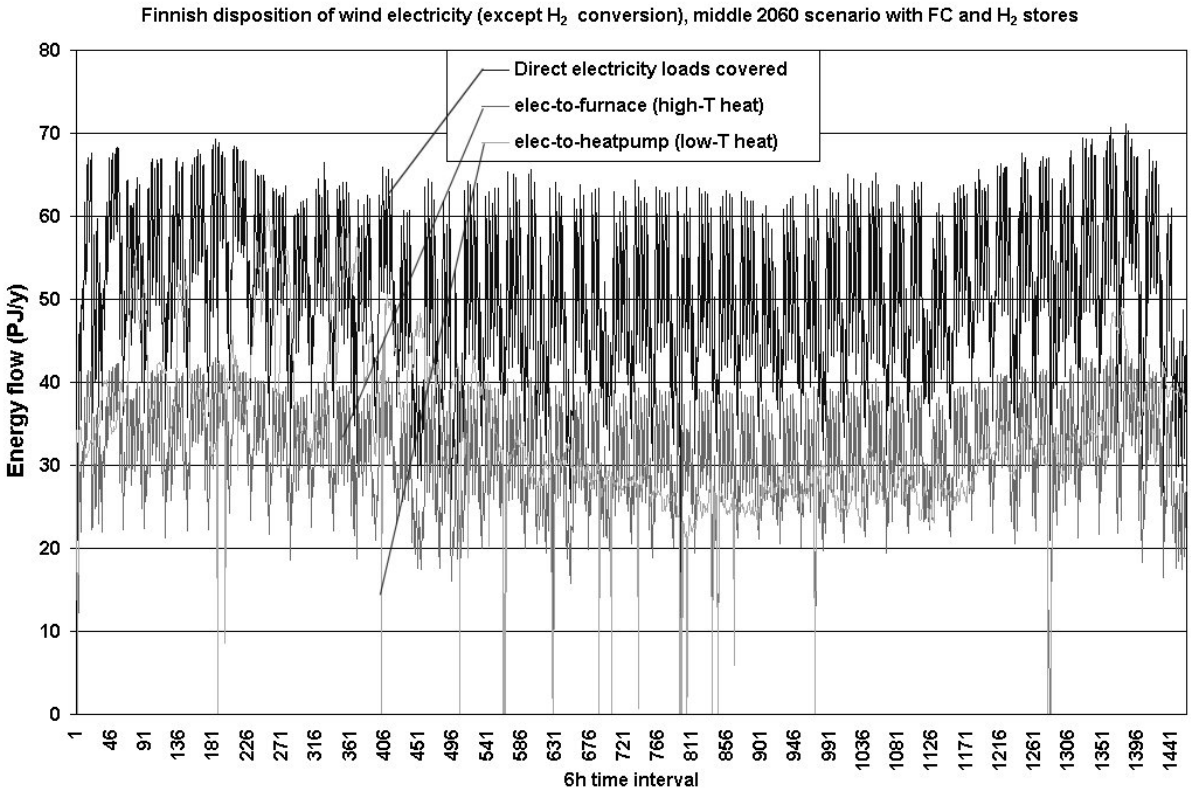


Figure 14. Disposition of wind power generated in the 2060 scenario for Finland.

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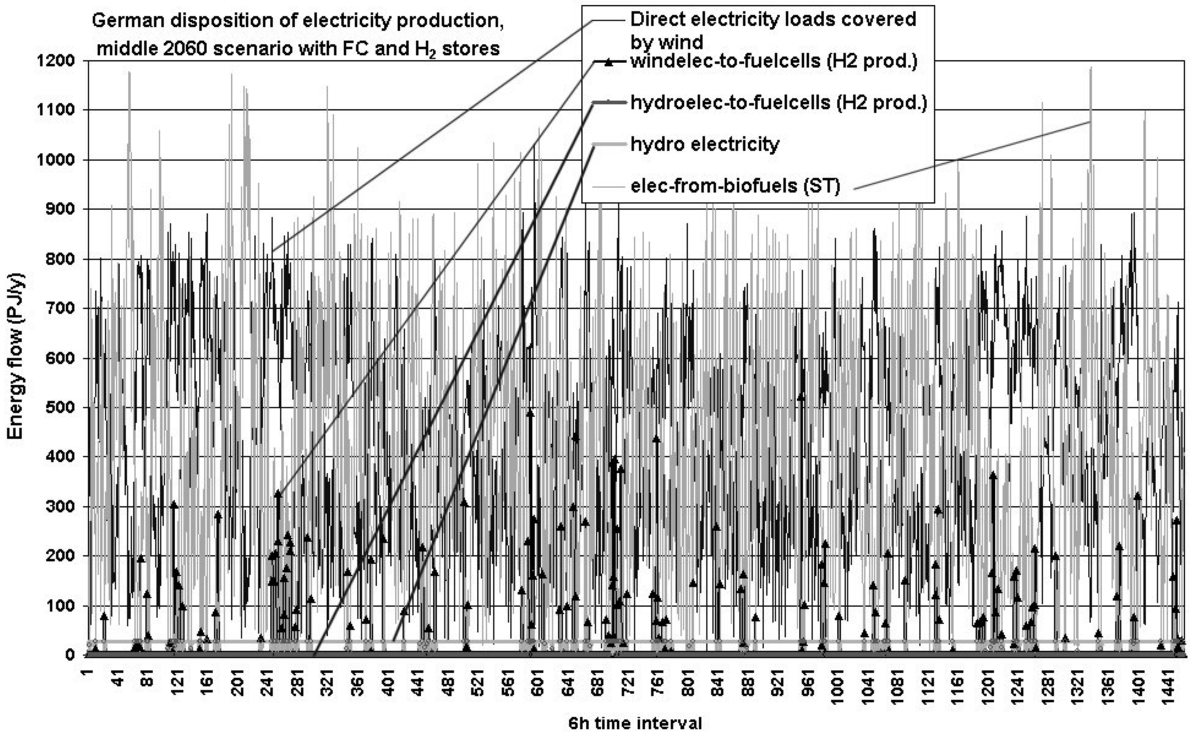


Figure 15. Disposition of wind power generated in the 2060 scenario for Germany in isolation. Only part of the dedicated electricity demands can be covered by wind. Any surpluses are converted to hydrogen, but the largest supplier of electric power is stipulated to be steam turbines (ST) fuelled by biomass, in this scenario not considering imports of power. However, the indigenous sources of biomass are also insufficient, and the deficit is on average 980 PJ/y.

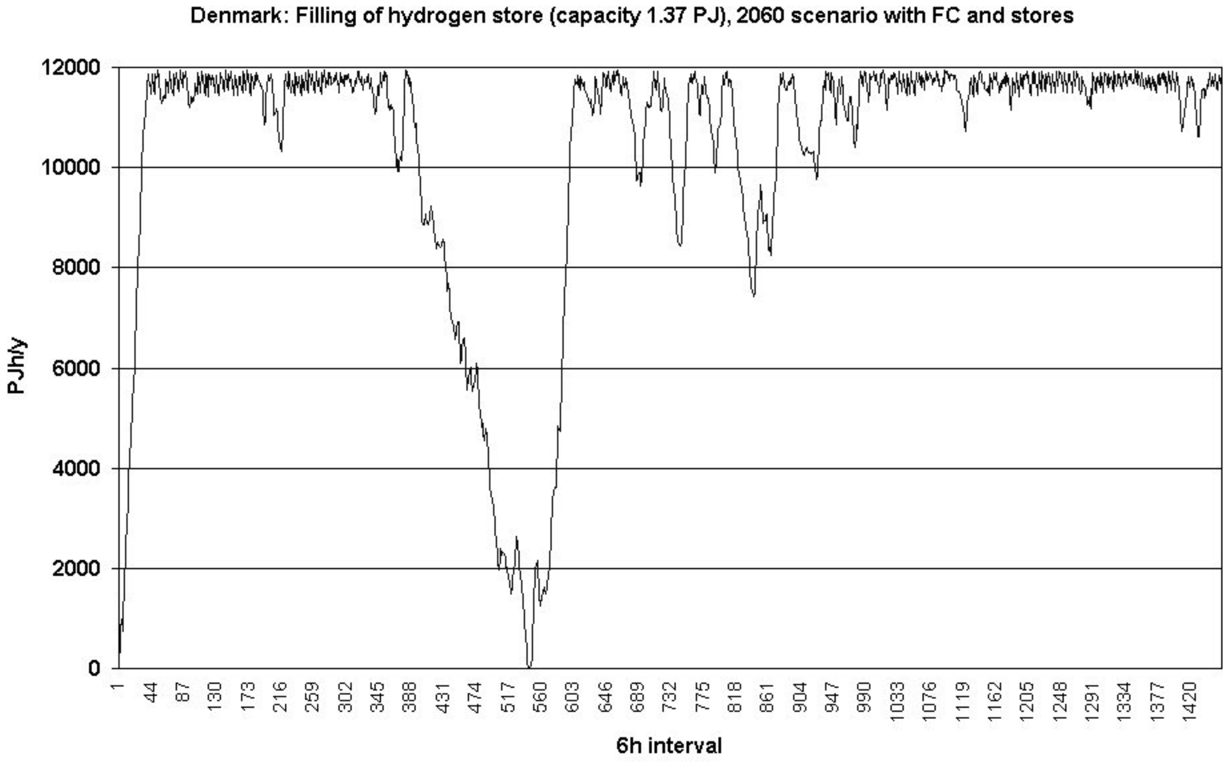


Figure 16. Variations in filling of hydrogen stores in Denmark, over the simulation year.

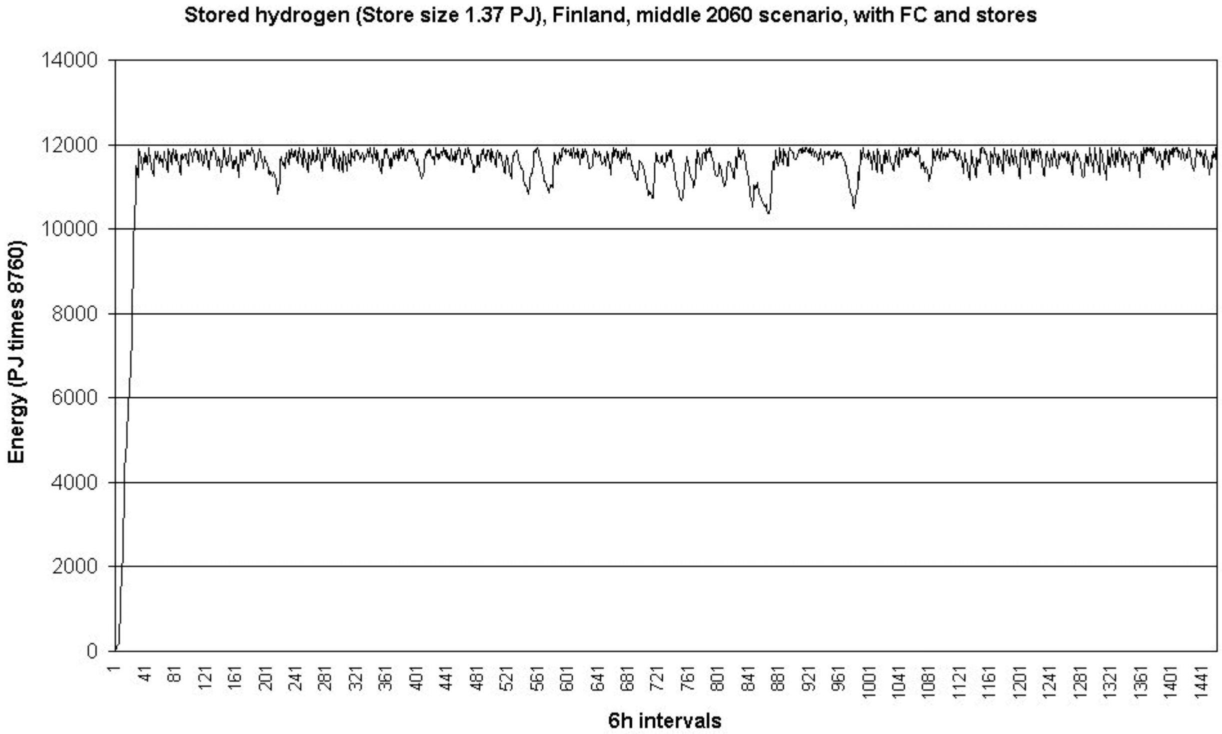


Figure 17. Variations in filling of hydrogen stores in Finland, over the simulation year.

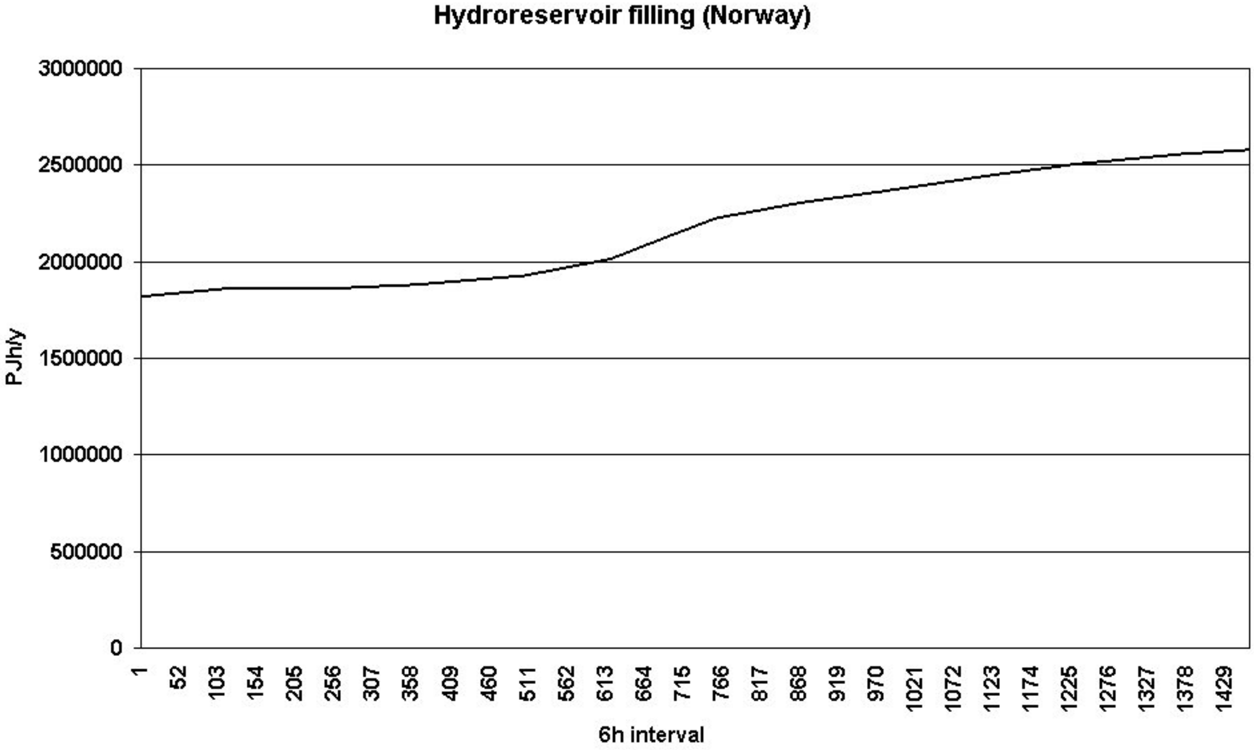


Figure 18. Water level (in energy units) of Norwegian hydro reservoirs, in isolated scenario where a large surplus is built up during the year.

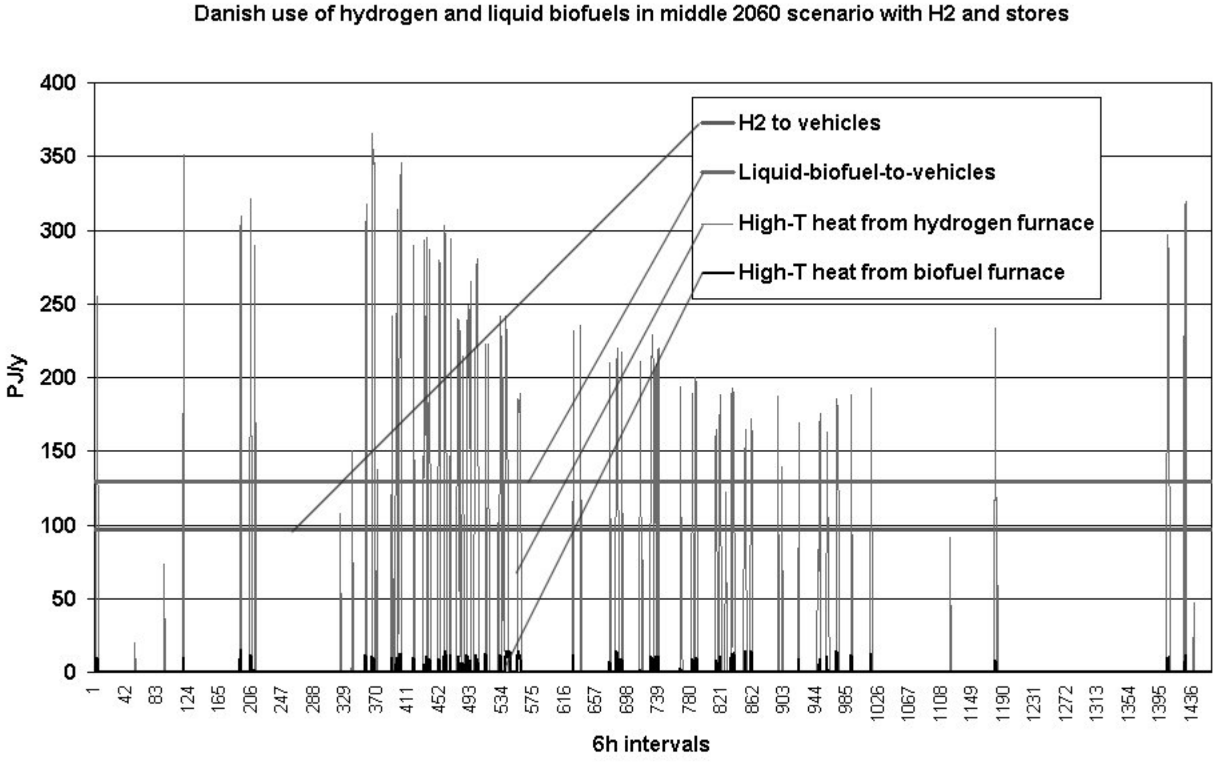


Figure 19. Disposition of produced biofuels and hydrogen in the 2060 scenario for Denmark. Half of the transportation end-use energy is covered by hydrogen and half by biofuels. For producing process heat, hydrogen has priority over biofuels, for reasons of environmental impacts. Most high-temperature heat is produced by electric furnaces, so fuels are used only in periods of insufficient wind.

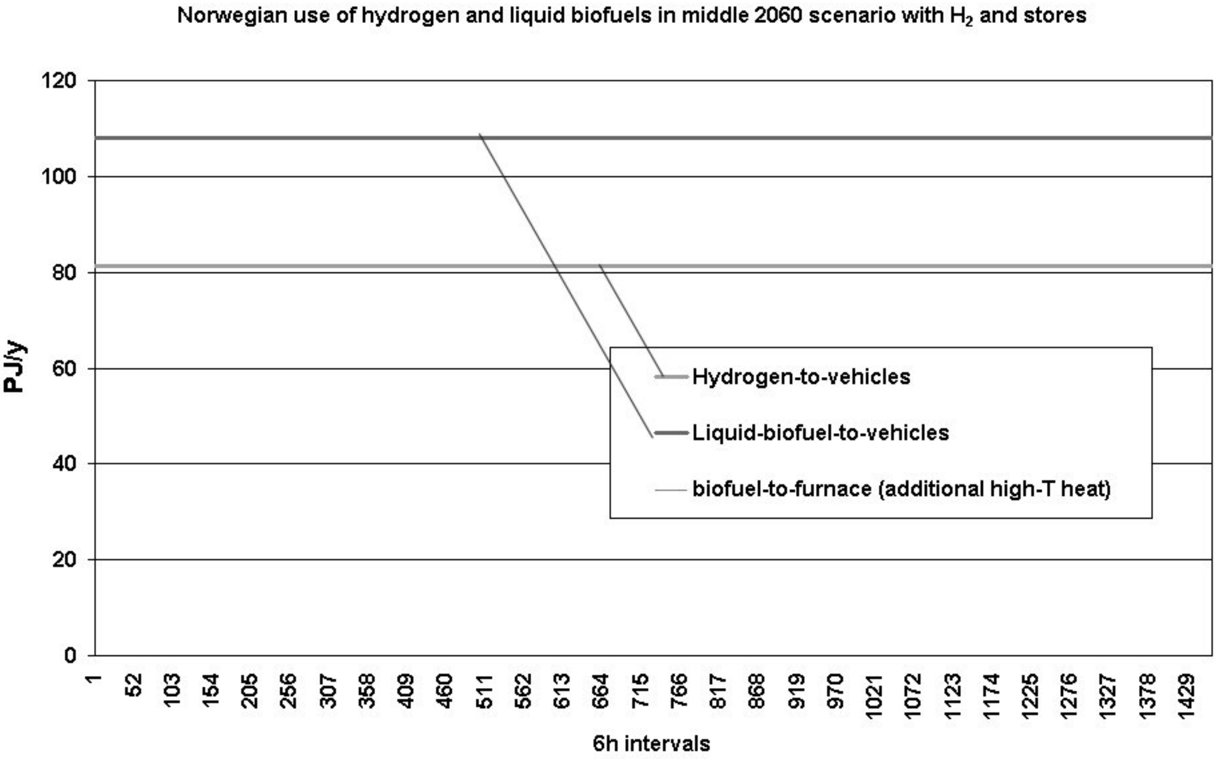


Figure 20. Use of hydrogen and biofuels for transportation in the 2060 scenario for Norway. High-temperature process heat is already fully covered by electric furnaces. Sweden and Finland have similar patterns.

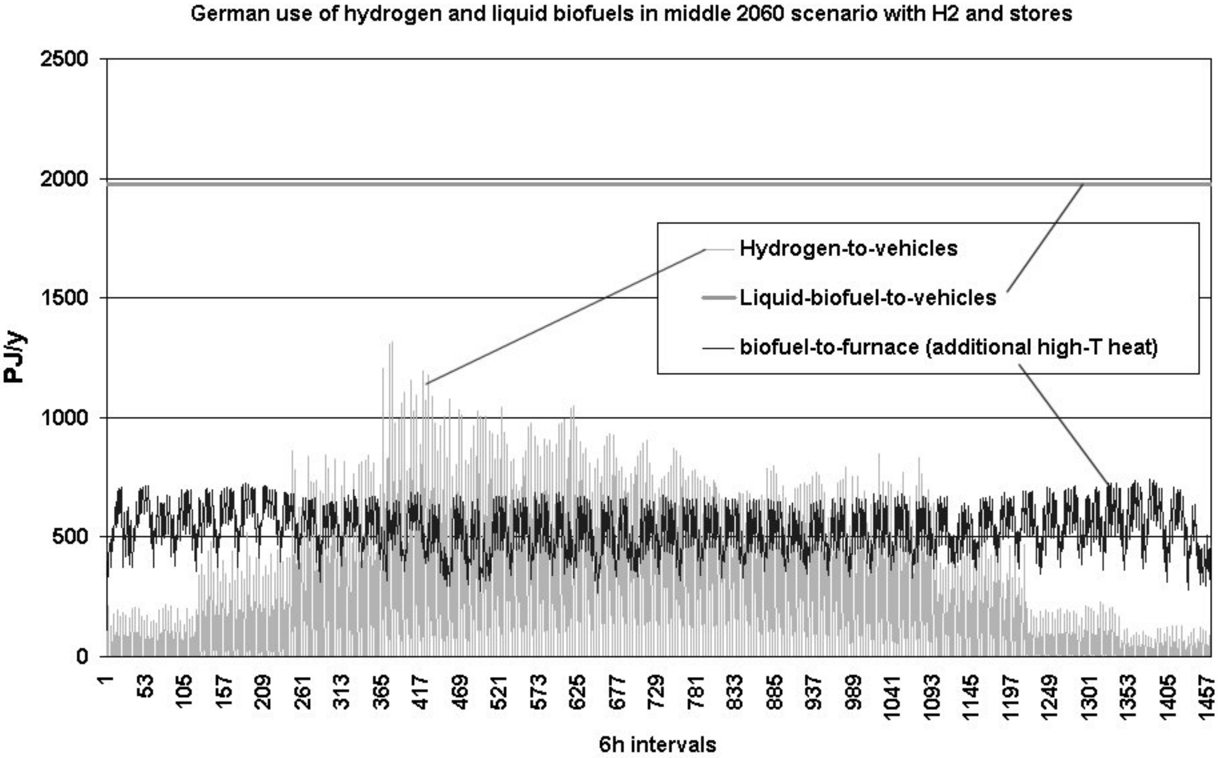


Figure 21. Use of hydrogen and biofuels in the 2060 scenario for Germany in isolation. High-temperature process heat is seen to be largely covered by biofuelled furnaces. Hydrogen produced by wind and hydro is insufficient to satisfy the 50% demands in the transportation sector, particularly during winter months. As mentioned in the caption below Figure 15, there is a substantial requirement for biofuel imports to the German transportation sector.

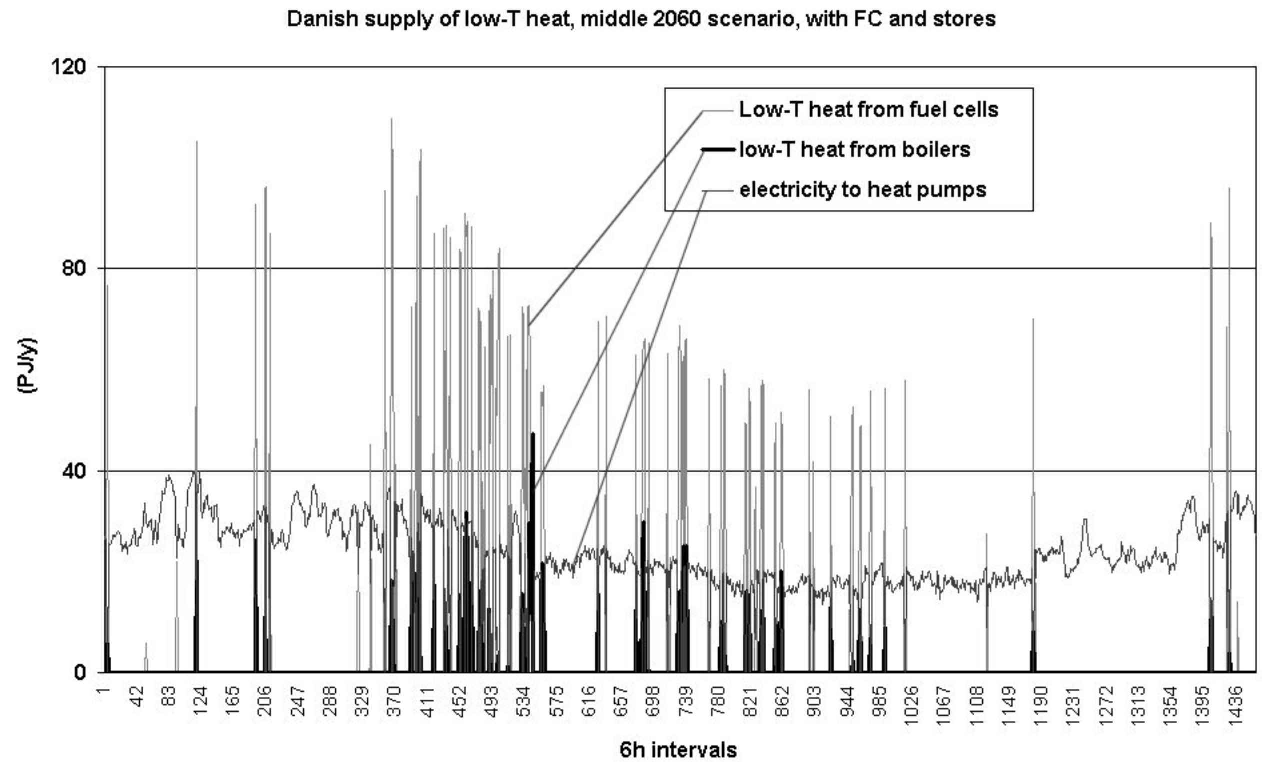


Figure 22. Provision of low-temperature heat in Danish 2050 scenario, from fuel cell heat losses, electric heat pumps and as lowest priority plain boilers using biomass fuel. The other countries exhibit fairly similar distributions.

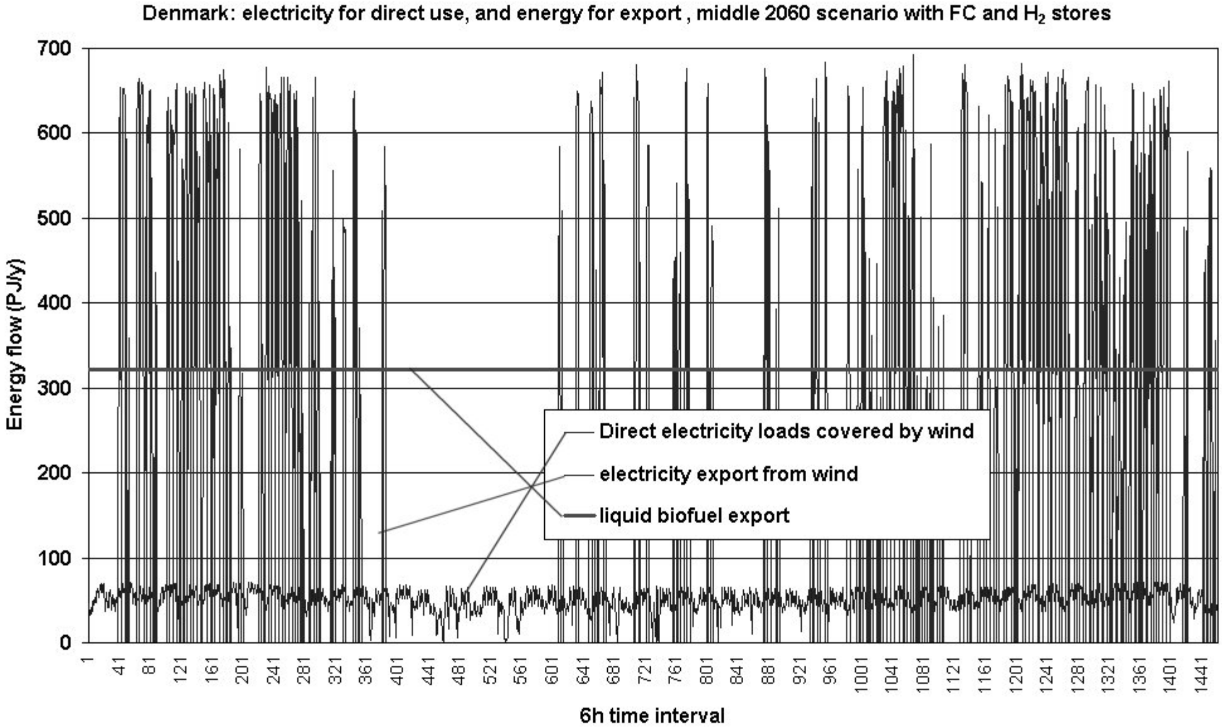


Figure 23. Potential energy exports from Denmark in the 2050 scenario, indicating a liquid biofuel export potential spread evenly over the year (although it does not have to be) and an electricity export potential in periods of wind power surpluses. The direct coverage of domestic loads by wind is shown at bottom, indicating the occasionally very large surplus available for export during particular hours (suited for hydrogen production, which could be accomplished in the country importing, in order to avoid long-distance piping of hydrogen).

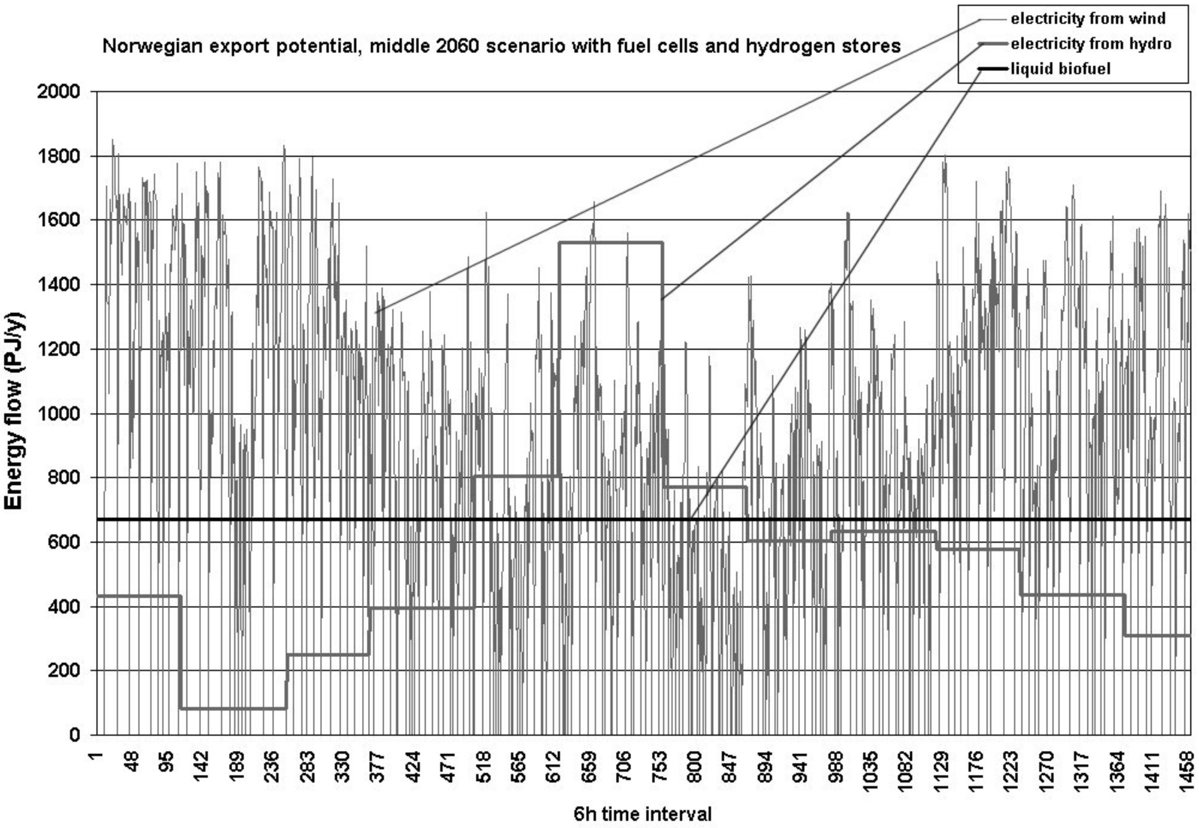


Figure 24. Potential energy exports from Norway in the 2050 scenario, indicating a biofuel and a variable wind power export potential, and further a hydro power export potential, which is shown as proportional to the monthly inflow of water into the reservoirs, although this may not be the actual distribution of exports.

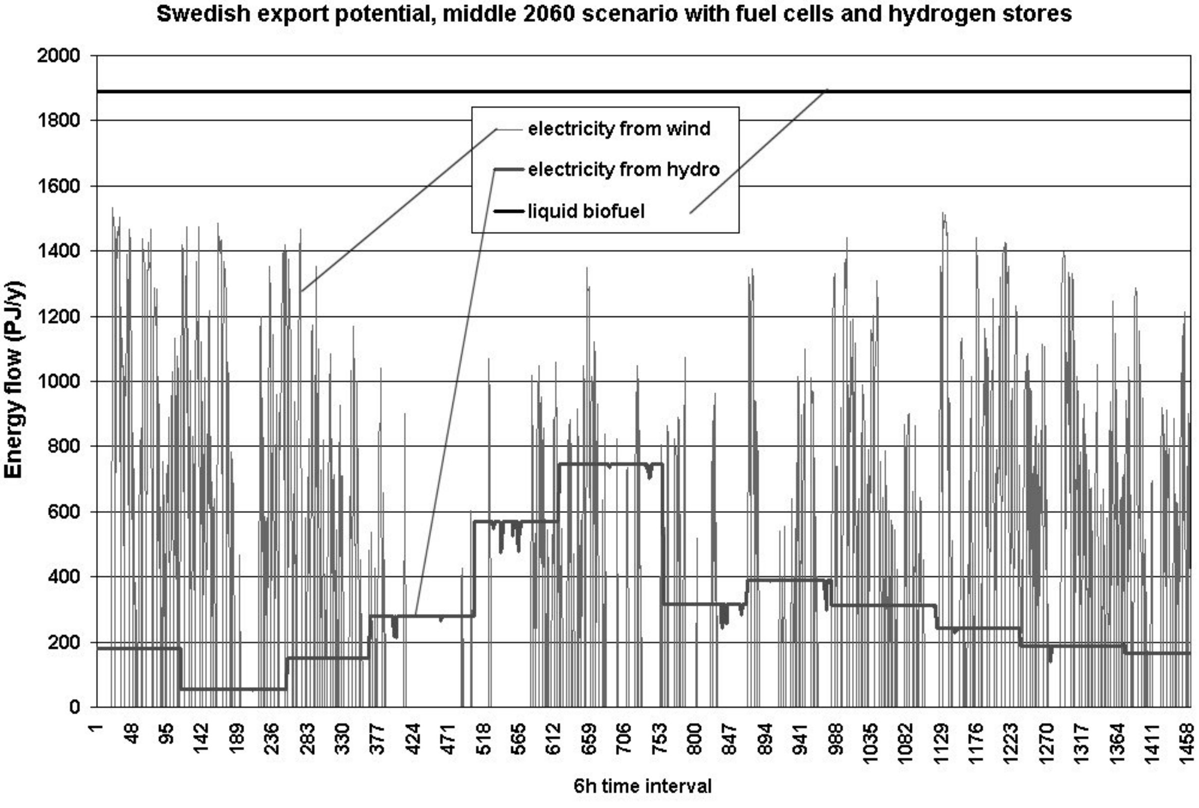


Figure 25. Potential energy exports from Sweden in the 2050 scenario. Cf. caption to Figure 24.

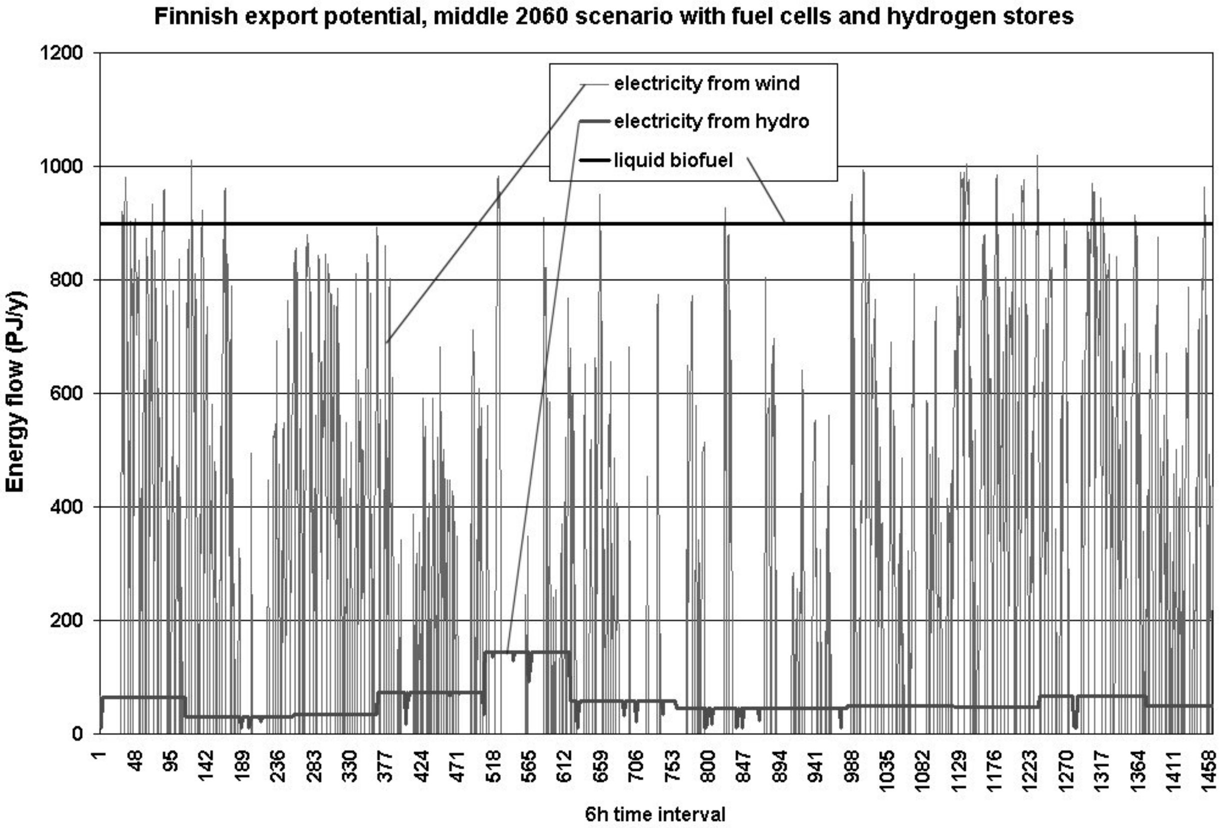


Figure 26. Potential energy exports from Finland in the 2050 scenario. Cf. caption to Figure 24.

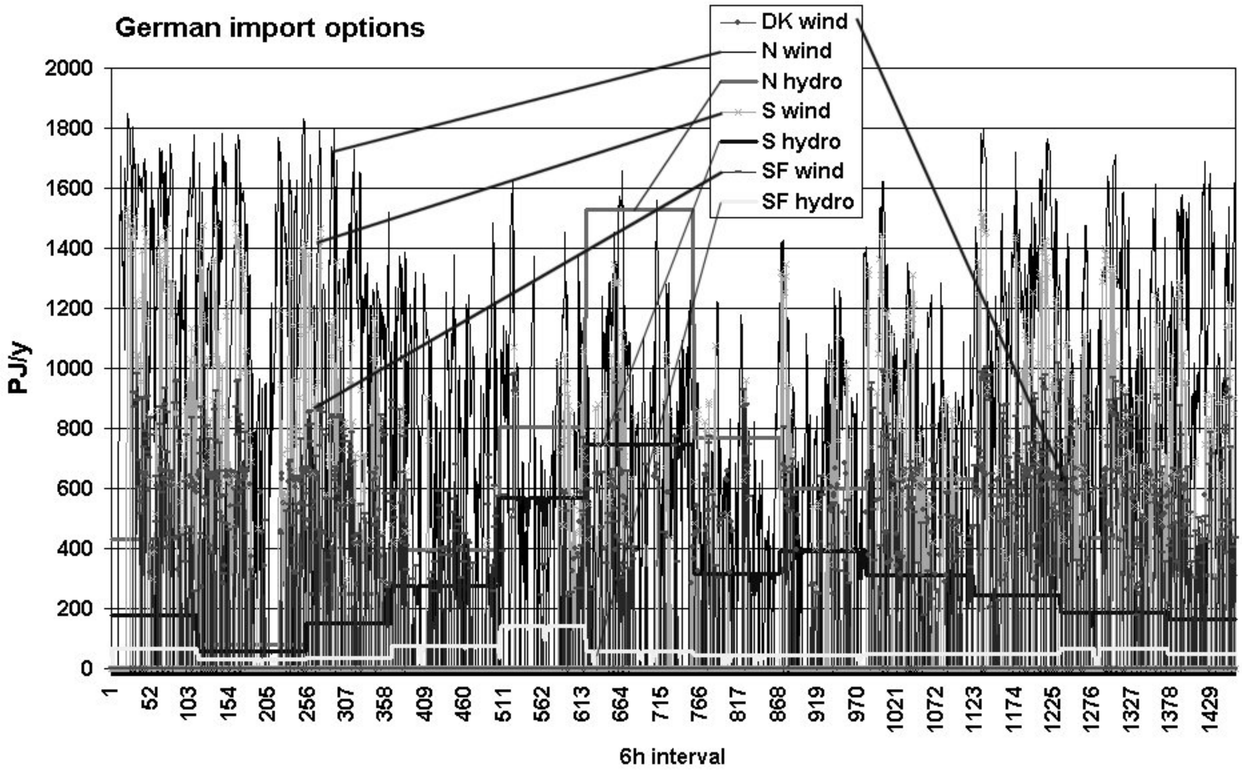


Figure 27. Import options for Germany, which in the 2060 has a considerable import need. The potential Nordic exports from Figures 23-26 are plotted together, in order to indicate their relative size. The total availability of German options for import exceeds the requirements, and a choice may be made between electricity or fuel imports, or a combination of these. Also imports from nearby countries may be preferable, due to transmission costs.

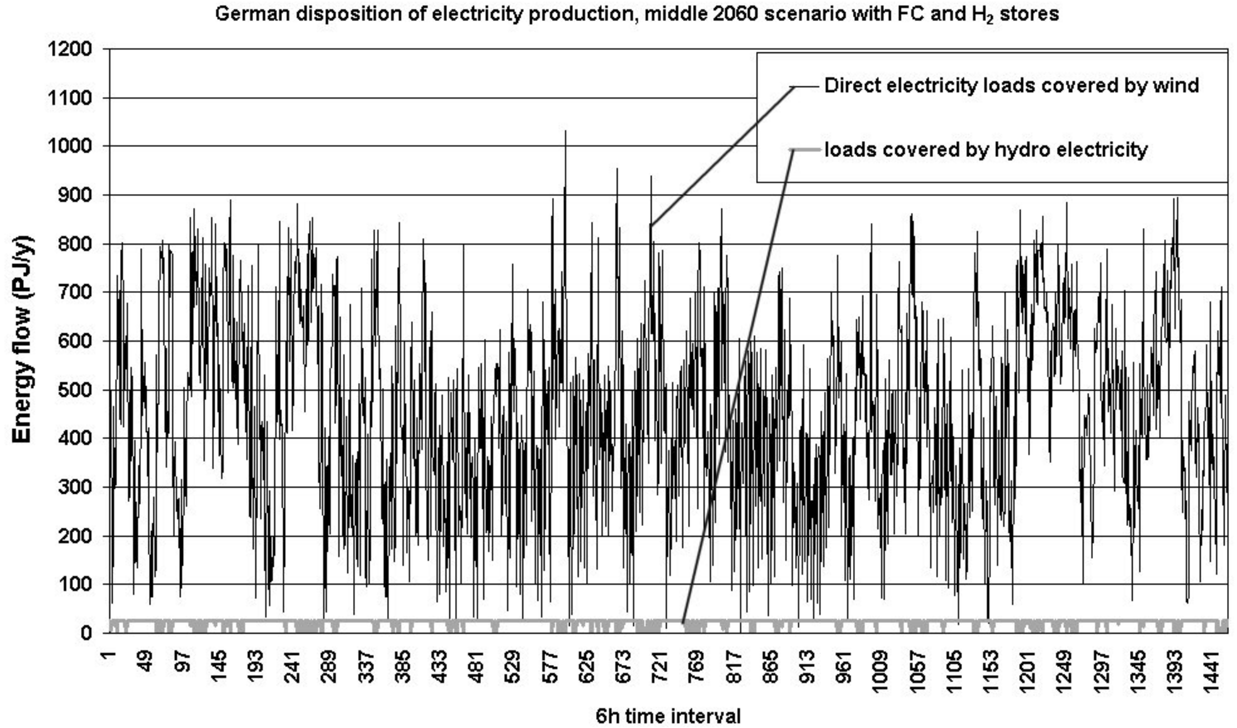
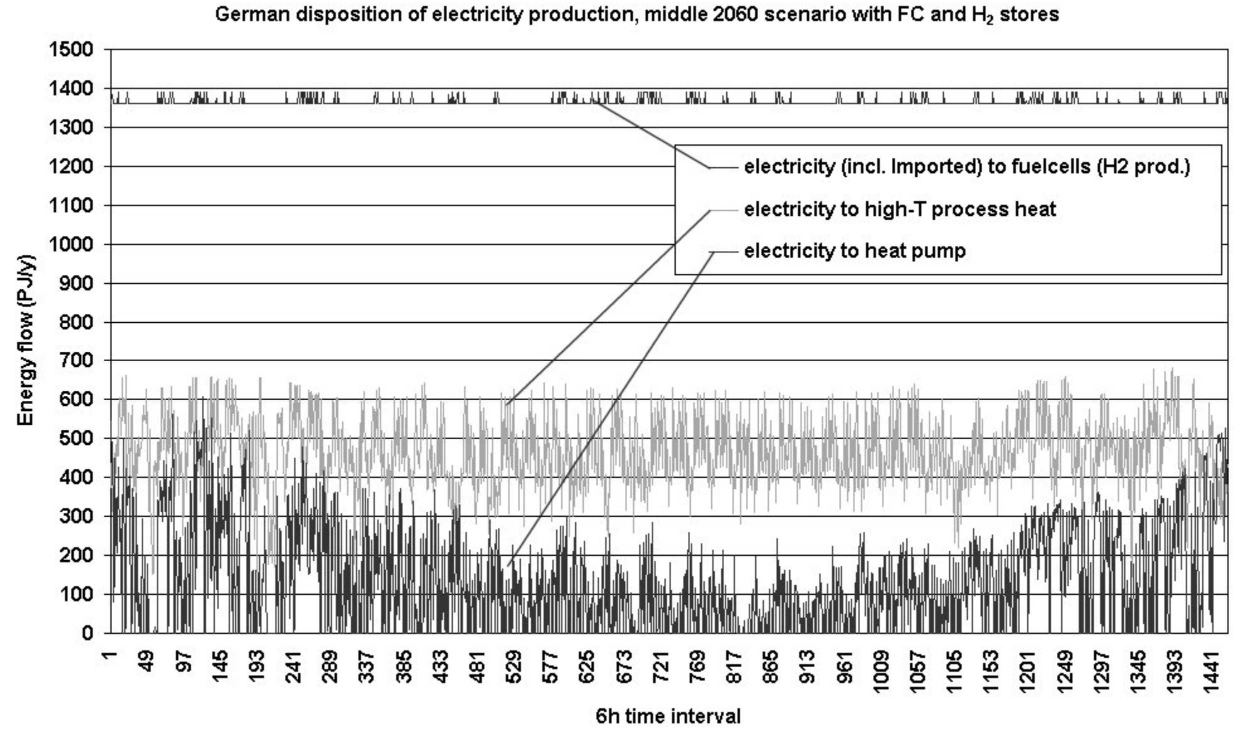


Figure 28. Disposition of wind power generated in the 2060 scenario for Germany as well as imports of power from the Nordic countries (direct uses above, indirect ones below). Availability of electricity and fuel imports options makes the disposition of indigenous production different from that in the isolated scenario. The hydrogen production from electric power will be used in the transportation sector.



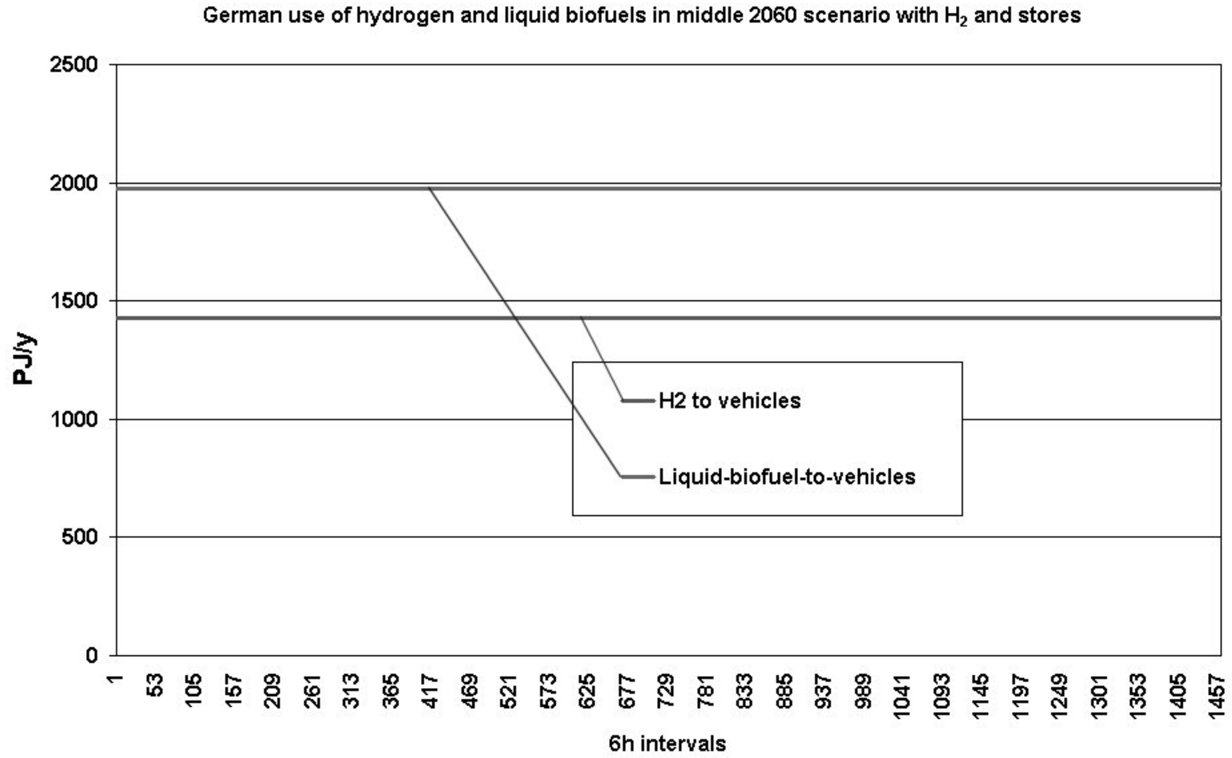


Figure 29. Disposition of fuels in the German 2060 scenario with full import options. The 50-50% split between hydrogen and liquid biofuels can now be fully supported by the (large) supplemental combination of power and fuel imports.

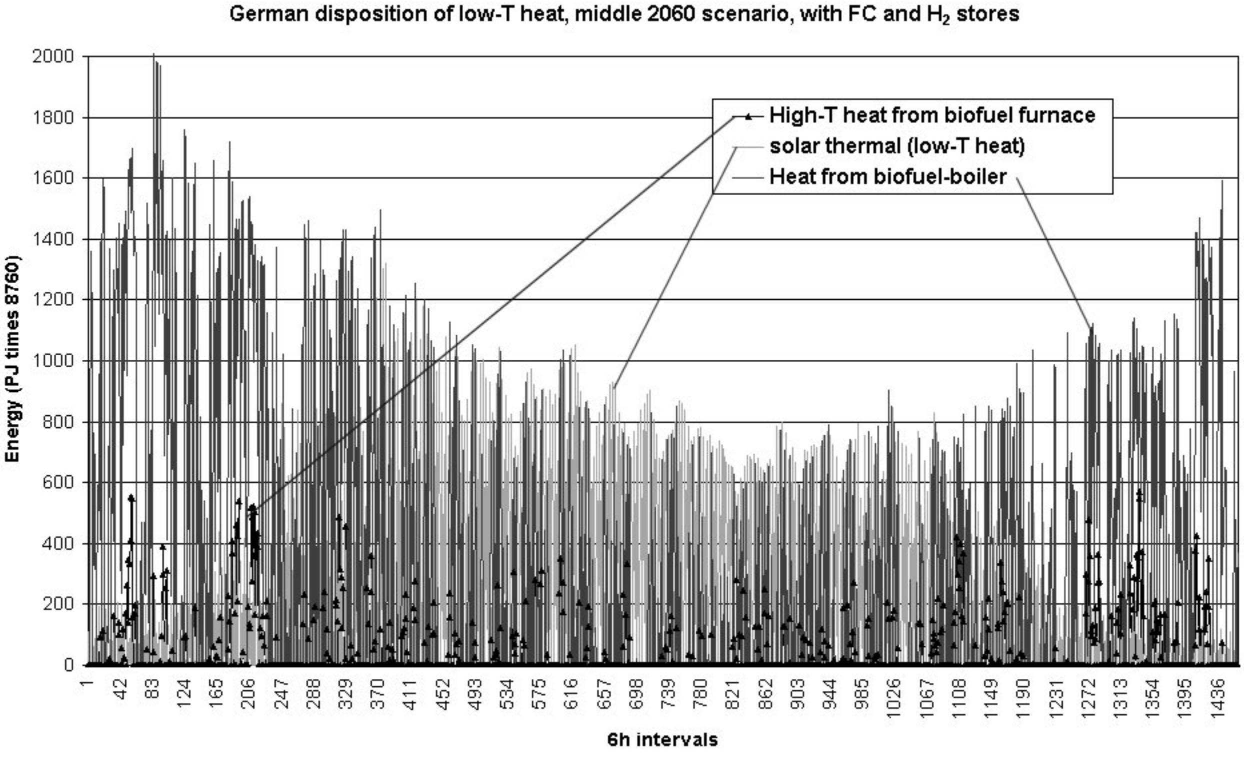


Figure 30. Disposition of low- and high-temperature heat in the German 2060 scenario with full import options. Cf. Fig. 21 for high-temperature heat in the case of an isolated Germany.

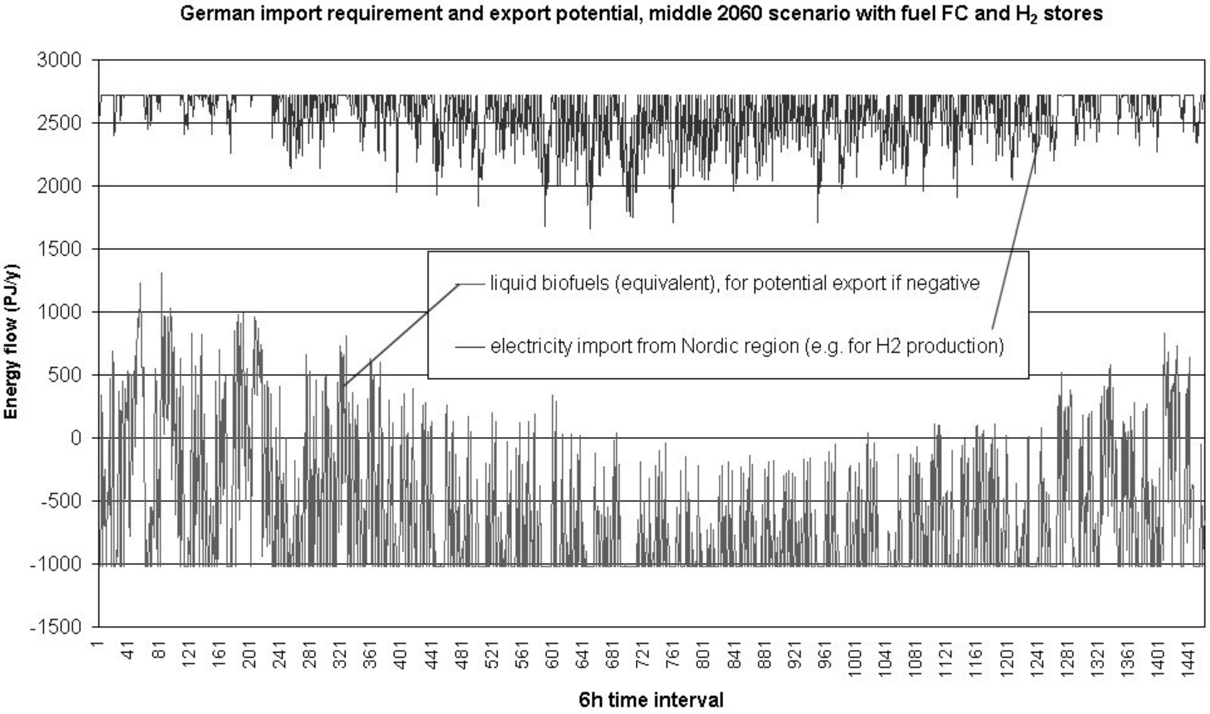


Figure 31. Import needs and export options for Germany in the 2060 scenario. The large import of surplus electricity from the Nordic countries makes the liquid fuel situation much more relaxed, with occasional periods of potential export and other periods of import, which can be seen to be avoidable by simply storing the biofuels.

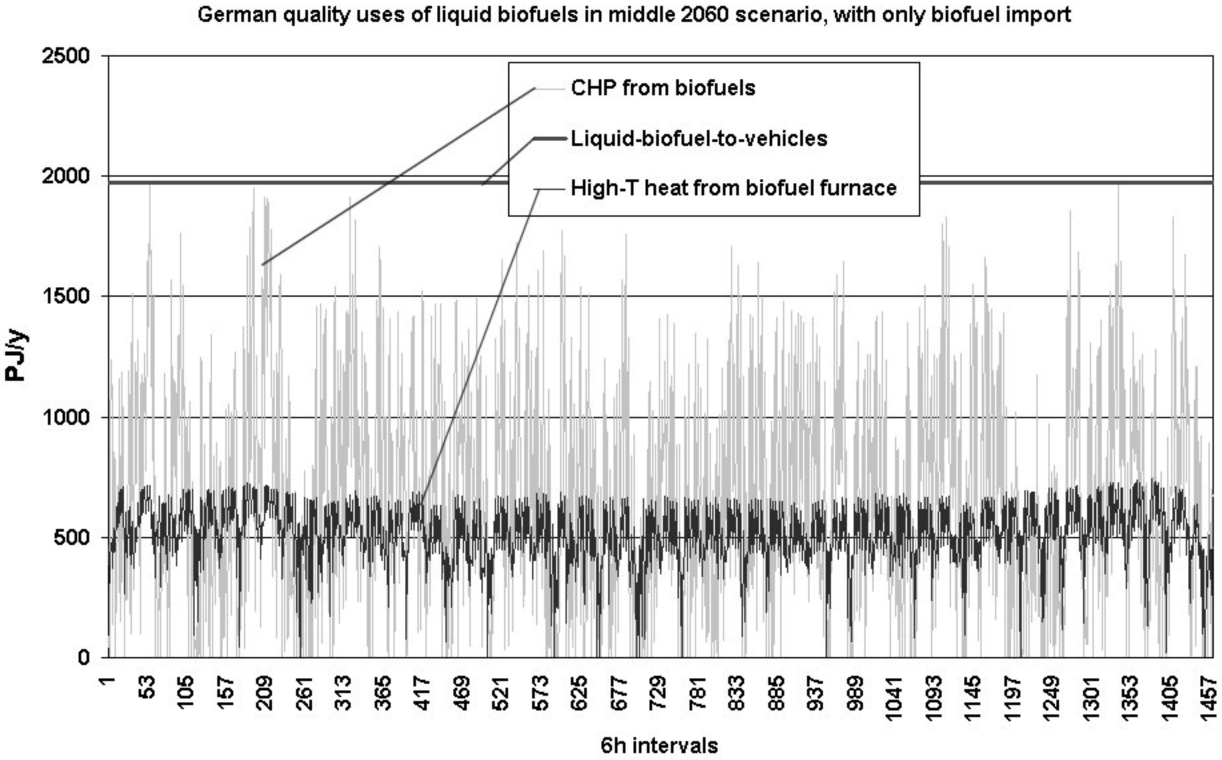


Figure 32. In the variant where Germany only imports biofuels by 2060, these are used to produce power in combined heat and power plants, when indigenous wind and hydro production is insufficient. Further uses of biofuels are for high-temperature process heat and vehicle fuels (now taking over much of the role played by hydrogen-fuelled fuel cell-vehicles in the scenario where electricity imports were an option).

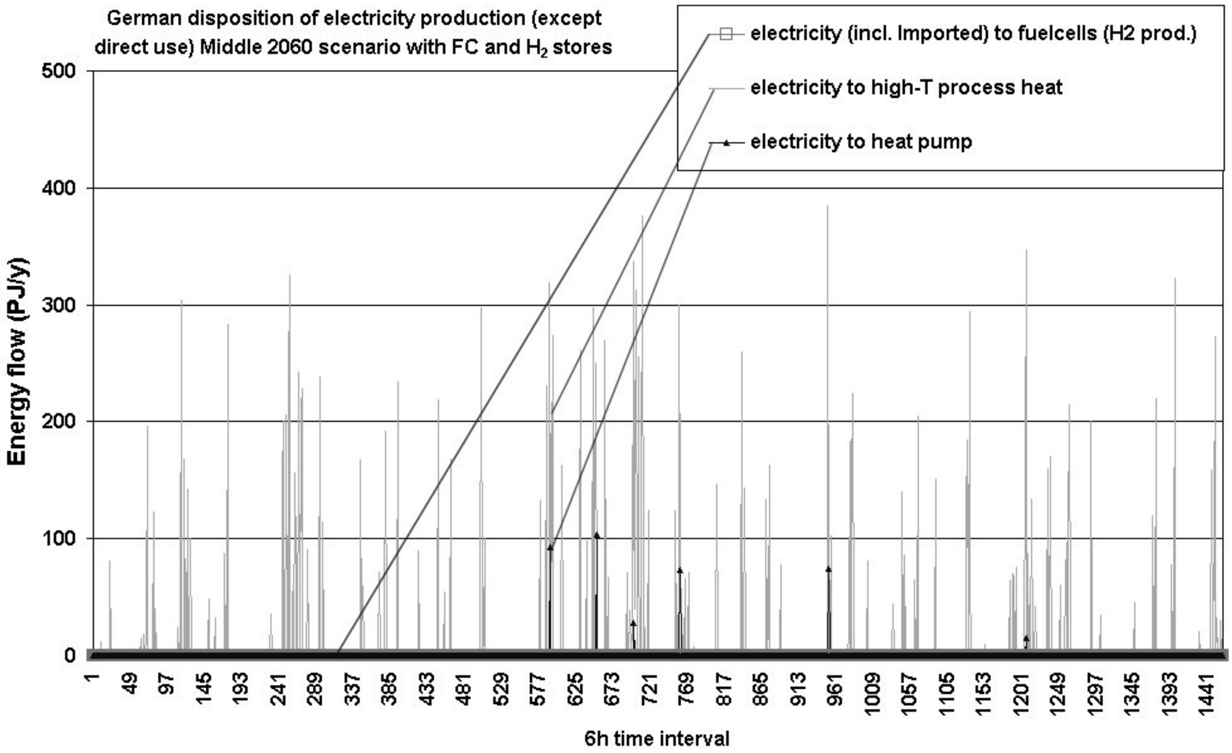


Figure 33. In the variant where Germany only imports biofuels by 2060, there is much less electricity available for hydrogen production and heat supply through furnaces and heat pumps. The balance must be supplied by biofuels, with the time distribution shown in Figure 32.

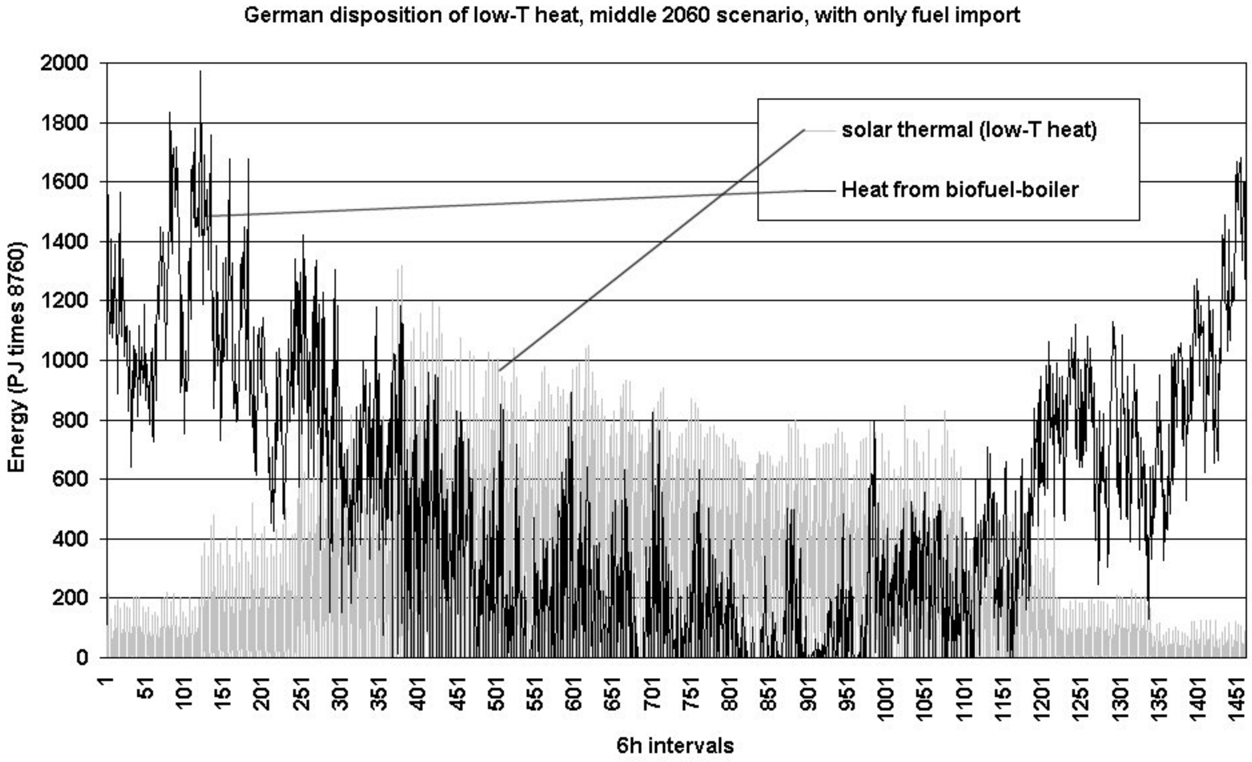


Figure 34. In the variant where Germany only imports biofuels by 2060, there are low-temperature heat demands that cannot be supplied by solar thermal collectors and must be covered by biofuels in boilers.

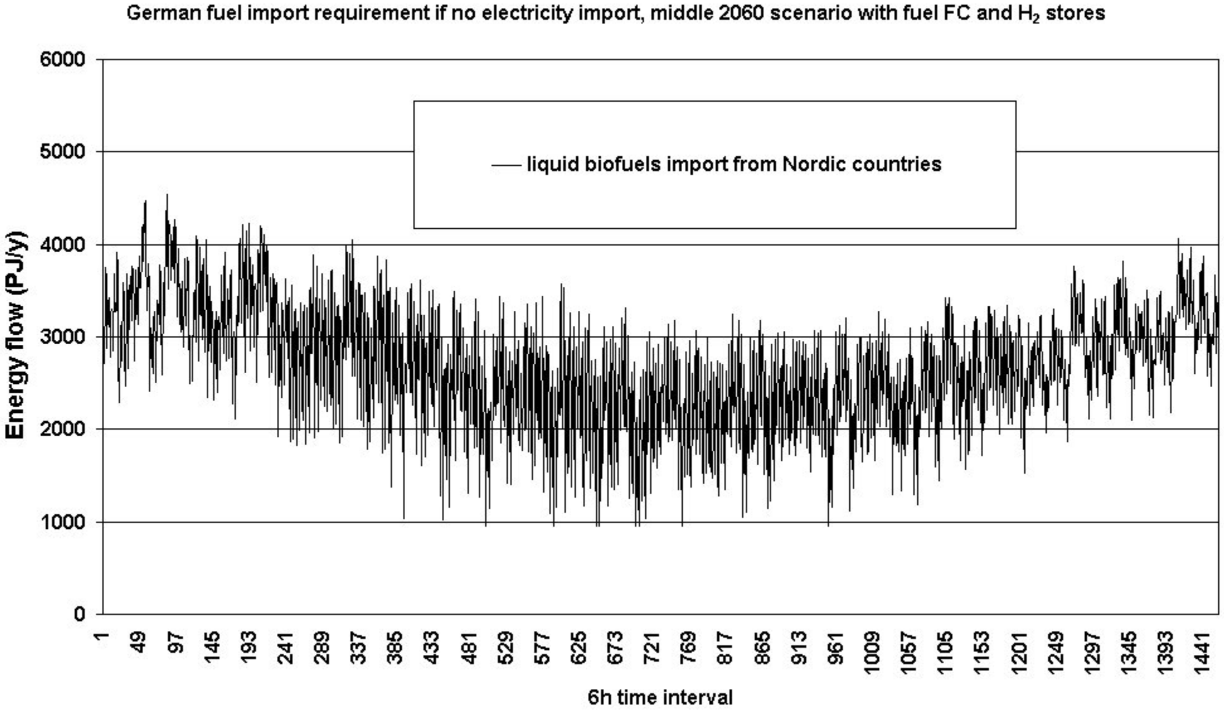


Figure 35. In the variant where Germany only imports biofuels by 2060, the total time series of biofuel import requirements is shown. Because biofuels may be stored, this need not coincide with the actual time distribution of imports.

Chapters 4 and 5*

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* Contribution from Risø to Comparative assessment project, written by Peter Meibom, 2008, with input from ea-energy

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Summary of Balmorel results

The Balmorel model (www.balmorel.com) has been used to analyse the long-term integration of wind power production focusing on the possibilities given by:

- Hydrogen production and hydrogen storage
- Power exchange between countries

For this purpose the Balmorel model has been extended to include production, storage and consumption of hydrogen.

Two studies have been carried out with Balmorel:

1. Investigation of a possible long term investment path from 2005 until 2050 for the Scandinavian energy system focussing on renewable energy in the supply sector and on hydrogen as the main fuel for road transportation, covering up to 70 percent of all road transport in 2050. The transformation during time from a mainly fossil fuel based to a mainly renewable energy based energy system was the focus of this study. It has been accepted for publication in the International Journal of Hydrogen Energy.
2. Calculation of the economic optimal energy system configuration for the Scandinavian countries and Germany in 2060 assuming a nearly 100% coverage of the energy demands in the power, heat and transport sector with renewable energy sources. Different assumptions about the future success of fuel cell technologies have been investigated as well as different electricity and heat demand assumptions.

The results of both studies depend on the assumptions done which among other thing encompass the energy demands for electricity, heat and transport, and the technology data e.g. investment costs. Making studies covering 2050-2060 off course make such assumptions very uncertain. The studies performed should therefore more be seen as illustrations of future energy systems that due to the modeling methodology are the most cost efficient under the assumption made, while obeying a number of technical restrictions concerning demand-supply matching and the usage of power plants and transmission lines.

A main conclusion of study 1 is that with an oil price at 100 US$/barrel and technology costs as listed in table 3, it is economical optimal to cover 95 percent of the power and district heat production in the four Scandinavian countries by renewable energy in 2050. Only remaining non renewable plants are the new Finnish nuclear power plant and a few natural gas fired heat boilers. The modelled energy system supplies the transport sector with hydrogen produced by electrolysis and steam reforming of natural gas. In 2050 this means that 65 percent of the transport work in the Scandinavian countries is based on renewable energy. A system power price can be derived from the model and in 2050 the yearly average power price in the scenario is 55 €/MWh and hydrogen is produced at a price around 17 Euro/GJ (yearly average).

The study of the all renewable energy scenarios for the energy, heat and transport sectors in Germany and the Scandinavian countries in 2060 showed that under the assumptions made, it is feasible to fulfil the energy demands with renewable energy sources coming from within the countries. Furthermore a doubling of the electricity and heat demand relatively to the base case could be covered with renewable energy sources. Germany is the big consumer of energy relatively to the Scandinavian countries, so there is a large import of electricity into Germany coming from hydropower in Norway and Sweden and wind power from mainly Denmark, and a large import of biomass from the forests of Sweden, Finland and Norway. The need for electricity imports into Germany leads to a significant increase in the transmission capacities between Norway and Denmark, and between Denmark and Germany.

Germany uses solar panels and CHP plants using biomass to produce heat, where as the Scandinavian countries use electricity in heat pumps.

The variability of wind power production was handled by varying the hydropower production and the production on CHP plants using biomass, by power transmission, by varying the heat production in electric heat boilers, and by varying the production of hydrogen in electrolysis plants in combination with hydrogen storage. Investment in hydrogen storage capacity corresponded to 1.2% of annual wind power production in the scenarios without a hydrogen demand from the transport sector (ESTO and NOFC), and approximately 4% in the scenarios with a hydrogen demand from the transport sector (FC and HDFC), i.e. only a small fraction of the wind energy production was needed to be stored as hydrogen. Even the scenarios without a demand for hydrogen from the transport sector saw investments in hydrogen storage due to the need for flexibility provided by the ability to store hydrogen. The storage capacities of the electricity storages provided by plug-in hybrid electric vehicles in ESTO were too small to make hydrogen storage superfluous.

The direct conversion of biomass to hydrogen was not used under the economic assumptions made in that the model preferred conversion of biomass to electricity and then to hydrogen. Heat pumps were used to provide the bulk of the heat production in the Scandinavian countries with electric heat boilers more being used to provide flexibility.

Both the sceanario with successful introduction of fuel cell technologies, FC, and the scenarios without fuel cells, NOFC and ESTO, were able to handle the variability of wind power production. The differences between FC and NOFC/ESTO were mainly that FC needed a significantly larger hydrogen storage. Furthermore NOFC/ESTO had approximately 3-4% lower total costs compared to FC.

4 Economic optimisation using Balmorel

The Balmorel model (www.balmorel.com) has been used to analyse the long-term integration of wind power production focusing on the possibilities given by:

- Hydrogen production and hydrogen storage
- Power exchange between countries

For this purpose the Balmorel model has been extended to include production, storage and consumption of hydrogen.

Two studies have been carried out with Balmorel:

3. Investigation of a possible long term investment path from 2005 until 2050 for the Scandinavian energy system focussing on renewable energy in the supply sector and on hydrogen as the main fuel for transportation, covering up to 70 percent of all road transport in 2050. The transformation during time from a mainly fossil fuel based to a mainly renewable energy based energy system is the focus of this study. It has been accepted for publication in the International Journal of Hydrogen Energy.

4. Calculation of the economic energy system configuration for the Scandinavian countries and Germany in 2060 assuming a nearly 100% coverage of the energy demands in the power, heat and transport sector with renewable energy sources. Different assumptions about the future success of fuel cell technologies have been investigated as well as different electricity and heat demand assumptions.

The first study was carried out using input data existing at Risoe in an early stage of the project. The variation in time of electricity and heat demand and wind power production was represented by dividing each yearly simulation into 52×5 = 260 time steps, i.e. 52 weeks each divided into 5 time steps. With this time resolution the model solves relatively fast making it feasible to run the time period 2005-2050 with 5 year steps.

In the second study carried out later in the project period, the input data presented in chapter 2 and 3 was used in Balmorel. The time series used have a 6-hourly time resolution giving 52×28 = 1456 time steps making the model larger and slower. As the transformation from a fossil to a renewable based energy system had already been analysed, it was decided to concentrate on 2060 as an example of an energy and transport system based nearly 100% on renewable energy sources. The importance of hydrogen in such an energy system was analysed.

This chapter documents the analyses undertaken and presents the results. First the Balmorel model is described. Next the implemented model extensions of Balmorel is documented. Then the study of the development of the Scandinavian power system from now to 2060 is presented and finally the analysis of a North European power system in 2060 is described.

1.1 The Balmorel model

The Balmorel model is a partial equilibrium model of an electricity system with combined heat and power [1]. The model is linear, and assumes perfect competition. The objective function maximizes the social surplus (the sum of consumer and producer surplus), which corresponds to minimizing the operation costs in the whole system in the case of fixed electricity demands. The model is multi-regional consisting of regions connected by transmission lines. It takes into account the balance between supply including net export and demand in each region, capacity restrictions for production units and transmission lines, technical restrictions for CHP plants, balance equations for district heating, hydropower and electricity storages, and derives electricity market prices from marginal system operation costs.

Data in the model combine historical data (for electricity and heat demand, wind power production and others) with scenarios for the future development in heat and power demand, installed capacity and others.

The Balmorel model can be run in three different modes:

1. BB1: A model run with a yearly optimization horizon, more aggregated time resolution than hourly, and without endogenous investments.
2. BB2: A model run with yearly optimization horizon, more aggregated time resolution than hourly and with endogenous investments.
3. BB3: A model run with weekly optimization horizon, hourly time resolution and without endogenous investments.

Sequential solutions of the model in mode BB2 for different years and with resulting investments transferred from one year to the next can thus be used to simulate investment paths over a longer time horizon. The investments in production and transmission capacity generated by running BB2 can be transferred and used in BB1 and BB3. BB1, BB2 and BB3 share the same input data with the hourly time series used in BB3 being aggregated into the time resolution used in BB1 and BB2. The yearly optimization horizon used in BB1 and BB2 is suitable when optimizing seasonal storage, such as determining the optimal use of water stored in hydropower reservoirs. Running BB1 and BB2 with time steps corresponding to 52 weeks each sub divided into a number of time steps makes the transfer of results concerning the usage of seasonal storage from BB1/BB2 into BB3 relatively straight forward. For example the weekly use of hydropower calculated in BB1/BB2 is introduced in BB3 as a restriction specifying the weekly hydropower production in each week and region. BB3 can then determine how this weekly hydropower production is distributed on hours.

The power exchange between the regions modeled is determined endogenously, according to relative prices and transmission capacities. The exchange between the modeled countries and countries outside the model (third countries) can be represented by:

1. A time series specifying the exchange per time period.
2. A time series specifying the price in the third country per time period.
3. A combination of 1 and 2 specifying prices in the third country dependant on the amount exchanged per time period.
4. As 3 but with the price interface calibrated using BB1/BB2 to ensure a certain yearly net exchange between the model country and the third country.

Each country in the model is divided in regions, which is the level power production and demand is balanced (there is exhange of power between regions). Regions can be divided into areas which is the level for balancing production and demand for district heating (there is no import or export of district heat between areas). Power demand is given on region level while district heating demand is given on area level.

The electricity grid is modeled at the level of transmission lines between regions. Areas are introduced to represent district heating grids e.g. to represent a grid with a certain number of CHP plants and heat boilers and a certain time variation of heat demand. Each production unit is situated in an area.

The functionality of Balmorel is continuously being extended. Recently the Balmorel model has been extended to include the Danish natural gas transmission system (see project report and documentation available from http://www.balmorel.com/). This extension is not used in this study.

1.2 Modeling of hydrogen

The following elements are modeled:

1. Hydrogen demand from sectors not included in the model e.g. the transport sector.
2. Hydrogen production using electrolysis, steam reforming of natural gas, or production from biomass.
3. Hydrogen storage.
4. Power and/or heat producing units using hydrogen as fuel.

The hydrogen demand is specified on regional level, where as hydrogen production and hydrogen storage technologies belongs to an area. A hydrogen system in a region is characterized by hydrogen production plants of different type producing hydrogen that either can be stored or used outside the power system. The stored hydrogen can either be used outside the power system or by power or heat producing units within the area using hydrogen as fuel. The model will not choose to both produce hydrogen from electricity and use hydrogen to produce electricity within the same time step. The hydrogen distribution system with a region is not included in the analysis. It has been analysed in [2].

1.2.1 Hydrogen demand from sectors not included in the model

The hydrogen demand from sectors which are not included in the model is characterized by being determined by assumptions exogenous to the model. Hydrogen consumption from units included in the model e.g. power plants will be determined by the optimization of the operation of the units done by the model.

The same possibilities for modeling of the exogenous hydrogen demand as mentioned with regard to modeling of power exchange between a country included in the model and third countries exist (see above). Of these we have currently implemented possibility 1 (A time series specifying the hydrogen demand per time period), but the other possibilities are straight forward to implement. The hydrogen demand is specified for each area.

1.2.2 Hydrogen production

Electrolysis plants, steam reforming plants using natural gas and hydrogen production from biomass are implemented. They are characterized by a fixed ratio (efficiency) between usage of feed stock (electricity, natural gas or biomass) and hydrogen production. Their investment costs are specified by MWh/h of hydrogen production capacity. They deliver hydrogen into the area where they are defined. Thereby the competition between using electricity or other feed stocks for hydrogen production can be captured to some extent.

1.2.3 Hydrogen storage

In BB1/BB2 the hydrogen storage is optimized over a year with the restriction that the start level in the storage must be equal to the end level in the storage, i.e. that the energy content of the storage is the same in the start and the end of the year. This applies due to to normal year assumptions for hydro inflow and wind. The energy content level to have in the start and end of the year is chosen by the model. The start level of the storage in each week (S) is saved from a BB1/BB2 run.

In BB3 the hydrogen storage is optimized over a week with the restriction that the start level in week S being equal to the start level for week S found from a corresponding BB1/BB2 run, and the end level in week S being equal to the start level for week S+1 found in a corresponding BB1/BB2 run. BB1/BB2 can make investments in hydrogen storage capacity.

The loading and unloading capacities for hydrogen storage are proportional to the energy content capacity of the storage, i.e. the loading and unloading capacities are specified as number of hours of maximum loading/unloading for filling or emptying the storage. The investment costs are per MW of energy content capacity. A loading and unloading cycle loss is implemented:

1. LOADLOSS: loss proportional to the loading of the storage but represent losses from the whole cycle of loading and unloading.

1.2.4 Hydrogen consumption within the power system

Different types of power plants and heat boilers were already implemented, so we should only specify instances of the units that use hydrogen as fuel. We have chosen to describe the fuel cell power plants analagously to backpressure plants, which have a fixed ratio between heat and power production.

1.3 Analysis of optimal investment paths for future renewable based energy systems

This study investigates a possible long term investment path for the Scandinavian energy system focussing on renewable energy in the supply sector and on hydrogen as the main fuel for transportation, covering up to 70 percent of all transport in 2050.

The optimisation model Balmorel [1] covering the Scandinavian energy system is used. The model has been expanded to include the modelling of hydrogen production technologies, storage and hydrogen power plants.

The simulation shows that with an oil-price at 100 \$/barrel, a CO_2-price at 40 €/ton and the assumed penetration of hydrogen in the transport sector, it is economically optimal to cover more than 95 percent of the primary energy consumption for electricity and district heat by renewables in 2050. When the transport sector is converted as assumed 65 percent of the road transport relies on renewable energy. The use of a constant CO_2-price during the scenario period can be seen as a global or EU quota marked where the number of quotas is reduced significately up to 2050 or a regional agreement on destroying quotas to secure this development.

1.3.1 Modelling Methodology

Optimal power system configurations in, e.g., 2050 can be derived by running the Balmorel model with endogenous investments for the period (2005-2050) using 5-year steps. The approach is illustrated in figure 1.

The Balmorel model results will enable an analysis of the dependencies between the performance of the hydrogen energy chain and parameters such as share of fluctuating production in the power system, fuel prices and CO_2 prices.

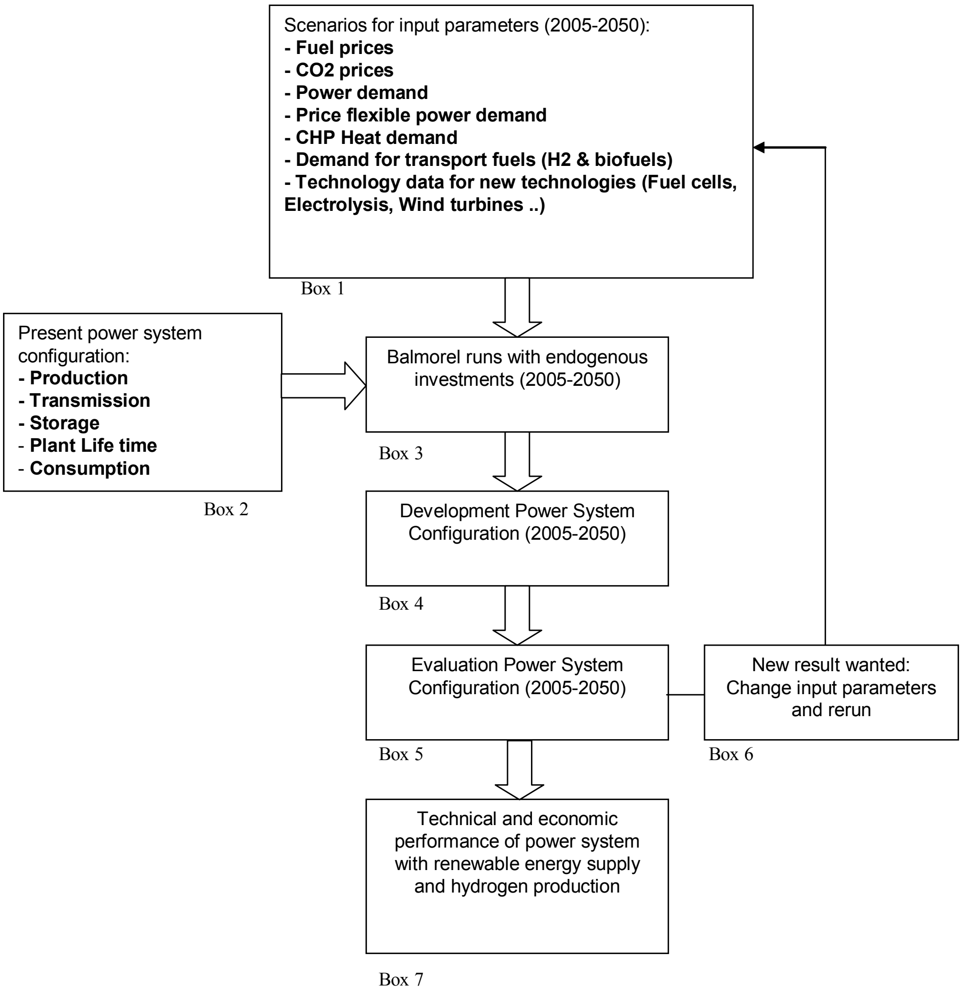

Figure 1 Overview of the methodology used for analysing future investment paths.

The working flow in the analysis starts with the creation of a database with existing technologies (box 2) in the energy system (power plants, heating plants, heat storages etc.). Then scenario specific parameters are added to the database; those include demand predictions; future available technologies; fuel prices; and externalities (box 1).

For long term investment scenarios, as treated in this paper, Balmorel will typically run with a more aggregated time resolution than one hour, e.g., 5 periods within each of the 52 weeks in a year, adding up to 260 time-slices per year. Box 3 and 4 in figure 1 represents model simulation with endogenous investments and output of modelling results in a result-database ready for inspection.

The evaluation of the resulting energy system is carried out by checking total economy for the scenario, power and heat production divided on technologies and fuel, production of hydrogen and environmental effects (box 5). If a certain goal for the future energy system is not fulfilled such as a target for installation of wind power or for CO_2-emission, then the input parameters are adjusted (box 6) and the model is run again.

It is also important whether the found energy system can function with a more detailed time resolution enabling better representation of load and wind power variability. To investigate this, the model can run on an hourly basis for a chosen year or for a period in a year. In this mode the model does not undertake investments but uses the energy system found previously and then tests if there will be capacity shortage or power/heat surplus in some time-steps (box 5). If the system is not in balance in every time-step corrections in input parameters are necessary, e.g., the inclusion of more technologies which can solve the given problem or adding more restrictions on the investment in the different technologies, e.g., securing sufficient back-up capacity.

When the evaluation turns out successfully then the results from the scenario modelling describe a sound proposal for an economically optimal energy system given the scenario specific input parameters (box 7).

The presented Balmorel covers four of the Nordic countries: Denmark, Norway, Sweden and Finland. Each country is divided into several regions (except from Finland where there only is one region) in order to model the effect of the most important bottle necks in the Scandinavian transmission grid, see figure 2. The area is modelled as a closed system with no exchange of heat and power with e.g. Russia and Germany.

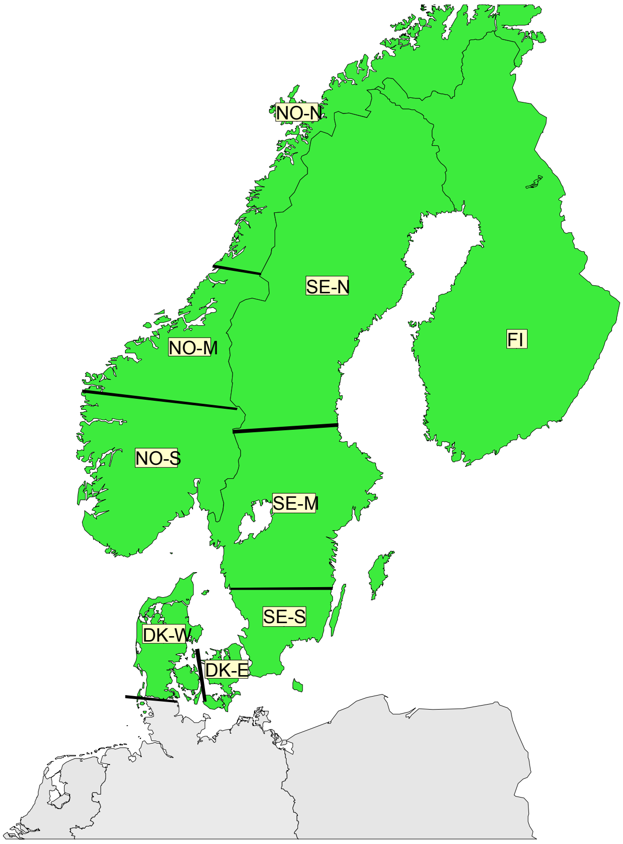

Figure 2 Countries and regions in the applied Balmorel model

Between regions the transmission lines have capacity constraints on the export and import of power from region to region. Electricity is balanced at a regional level including the effect of power transmission between regions. Each region is subdivided into areas. Areas are introduced to represent heating grids, e.g., to represent a district heating grid with a certain number of CHP plants and heat boilers and a certain time varying heat demand. Each production unit is allocated to an area. District heat demand and supply are balanced on area level, i.e., district heating is not traded between areas. This particular model has two areas in each region – an urban area and a rural area. The number of areas can be increased if more detailed analysis is to be made.

1.3.2 4. A renewable energy system in the Scandinavian countries?

The industrialised countries might have to stop emitting GHG from energy conversion and transportation by 2050. In the energy conversion sector many different renewable energy technologies can play a role and in the transportation sector more efficient vehicles, electrical vehicles, fuel cell vehicles etc. are some of the possible future technologies. In this scenario we assume hydrogen driven fuel cell vehicles becomes the main solution in the future transport system. In energy conversion wind and biomass will be the main sources replacing fossil fuel.

Demand for energy is given exogenously to the Balmorel model, as shown in figure 1, and is therefore not a part of the optimisation. In the following we describe the used assumption for the exogenous parameters to the model.

Hydrogens share of the road transport work is assumed to grow from 2010 to 2020 and then increase linearly from 2020 through the period reaching 70 percent in 2050 in all countries, see figure 3. This scenario consequently assumes that many problems related to hydrogen based systems are solved - like durability of the fuel cells and development of safe, compact, light onboard hydrogen storage facilities etc.

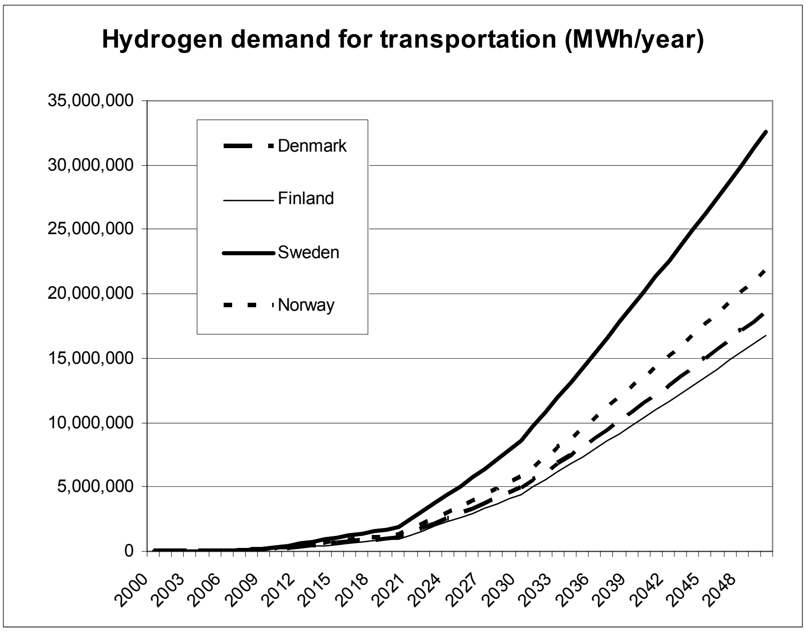

Figure 3 Hydrogen demand for road transport in the four Scandinavian countries

A society with focus on environmental problems probably also has focus on energy savings. So even though the Scandinavian countries is expected to have an economic growth around 1-2 percent per anno until 2050, it is assumed they manage to keep electricity and district heating demand on the same level as in 2005 – similar to the Danish Governments energy saving plan from 2004 [3].

Table 1 Electricity and district heat demand including distribution losses i.e. ab plant.

(TWh/Year)	Denmark	Norway	Finland	Sweden
Electricity demand	34	119	83	143
District heat demand in CHP areas	32	2	65	33

Fuel prices and a CO_2-price may be the drivers to reach a 100 percent renewable energy system in the Scandinavian countries. By increasing the price assumptions until the model phases out all fossil power and heating plants, will then give a set of boundary conditions making it socio-economically favourable to phase out fossil fuels.

Future correlations between fuel-prices are difficult to predict accurately, so in this paper it is assumed that all fuel prices follow the oil price with constant price elasticity, as shown in table 2. If we take coal as an example the coal price will increase by 0.5% if the oil price increase by 1%.

Table 2 Fuel prices used in the scenario and price elasticities to oil price. The fuel prices include transport and handling. The prices are assumed to grow linearly from the low level in the table reaching the higher level in 2030 and staying at this level throughout the scenario periode.

	Fuel oil	Natural gas	Coal	Biomass	Uranium
Base price (€/GJ)	9.0-13.0	6.4-8.5	2.0-2.5	4.5-4.8	0.6-0.8
Price elasticity to oil price	1.00	0.78	0.50	0.20	0.50

The elasticities is a rough estimate based on future prices used by the Danish Energy Agency. The use of elasticities is a way of reducing the number of free parameters when simulating different scenarios with the model. A fuel oil price at 9.0 €/GJ resample's an oil market price around 70 US$/barrel. In the simulated scenario the oil price is assumed to grow linearly from 70 US$/barrel in 2006 to 100 US$/barrel in 2030 and stay at this level throughout the period. We use a constant and relatively high CO_2-price at 40 €/ton CO_2.

When simulating, the model invests in new technologies when needed to meet demand year by year, hour by hour or when it is economically attractive. Table 3 shows the technologies the model is allowed to choose from in this setup. Many more technologies could be relevant and should be added to the database.

Table 3 Technologies from which the model can choose when simulating.

Tech-code	Description	Period available	Invest-ment costs (M€/MW)	Variable costs (€/MWh)	Annual costs (k€/MW)
OC-ADGT-NG	Open cycle gas turbine	2005-2050	1.9	1.5	50
ST-biomass-ENS	CHP plant – biomass	2010-2050	1.3	2.7	25
WI-offshore-ENS I	Offshore wind	2005-2020	2.0	8	8
WI-offshore-ENS II	Offshore wind	2021-2050	1.5	5	5
WI-onshore-ENS I	Onshore wind	2005-2020	0.95	9	0
WI-onshore-ENS II	Onshore wind	2021-2050	0.80	8	0
ST-Coal-ENS	CHP plant	2010-2050	1.2	1.8	16
HO-B0-WO	Heat boiler – biomass	2000-2050	0.32	4.02	19.28
HO-B0-NG	Heat boiler – natural gas	2000-2050	0.05	0.67	0.54
EH-P0	Heat pump	2000-2050	0.30	1.21	2.72
CC-NG-ENS	Combined Cycle – natural gas	2010-2050	0.7	1.5	12.5
CH4TOH2	Steam reforming plant	2010-2050	0.08	0	5
H2CHP-30-CEN	SOFC – CHP plant	2020-2050	0.5	6	4
H2CHP-20-CEN	SOFC – CHP plant	2006-2050	1.8	7	5
EL2H2-SO30-CEN	Solid Oxide Electrolysis	2020-2050	0.18	0	5
EL2H2-SO10-CEN	Solid Oxide Electrolysis	2010-2020	0.5	0	6
EL2H2-SP30-CEN	Solid Polymer Electrolysis	2020-2050	0.16	0	6
EL2H2-SP20-CEN	Solid Polymer Electrolysis	2010-2020	0.4	0	6
EL2H2-AL10-CEN	Alkaline Electrolysis	2006-2020	0.1	0	6
H2STO-30-CEN	H2-Storage – cavern	2020-2050	0.0058	0	0
H2STO-20-CEN	H2-Storage – cavern	2010-2020	0.0072	0	0
H2STO-10-CEN	H2-Storage – cavern	2006-2010	0.0096	0	0

No new nuclear are included in this version of the database. Only the new Finnish nuclear plant currently under construction is expected to exist all through the scenario period.

Availability of resources is another important parameter in simulating future energy systems. How much biomass can be used for energy production and how many MW wind turbines can be erected in each country etc? In the presented simulation we have used restrictions on biomass and wind as shown in table 4.

Table 4 Maximum allowed utilization of resources in the simulation.

	Denmark	Norway	Finland	Sweden
Biomass (PJ/year)	81*	115**	251*	209*
Wind power (MW)	20,500**	37,500**	10,000**	20,500**

* Potentials taken from the Green-X project [4]
** Potentials estimated in this project

1.3.3 5. Results

In the following results from the simulation are presented. Compared to the analysis method described in figure 1, these results are represented by box 4 "Development, Power System Configuration (2005-2050)". Hereby, we have the first results to evaluate according to system operation conditions and fulfilment of different goals (like a 100 percent renewable energy supply). The results show, that we almost reach a 100 percent renewable based energy supply in 2050 with the given set of exogenous parameters. The only non renewables are Finnish nuclear power; natural gas for steam reforming (covers 28 percent of the hydrogen production) and heat boilers; and the remaining 30 percent of the transport still based on fossil fuel. 95 percent of the fuel consumption for heat and power production in 2050 is by covered by renewables, see table 5.

Table 5 Gross energy consumption for district heat and power production divided on fuels in the scenario year 2050 and the share of power production divided on fuels.

Fuels for heat and power production	Fuel share	Share of power prod.
Waste	6 %	1 %
Nuclear	5 %	3 %
Hydro	32 %	41 %
Wind	35 %	44 %
Biomass	22 %	11 %

Existing power and heat capacity in the model is decommissioned when reaching the expected end of lifetime. Most plants have a lifetime around 30 years, so after 2035 most of the capacity running today will be gone. In figure 4 the decommissioning of existing plants are shown except from hydro power which are assumed to be prolonged all throughout the scenario period. In Denmark already existing power capacity is gone in 2035 except for a few CHP plant using municipal waste as fuel, which are assumed to be gradually replaced by similar technology. In Finland only their newest nuclear power plant will survive to 2050. This plant is assumed to generate power from 2011 and the expected lifetime is 50 years. In Norway there are only very limited capacity besides the hydro power and in Sweden the last nuclear plant is closed before 2040.

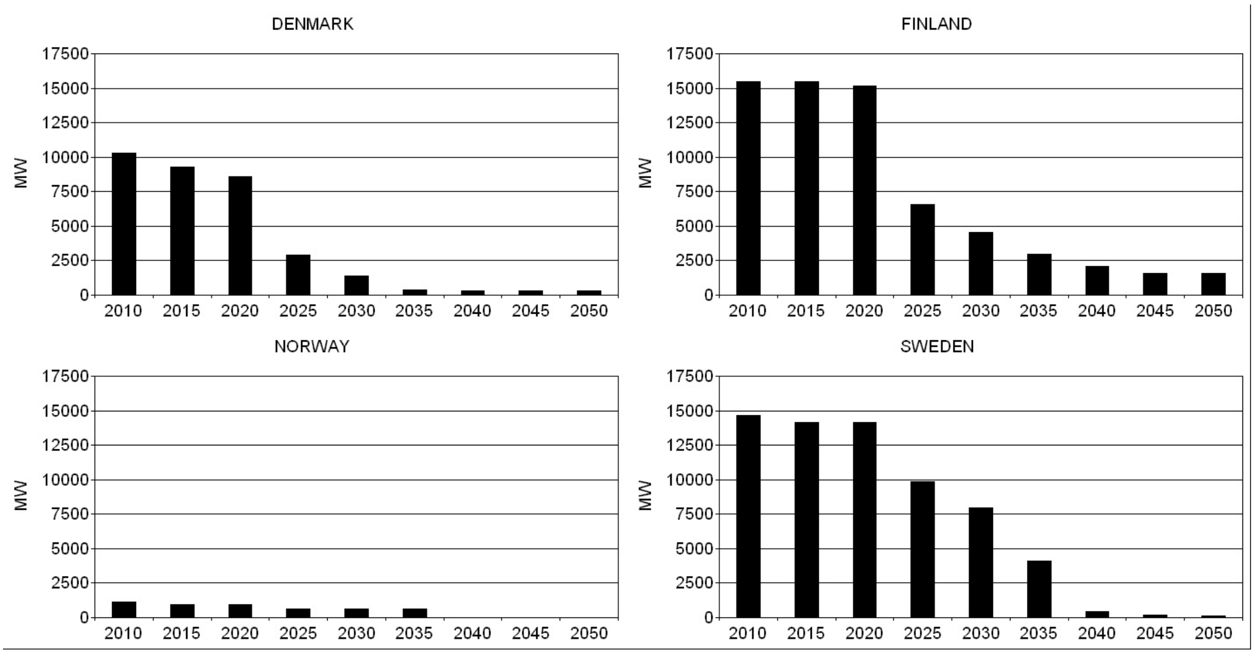

Figure 4 Decommissioning of existing power plants in the Balmorel model. The figure shows all existing power producing plants except from hydro power.

Which power producing technologies Balmorel chooses to build in the simulation is shown in Figure 5. What cannot be seen from the figure is that Balmorel also tells in which region and area to build the power plants (each country is divided in several regions, see figure 2).

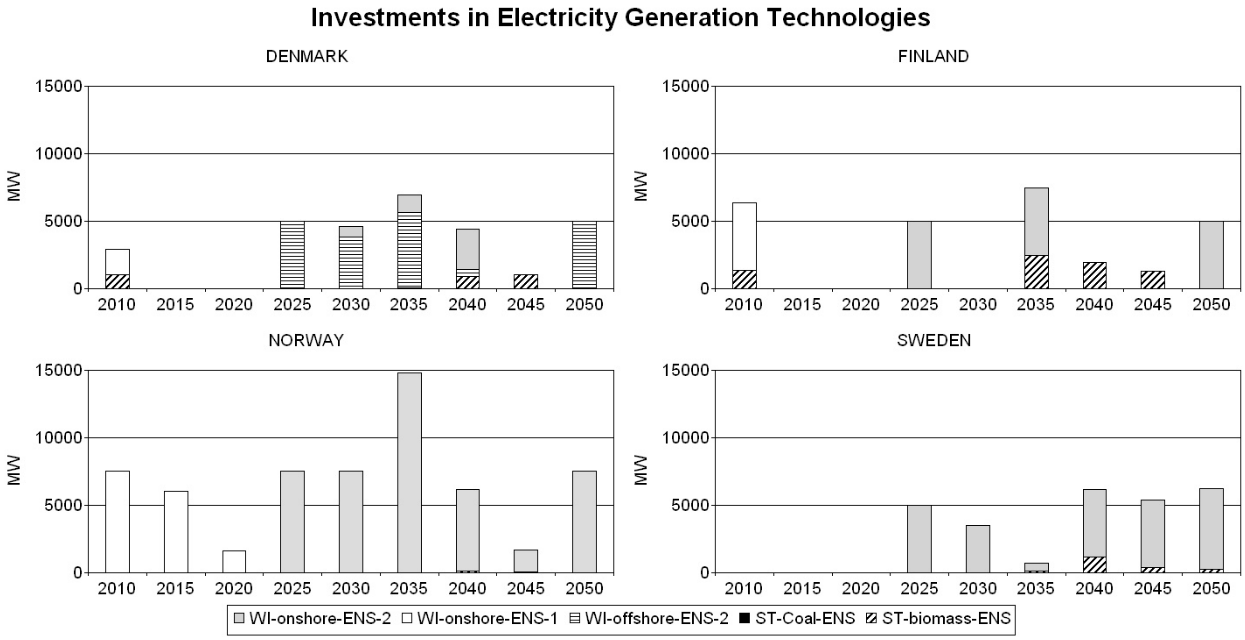

Figure 5 Investments in power capacity in five year steps – e.g. the number in 2035 covers investments for the period 2031 to 2035.

Figure 5 also shows that the fuel prices and CO_2-price used for this simulation favours wind power. Around 2035-2040 the wind potential is though fully developed and then biomass power plants enters again to supply a still increasing power demand due to hydrogen production via electrolysis. Another reason for investing in thermal power is an increasing need for regulating power to balance the intermittent wind power. Apart from electricity generating and hydrogen producing technologies the model also invests in bridging technologies such as heat pumps and hydrogen storage, which can help balancing the power system. In Denmark, as an example, the model invests in more than 3 GW central heat pumps and in the whole model area more than 10 GW heat pumps is implemented. Also power transmission line capacity between the regions is increased to secure an efficient utilization of the wind power. All in all transmission capacity is increased by 11 GW between the regions. This should be compared to the existing connectors, which are more than 27 GW. Investments in transmission lines, though not performed on market terms, is assumed to be undertaken in a manner which maximizes the social surplus.

Figure 6 shows fuels used for hydrogen production in each of the four Scandinavian countries. Electrolysis is the preferred source of hydrogen for several reasons: An increasing electricity demand stabilises a system with a lot of wind power; and electrolysis together with hydrogen storage can utilise wind peaks and stop producing when there is no wind.

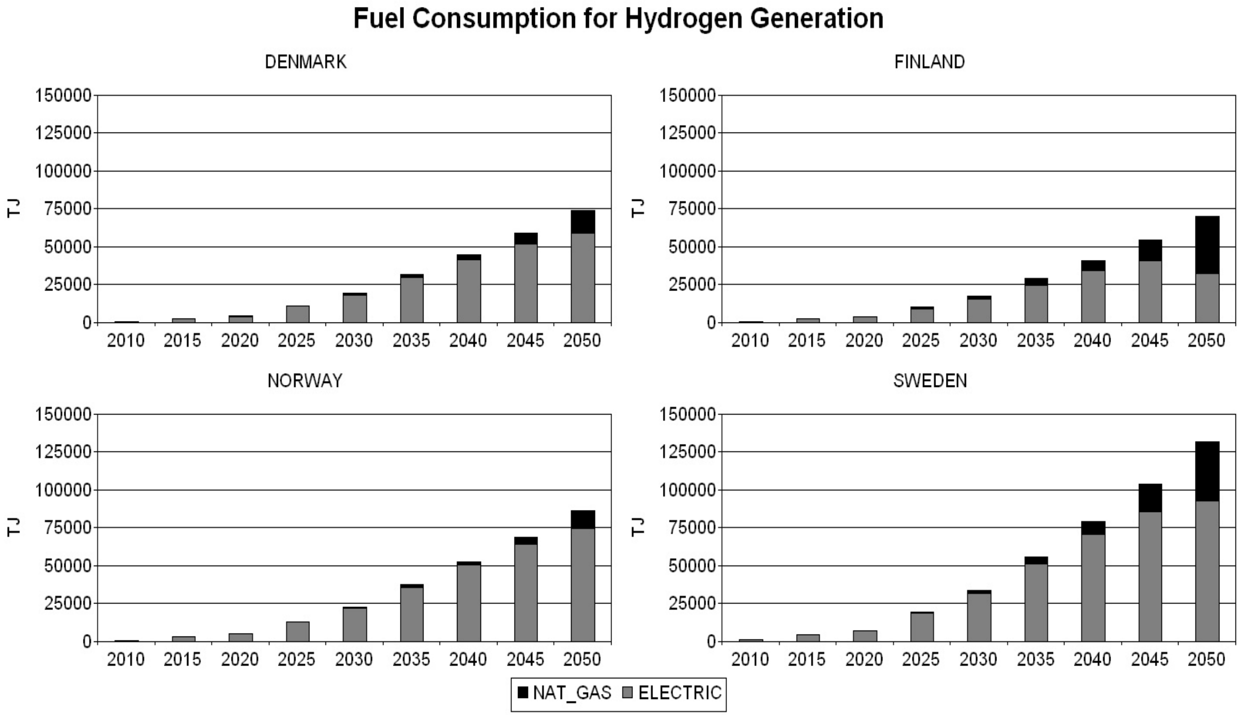

Figure 6 "Fuels" used for hydrogen production. Natural gas is used in steam reforming plants and electricity for electrolysers.

In the simulation there are only limited investments in hydrogen storage, specifically a small storage facility in western Denmark. The hydrogen storage solution is not so attractive because it induces additional energy losses. The model therefore chooses to invest in steam reforming capacity to supplement the electrolysis. The share between steam reforming and electrolysis differs from region to region depending on the local setup of the energy system. In figure 7 it can be seen, on an aggregated level of all four countries in 2050, how the steam reforming plants supplements the electrolysers. When electricity production from wind power goes down the steam reforming plants increase production. The hydro power in Norway and Sweden will reduce this effect as long as there is free capacity on hydro. But in the winter time the power system is stressed due to the use of electricity for heating in Norway; Sweden; and Finland and therefore the steam reforming plants will produce more in this period.

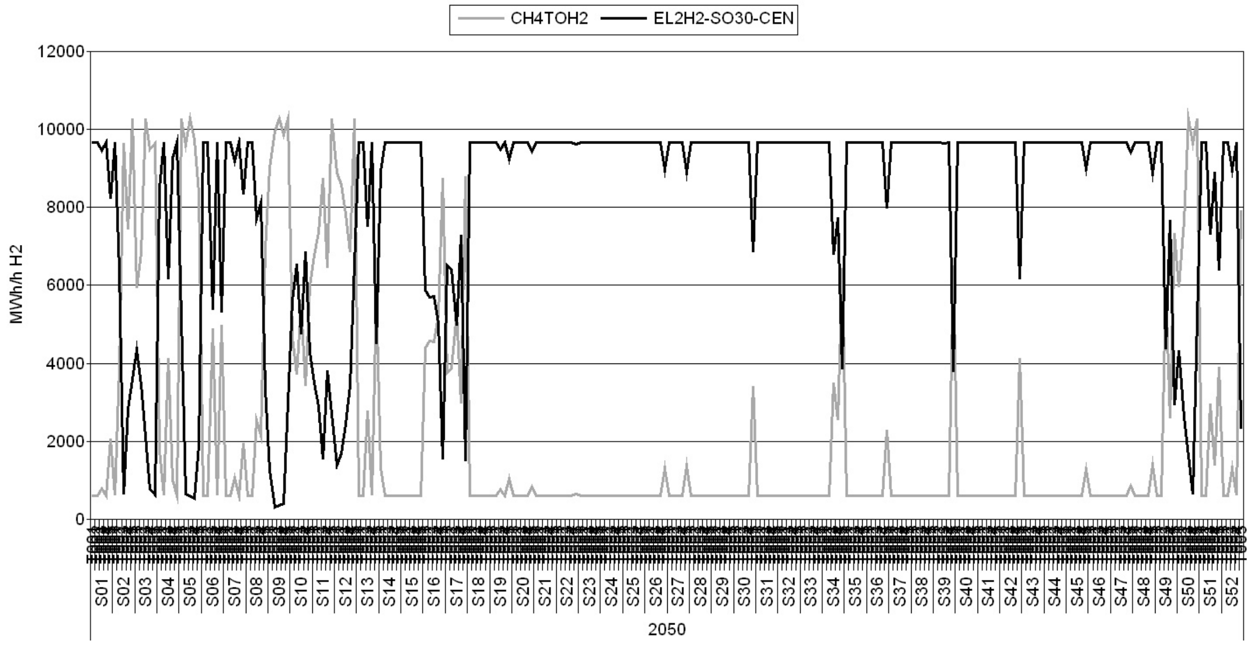

Figure 7 Production of hydrogen aggregated for Denmark; Norway; Sweden; and Finland in 2050. Divided on electrolysers and natural gas steam reforming plants (Natural gas steam reforming plant "CH4TOH2", Central Solid Oxide Electrolysers "EL2H2-SO30-cen"). The Y-axis show produced hydrogen at each time step while the X-axis represent 52 weeks each divided in 5 time steps.

Figure 8 shows an example of how the hydrogen storage in Western Denmark is utilised during the year 2035. The storage is filled in periods with surplus wind power and emptied when there is no or low wind.

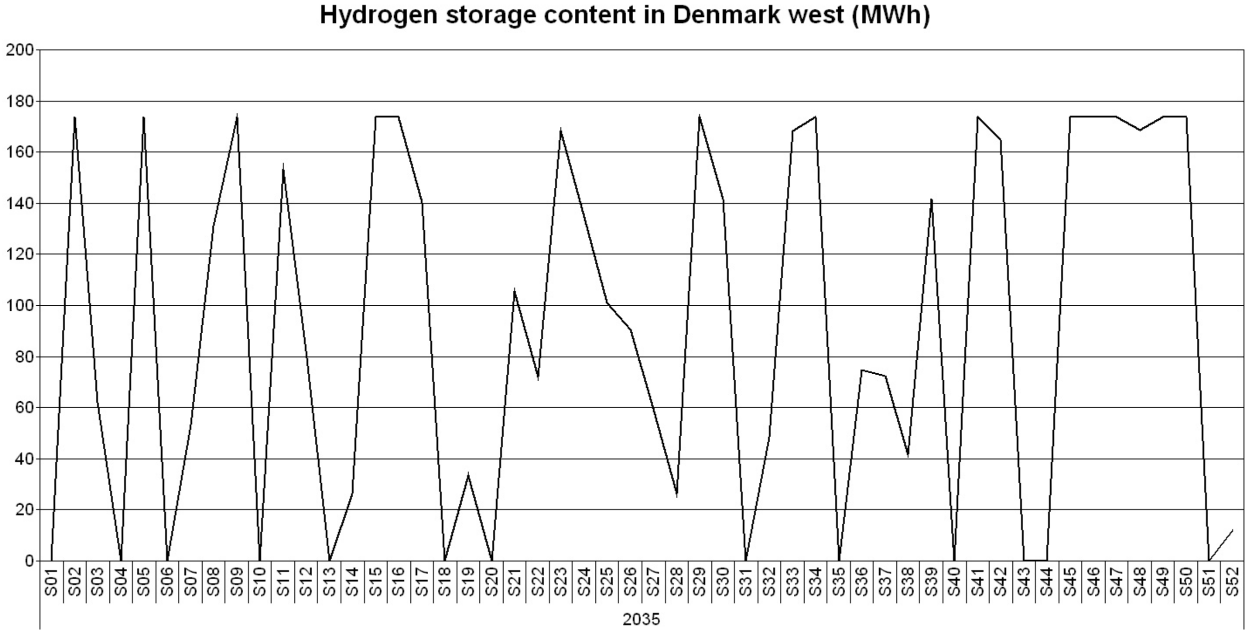

Figure 8 Hydrogen content, during the year 2035, in the storage in western Denmark.

In an optimisation model like Balmorel a production price for power can be determined as the marginal value of the restriction ensuring balance between power supply and demand in each time step. This corresponds to the production price on the marginal power plant producing in the time step. Likewise with production prices of heat and hydrogen. In our scenario, with the described combination of power producing technologies, the average system power price fluctuates around 55 €/MWh. In the same way the average system hydrogen price is found to be varying around 60 €/MWh or 17 €/GJ. Jensen; Larsen; and Mogensen [5] has estimated a hydrogen production price at 5 US$/GJ (3.5 €/GJ) using a power price at 3.6 US$/GJ (9 €/MWh). If their power price is scaled up to the same level as in our scenario their hydrogen production price will be 20-23 €/GJ including investments (long term marginal costs). The corresponding price found in Balmorel is lower due to the power prices in periods where the electrolysis plants operates on average being lower than the average system power prices taken over all hours.

Even though old fossil fired capacity is present in the first simulation years (in Denmark and Sweden), it is more profitable to invest in wind power and then use the old plants as peak-load and for balancing. Full load hours for the existing fossil plants are therefore quit low.

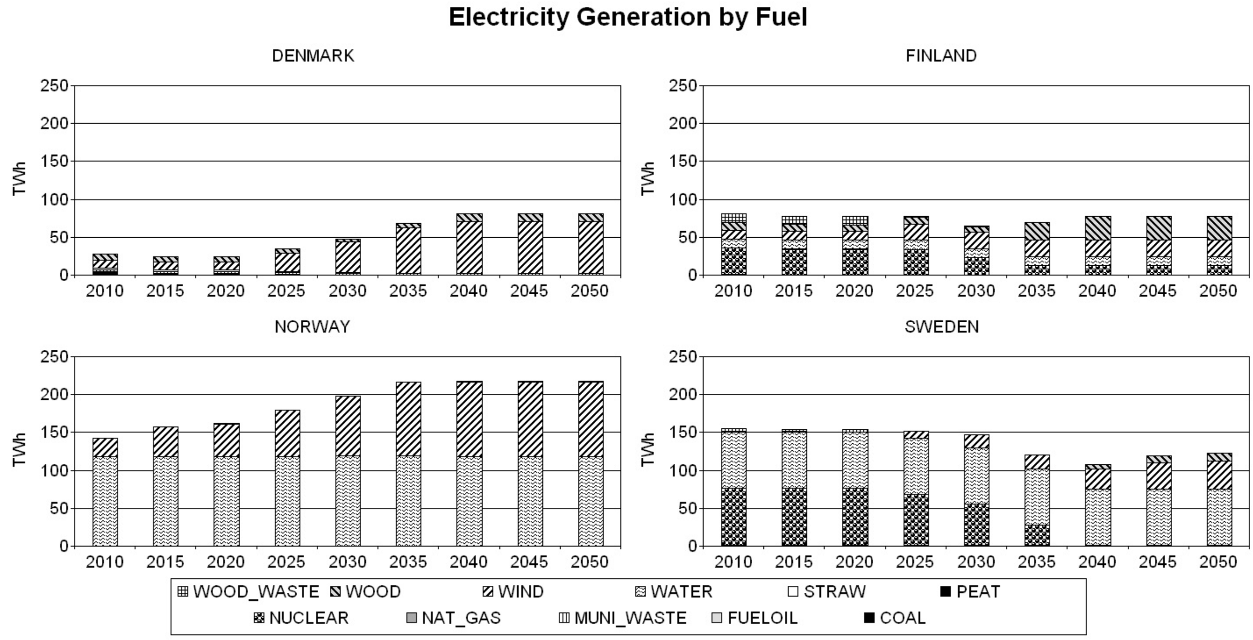

Figure 9 Fuels used for electricity production in each in country in the scenario years.

In Denmark coal is phased out by 2025 and from then the electricity production is covered by wind and biomass (see Figure 9). When reaching the upper level of allowed wind power in Denmark, then biomass power capacity is increased.

In Finland, 50 percent of the electricity is produced on nuclear until 2035 where all old nuclear plants are closed down. The remaining 50 percent is produced from wind, hydro and biomass. From 2035 only the newest nuclear power plants still produces and wind and biomass replaces the decommissioned nuclear.

Norway increases their wind power share as the demand for hydrogen increase. They reach their maximum allowed installed capacity in 2035 and after that the ratio between wind and hydro power is constant. Norway's role as net power exporting country declines from 2040 as they stop increasing their total capacity.

Sweden replaces the decommissioned nuclear power plants with wind power and by increased import. From 2040 they also build biomass based power plants.

In figure 10 the yearly power transmission between the four countries can be studied. Norway exports a lot to Denmark and Sweden but with decreasing amounts after 2035. Denmark exports mainly to Sweden who exports similar volumes to Finland.

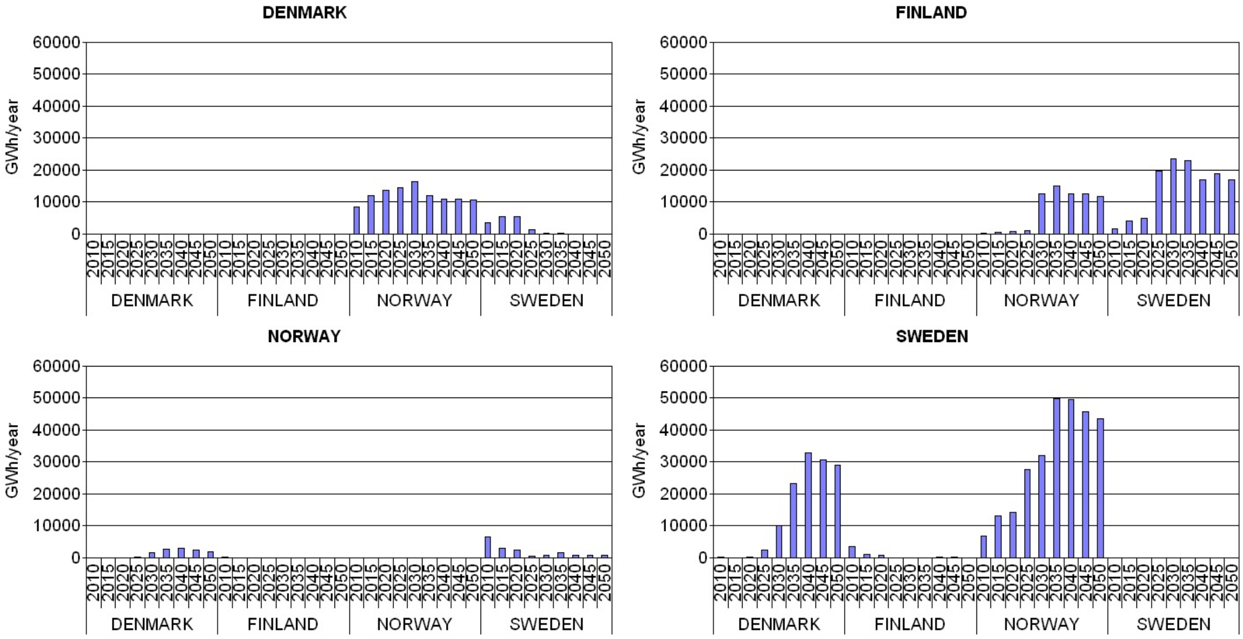

Figure 10 Yearly power import for each country divided on countries and scenario years.

1.3.4 7. System stability

The system stability of the scenario for the four Scandinavian countries is then tested by running Balmorel in a more detailed time resolution (hour by hour) for a chosen year. The year tested is 2040 because at this time intermittent power production in the energy system has reached maximum allowed level.

By doing an hour by hour simulation of the energy system found by the BB2 version of Balmorel, it is found that the power system has a capacity deficit greater than 9 GW in 160 hours a year and greater than 5 GW in 600 hours a year. These deficits can be explained by the difference in using aggregated time series for wind power production and hourly time series. The deficit gets this high because there is more than 80 GW wind power in the system in 2040 and a peak load power demand at the same size.

Next step, which not has been done in this work, is to handle the capacity deficit by introducing additional dispatchable production capacity on top of the amounts generated by BB1/BB2 or implement price flexible power demand. Depending on method, this would slightly change total energy balances and calculated emissions.

1.3.5 8. CO_2-effects in the Scandinavian Energy System year 2050

Using hydrogen for transportation will decrease the emission of CO_2 from the transport sector with same ratio as hydrogen replaces gasoline and diesel from the sector. But the hydrogen has to be produced and if it is produced by steam reforming of natural gas the overall reduction is limited. If the hydrogen is produced by electrolysis the impact on the CO_2-emission depends on the impact on the whole energy system configuration in the Scandinavian energy system. In 2050 the power production in the scenario does not emit CO_2, as the only fossil fuel based capacity left in the system is nuclear. 28 percent of the hydrogen for transportation is in 2050 produced by steam reforming of natural gas and thereby emitting around 6 Mt CO_2/year.

A transport sector still relying 100 percent on gasoline and diesel would emit around 80-90 Mt CO_2 per year in 2050. This should be compared to the emissions from the remaining 30 percent of the transportation still relaying on fossil fuel and the emissions from hydrogen production. The transport sector in the scenario therefore emits 30-33 Mt CO_2/year or one third of the fossil alternative. It can also be concluded that in the scenario 65 percent of the transport work is covered by renewable energy in 2050.

1.3.6 9. Conclusions

In this chapter a first scenario, heading towards a Scandinavian renewable energy system, according to the analysis method, visualised by figure 1, is carried out. A main conclusion is that with an oil price at 100 US$/barrel and technology costs as listed in table 3, it is economical optimal to cover 95 percent of the power and district heat production in the four Scandinavian countries by renewable energy in 2050. Only remaining non renewable plants are the new Finnish nuclear power plant and a few natural gas fired heat boilers. The modelled energy system supplies the transport sector with hydrogen produced by electrolysis and steam reforming of natural gas. In 2050 this means that 65 percent of the transport work in the Scandinavian countries is based on renewable energy.

A system power price can be derived from the model and in 2050 the yearly average power price in the scenario is 55 €/MWh and hydrogen is produced at a price around 17 Euro/GJ (yearly average).

It should be mentioned that no other externalities than the cost of CO_2 is included in the analysis.

1.4 Analysis of North European power system in 2060

Balmorel has been used to analyse a North European power, heat and transport system depending on renewable energy sources covering Germany and the Scandinavian countries in 2060. Apart from one nuclear power plant in Finland, all other energy production is based on hydropower, wind power, biomass, photovoltaics and solar heat. Only renewable energy sources within the countries are allowed to be used to test if these resources are sufficient to cover the demands for energy. Four model runs have been performed:

1. The first is named FC to indicate a scenario where it is assumed that fuel cell technologies are successfully developed leading to introduction of electrolysis based on fuel cells, fuel cell power plants and fuel cell cars.
2. Same as FC except that the electricity and heat demands are increased 100% in order to test if the renewable energy sources are sufficient to cover a case with less energy savings implemented. It is abbrivated HDFC to indicate a high electricity and heat demand version of the FC run.
3. It is assumed that fuel cell technologies are not coming into the market place. Hence combined cycle power plants using hydrogen are replacing fuel cell power plants, alcaic electrolysis are replacing fuel cell electrolysis, and electric cars are used in stead of fuel cell cars. It is named NOFC to indicate a scenario without fuel cell technologies.
4. Same as 3 except that the possibility for the electric cars of providing electricity storage to the power system are taken into account. It is named ESTO to indicate a scenario with electricity storage and without fuel cell technologies.

All cases include possibilities for investing in hydrogen storage, transmission lines, heat boilers using wood or electricity, heat pumps and heat storages, in order to analyse if integration of the variable wind power production will lead to introduction of hydrogen used as a storage option or alternatively handling of variable power production through power exchange and/or interaction with the heat system and use of heat storage. Power production using biomass is included as an alternative to wind power production. Two possibilities for hydrogen production is implemented: electrolysis or production from biomass.

To simplify the model and decrease calculation time the transmission grid is only represented by transmission lines between countries. To account partly for needed transmission investments within a country, the investment cost of a line is assumed proportional to the length of the line, and a international transmission line is assumed to connect load centres in each country thereby increasing the length of the line. The power exchanges between the countries included in the model and neighbouring countries outside the model is assumed to be zero.

It has been decided not to distinguish between low temperature heating demand covered by respectively district heating and heating supply located in individual buildings. The reasons are that individual heating supply has a lower heat loss in the heat distribution system, where as the larger heat production technologies in district heating systems will be cheaper than individual heating solutions due to economies of scale effects. The relative importance of these two issues is hard to judge in a study covering 2060. If the model did include a representation of the hydrogen distribution system, it would have been sensible to distinguish the two heating supply options, because they involve very different hydrogen distribution options. In summary it was decided not to distinguish between district heating solutions and individual heating solutions. Therefore a fuel cell CHP plant represents both larger fuel cells in district heatings systems and micro CHP solutions, likewise with heat boilers using wood or electricity and heat pumps.

The time resolution is 6 hourly corresponding to 1456 time steps for a year.

1.4.1 Data input

Time series

Within each country there is time series with 6 hourly resolution giving:

- The electricity demand including electricity used to provide high-temperature heat in industry.
- The demand for low temperature heat in buildings.
- The variability in the onshore wind power production.
- The variability in the offshore wind power production.
- The variability in electricity production from combined heat and photovoltaics panels.
- The variability in heat production from combined heat and photovoltaics panels.

The data input for electricity and heat demand time series as well as wind power production and solar time series is described in chapter 2.

Electricity, heat and transport demand

For FC, NOFC and ESTO the same electricity and heat demand is assumed as in chapter 3 and presented in Table 6. HDFC has twice the electricity and heat demand of FC.

Table 6 Electricity and heat demand in scenarios FC, NOFC and ESTO including distribution losses i.e. ab plant. HDFC has twice as high a electricity demand as given in the table.

(TWh/Year)	DK	N	S	SF	D
Electricity demand	17	17	32	22	339
Heat demand	18	22	36	26	240

The transport demand is the same as assumed in chapter 3. The model is not able to determine the optimal split between hydrogen and biofuel, so it is assumed that half of the transport demand is covered with biofuels and half with hydrogen. This leads to a larger demand for biofuels due to the higher efficiencies of a fuel cell compared to a Diesel or Otto engine. In scenarios NOFC and ESTO the demand for hydrogen is replaced with a demand for electricity having the same size as the demand for hydrogen. It is therefore implicitely assumed that the larger efficiency of the drivetrain in an electric vehicle compared to a fuel cell vehicle is counteracted by the larger weigth of the electric vehicle due to larger batteries. The demand for biofuels are subtracted from the biomass potentials before running the model, i.e. Balmorel only has to fullfill a demand for electricity, heat and hydrogen, but the biomass potential available for this is reduced due to the biofuel demand.

Table 7 Transport demand in scenarios FC and HDFC. In NOFC and ESTO the demand for hydrogen is replaced with the same demand for electricity.

PJ/Year	DK	N	S	SF	D
Biofuel	129	109	213	124	1974
Hydrogen	93	78	154	90	1426

Fuel potentials, fuel prices and CO_2 price

It is assumed that only non-fossil energy sources are available to investigate if the resources are sufficient to cover the energy demands for electricity, heat and transport. The potential renewable energy supply available is taken from Table 1 in chapter 3 with two exceptions:

1. This study assumes a 25% reduction in bio fuel availability due to a larger demand for food.
2. This study use historical values for hydropower production which are a little different from the values stated in Table 1, chapter 3.

As this study needs the biomass potential before conversion into biofuels, the biofuels potentials stated in Table 1 chapter 3 reduced with 25% have been converted into biomass potentials by division with an assumed biofuel conversion efficiency of 0.5.

Table 8 Potential renewable energy supply available for use in the North-European countries considered (PJ/year).

	DK	N	S	SF	D
Wind on-shore	64	167	201	147	157
Wind off-shore	358	974	579	391	177
Biomass from agriculture	362	77	167	74	2990
Biomass from forestry	87	785	2505	1770	1338
Biomass from aquaculture	230	335	480	308	162
Hydro		410	222	47	78
Solar PVT electricity					129
Solar PVT heat					368

Only two fuel prices are used namely a biomass price equal to 4.5 Euro/GJ and a nuclear fuel price of 0.6 Euro/GJ. Furthermore when the restriction on biomass potentials is binding, this leads to an endogenous increase in biomass price.

As there are no fossil fuel technologies in the scenarios, we do not need to assume a CO_2 price.

Investment possibilities

The investment possibilities are outlined in Table 9. Investment in nuclear and solar power technologies is not possible. The technology data is compiled from the new technology data compiled in this project and presented in an appendix to this report in combination with [6; 7]. The investments are annualised with a discount rate of 3%. The model expresses costs and prices in 2005 monetary values i.e. inflation is not included in the discount rate. Investment costs are specified relatively to the heat production capacity for heat pumps, and relatively to the heat storage capacity for heat storage.

Table 9 Technologies from which the model can choose when simulating.

Tech-code	Type	Fuel	Annualised investment costs [kEuro/MW]	Variable operation and maintenance costs [Euro/MWh]	Annual operation and maintenance costs [kEuro/MW]
CC-H2-ENS	Combined cycle CHP	HYDROGEN	28.1	1.5	12.5
EH-E9	Heat pump	ELECTRIC	2.7	0	1.2
EH-P0	Heat pump	ELECTRIC	40.3	0	1.5
EL2H2-AL10-CEN	Electrolysis	ELECTRIC	12.1	0	5.4
EL2H2-SO30-CEN	Electrolysis	ELECTRIC	11.1	0	5
EL2H2-SP30-CEN	Electrolysis	ELECTRIC	11.9	0	6
FuelProdBiomassH2-50	Hydrogen prod	HYDROGEN	201.6	0	150
H2CHP-30-CEN	Fuel cell CHP	HYDROGEN	41.9	6	4
H2STO-30-CEN	Hydrogen storage	HYDROGEN	0.0	0	0.0036
HO-B0-WO	Heat boiler	WOOD	16.4	4.017	19.3
ST-biomass-ENS	Extraction	WOOD	66.3	2.7	25
WI-offshore-ENS-2	Wind	WIND	100.8	5	5
WI-onshore-ENS-2	Wind	WIND	53.8	8	0
HEATSTO	Heat storage	HEAT	0.2		

Plants existing in 2060 before investment

Hydropower in D, N, S and SF is assumed to exist in 2060 with the same production capacities, hydro reservoir storage capacities, annual hydro inflow as today, i.e. no growth or decline of hydropower is assumed. One nuclear power plant in Finland is assumed existing in 2060 (the one being build presently and planned to come online in 2010). Photovoltaic and thermal collectors in D are assumed being build due to public support schemes, and are therefore not included in the investment analysis but introduced exogenously.

In case ESTO the amount of electricity storage provided by the electric cars need to be estimated. In EU 15 in 2004 there were 495 passenger cars per 1000 inhabitants [8]. It is assumed in ESTO that all passenger cars are plug-in hybrids using biofuels and electricity as fuel and there exist 500 passenger cars per 1000 inhabitants in 2060. Each plug-in hybrid has an electricity storage with an effective storage capacity of 10 kWh corresponding to an all-electricity driving range of approximately 100 km. This electricity storage is available for the power system. The loading and unloading capacity per car is defined by the grid connection assumed to correspond on average to a 3-phased 220 V, 10 ampere connection giving a loading and unloading capacity per car of 6,6 kW. On average 80% of all cars is assumed to be grid-connected thereby reducing the available instantaneous unloading/loading capacity. It is not reasonable to reduce the size of the electricity storage due to this, because during a short period e.g. 24 hours all passenger cars will be plugged in, so the storage capacity of all cars will over that period be available for the power system.

Table 10 The storage capacities and loading/unloading capacities of the electricity storages representing the sum of the electricity storages in plug-in vehicles in scenario ESTO.

	DK	N	S	SF	D
Population [M]	5.40	4.70	8.60	5.20	80.70
Cars [M]	2.7	2.35	4.3	2.6	40.35
Storage capacity [MWh]	27000	23500	43000	26000	403500
Unloading/loading capacity [MW]	14256	12408	22704	13728	213048

1.4.2 Results

Table 11 Annual resulting electricity, heat and hydrogen demand in the scenarios in TWh/Y.

Country	Electricity demand			Heat demand		Hydrogen demand	
	FC	HDFC	NOFC/ESTO	FC/NOFC/ESTO	HDFC	FC/HDFC	NOFC/ESTO
D	339	679	735	240	480	396	0
DK	17	34	43	18	36	26	0
SF	22	44	47	26	52	25	0
N	17	35	39	22	44	22	0
S	32	63	74	36	72	43	0

Table 11 shows the electricity, heat and hydrogen demands in each scenario. The electricity demand is highest in NOFC due to the transport demand being covered by electricity instead of hydrogen. The electricity demand is approximately 3.8 times higher in Germany relatively to the total electricity demand for the Scandinavian countries, the heat demand is 2.4 times higher and the hydrogen demand is 3.4 times higher, so the energy demands of Germany is dominating.

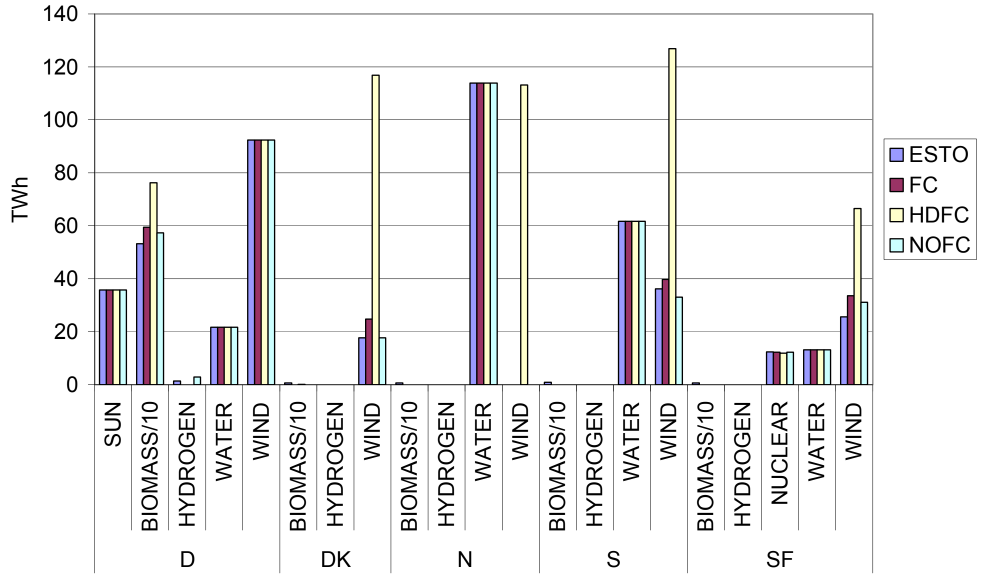

Figure 11 Annual electricity generation divided on scenarios, countries and fuels.The values for BIOMASS are divided with 10.

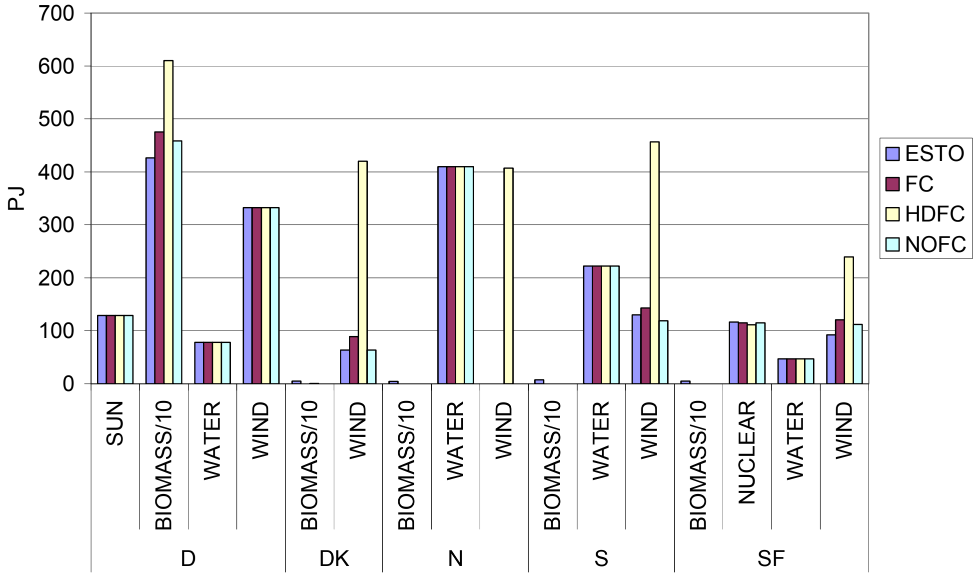

Figure 12 Annual fuel consumption for electricity generation divided on scenarios, countries and fuels. The values for BIOMASS are divided with 10.

Figure 11 shows the annual electricity generation distributed on fuels in each country and scenario. HYDROGEN indicate electric producting on power plants using hydrogen as input fuel. *Figure 12* shows the fuels used to produce electricity in each country and scenario. HYDROGEN are not included because it is produced from other fuels. *Figure 13* shows the investments in electricity generation equipment. It can be seen that the main source of electricity production is CHP plants using biomass in Germany. The second largest source is wind power production and then comes hydropower and nuclear. The main investments in electricity production is power plants run on biomass taking place in Germany, and wind power in all countries. Germany therefore use nearly all biomass available in the modelled region. In ESTO apprixmately 1000 MW CHP plants using biomass is buildt in respectively Denmark, Finland, Norway and Sweden, where as no investment in CHP plants using biomass in the Scandinavian countries are done in the other scenarios. No investment in fuel cell power plants is made. In scenario NOFC and ESTO investments in combined cycle plants using hydrogen as fuel is done in Germany. In HDFC the additional demand for electricity and heat is covered by additional investments in wind power in the Scandinavian countries and biomass power plants in Germany. The on-shore wind power resource is utilised fully in Denmark and Germany in all scenarios, and the same with the off-shore wind power resource in Germany.

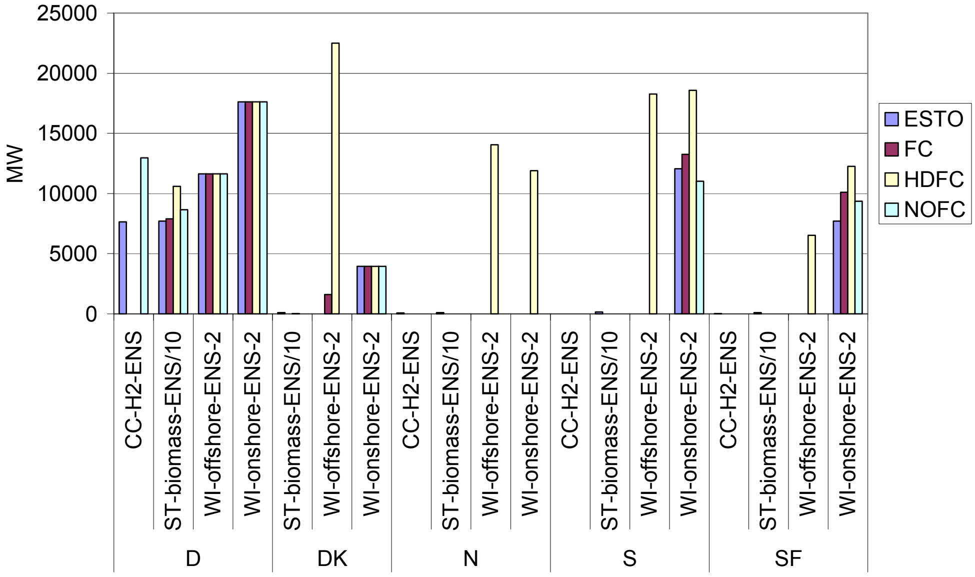

Figure 13 Investments in electricity generation equipment divided on scenarios and countries. The values for ST-biomass-ENS are divided with 10.

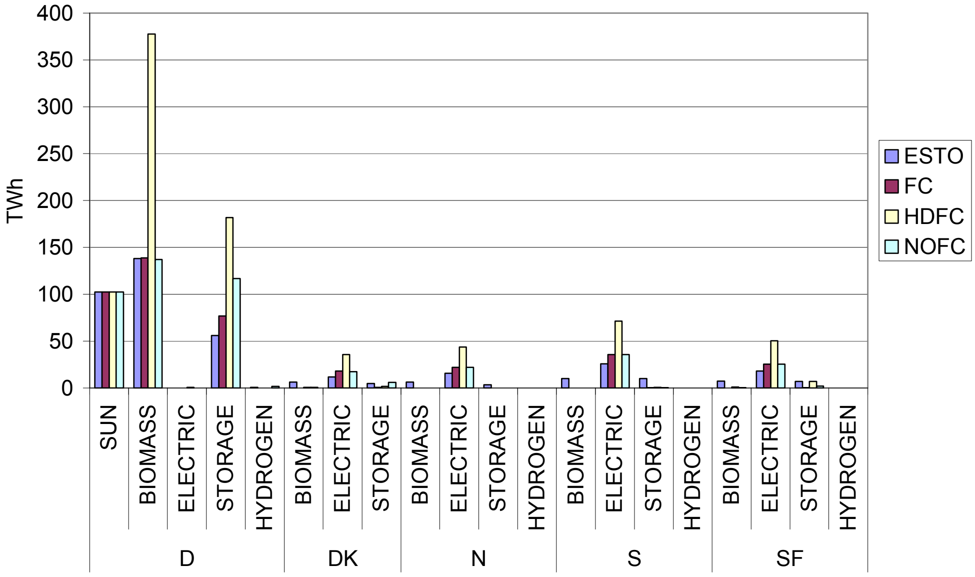

Figure 14 Annual heat generation divided on scenarios, countries and fuels. STORAGE indicate heat generation from unloading of heat storages.

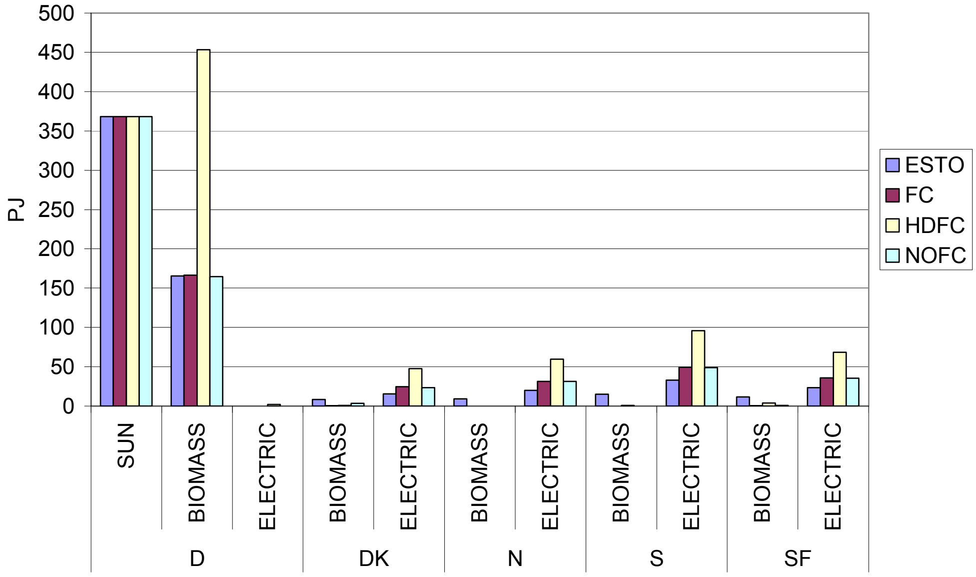

Figure 15 Annual fuel consumption for heat generation divided on scenarios, countries and fuels.

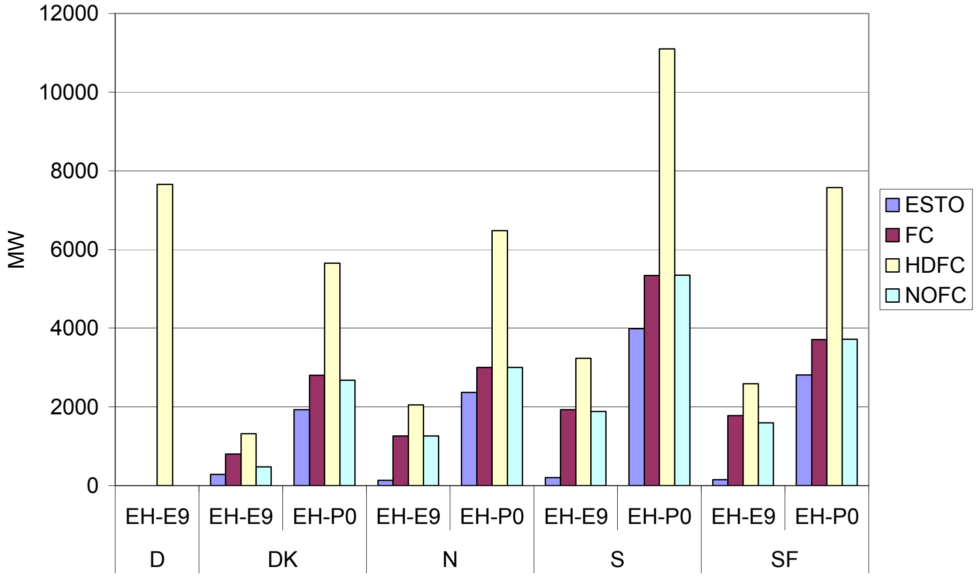

Figure 16 Investments in heat pumps and electrical heat boilers divided on scenarios and countries.

Figure 14 shows the annual heat generation distributed on fuels, countries and scenarios. *Figure 15* shows the fuel used to produce heat in each country and scenario, and *Figure 16* shows the investment in heat pumps and electrical heat boilers. It can be observed that heat is produced using sun and biomass in Germany, and electricity in the Scandinavian countries. In ESTO small amounts of biomass is also used in the Scandinavian countries. Hydrogen in very small amounts is used in ESTO and NOFC through the usage of combined cycle power plants using hydrogen. The model investment more in heat production capacity from heat pumps relatively to electric heat boilers. In ESTO the investments in electric heat boilers and heat pumps in the Scandinavian countries are lower than in the other scenarios. This is due to the existence of electricity storages in ESTO providing flexibility thereby making especially electric heat boilers less needed. The increased amount of wind power production in HDFC in combination with the higher heat demand relatively to the other scenarios causes more investment in heat pumps and electric heat boilers. In ESTO the annual heat production on electric heat boilers is only 0.3% of the annual heat production from heat pumps, for the other scenarios this ratio is 3-4%. So heat pumps produce most of the heat, and electric heat boilers are mostly used to provide a flexible electricity production technology.

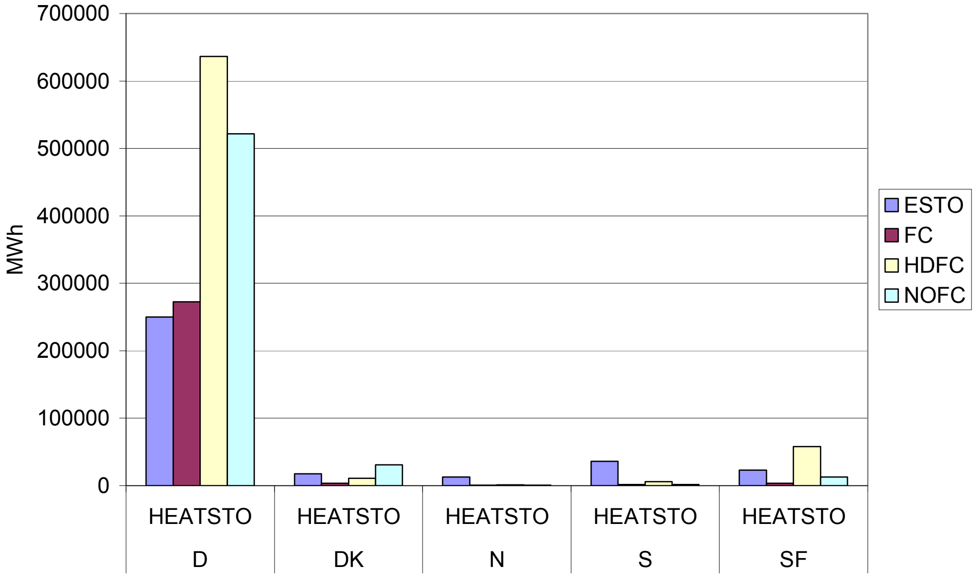

Figure 17 Investments in heat storage divided on scenarios and countries expressed as MWh of storage capacity.

Figure 17 shows the investment in heat storage. It is interesting that the existence of electricity storage in ESTO causes the investment in heat storage to be half of the amount in NOFC in Germany.

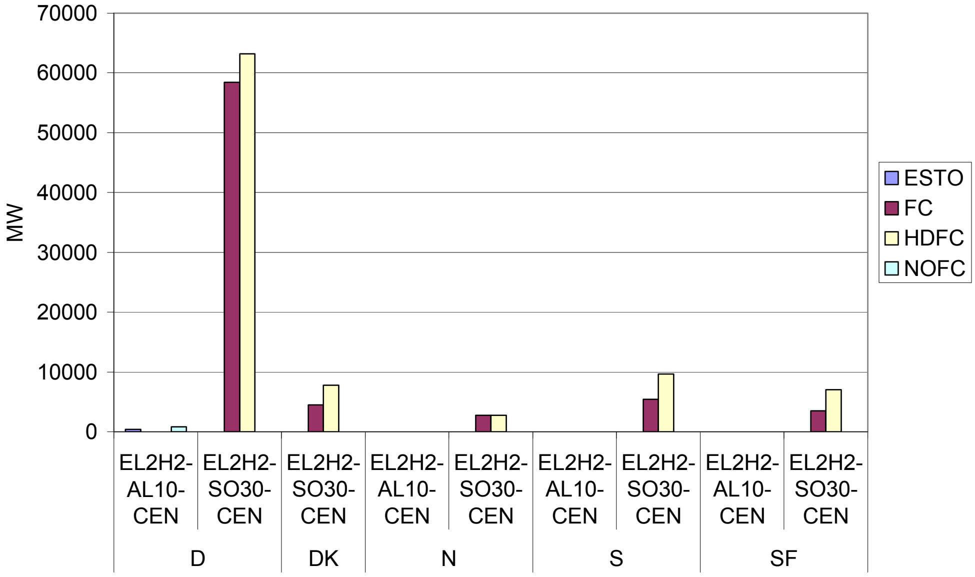

Figure 18 Investments in electrolysis plants divided on scenarios and countries.

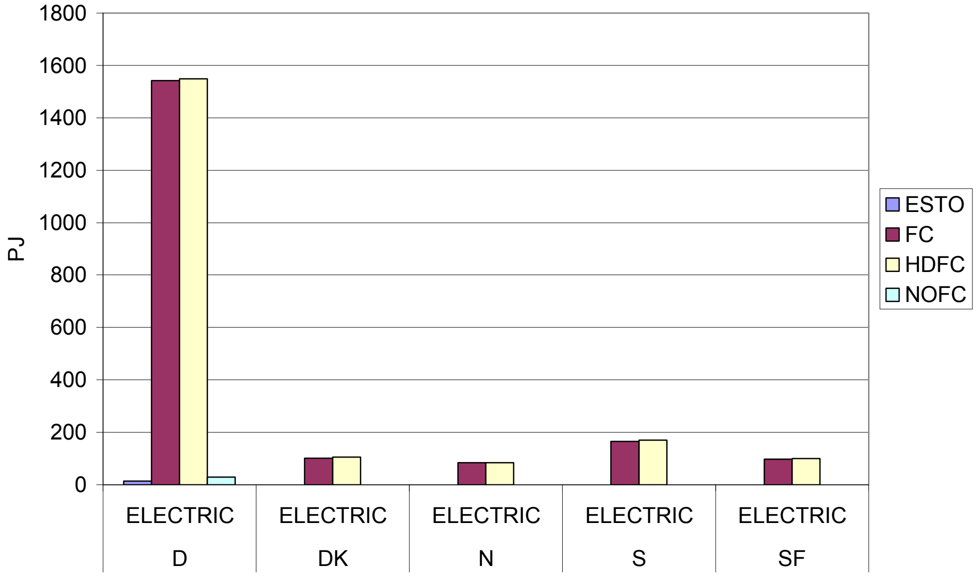

Figure 19 Annual fuel consumption for hydrogen generation divided on scenarios, countries and fuels.

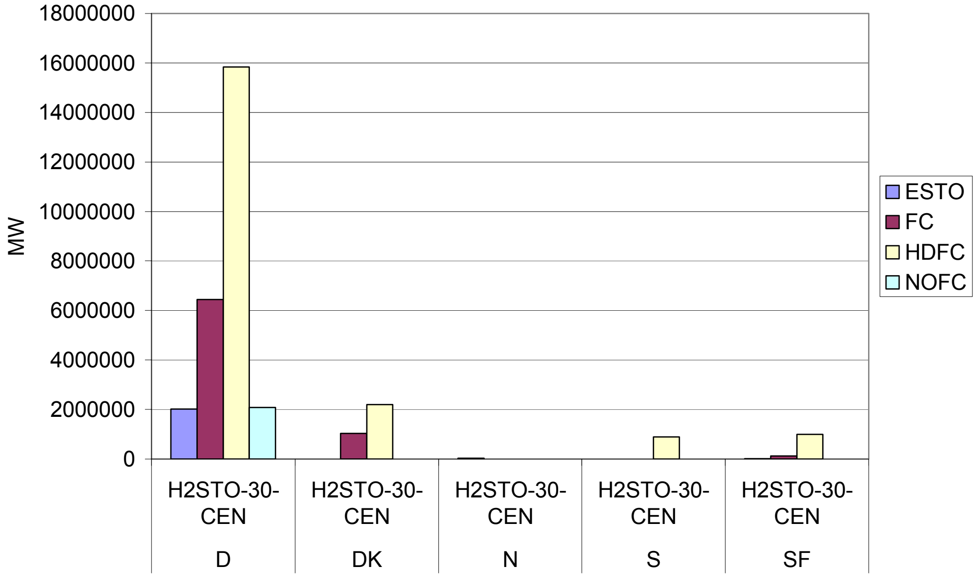

Figure 20 Investments in hydrogen storage divided on scenarios and countries expressed as MWh of storage capacity.

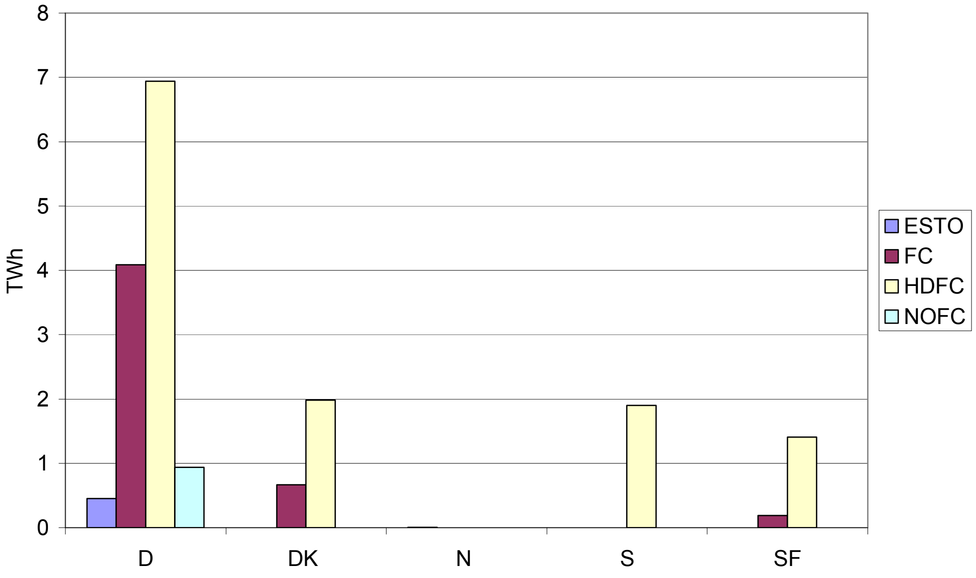

Figure 21 Annual loading of hydrogen storage divided on scenarios and countries in TWh..

Figure 18 shows the investments in electrolysis plants. *Figure 19* shows the fuels used to produce hydrogen in each country and scenario, and *Figure 20* shows the investment in hydrogen storage. From these figures in can be concluded that hydrogen is produced from electricity via electrolysis, i.e. the direct conversion of biomass to hydrogen is not attractive under the technology assumptions made. It is preferred to convert biomass to electricity and then to hydrogen. Total investment in hydrogen storage capacity in all countries are 2.1 TWh in ESTO and NOFC, 7.6 TWh in FC and 19.9 TWh in HDFC. So increasing wind power production leads to an increasing demand for hydrogen storage. This equal 1.2% of the annual total wind power generation in ESTO and NOFC, 4.0% in FC and 3.9% in HDFC. *Figure 21* shows the annual loading of the hydrogen storage. The total loading of hydrogen storage equal 0.3% of total wind power production in ESTO, 2.6% in FC, 2.4% in HDFC and 0.5% in NOFC. So only a small fraction of the wind power production needs to be stored as hydrogen. Although the hydrogen storages in ESTO and NOFC are of the same size, they are used more in NOFC due to the absence of electricity storage. It is noticeable that even ESTO and NOFC without an exogenous demand for hydrogen in the transport sector use hydrogen storage, i.e. the variability in wind power production require some hydrogen storage to cover the most extreme variability in the wind power production. The existence of electricity storage provided by plug-in hybrid electric cars in ESTO does not change this. This is because the electricity storages from the cars have relatively small storage sizes, e.g. 0.4 TWh in Germany, making them unsuitable for seasonal storage of electricity.

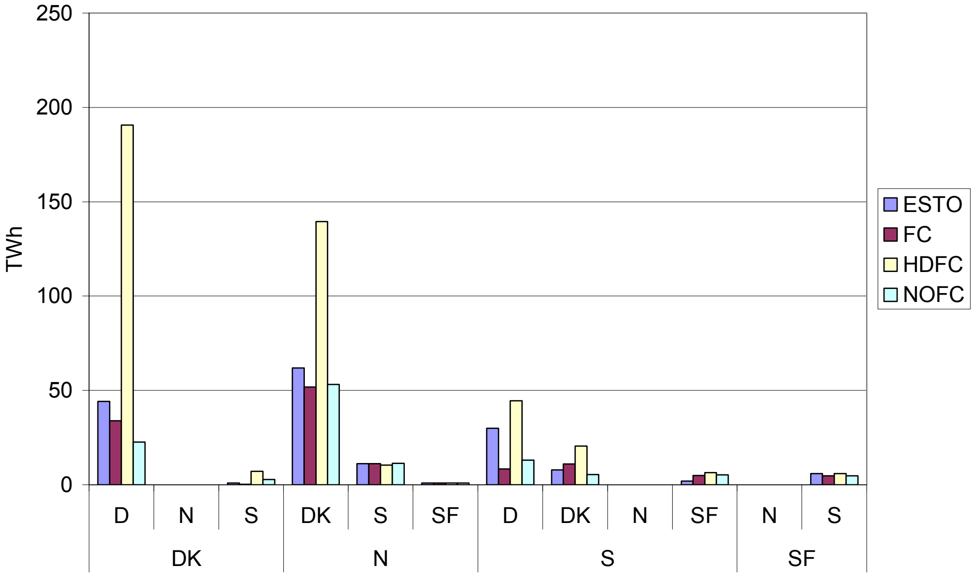

Figure 22 Annual power export from the country given in the bottom row to the country in the row above in the figure in TWh.

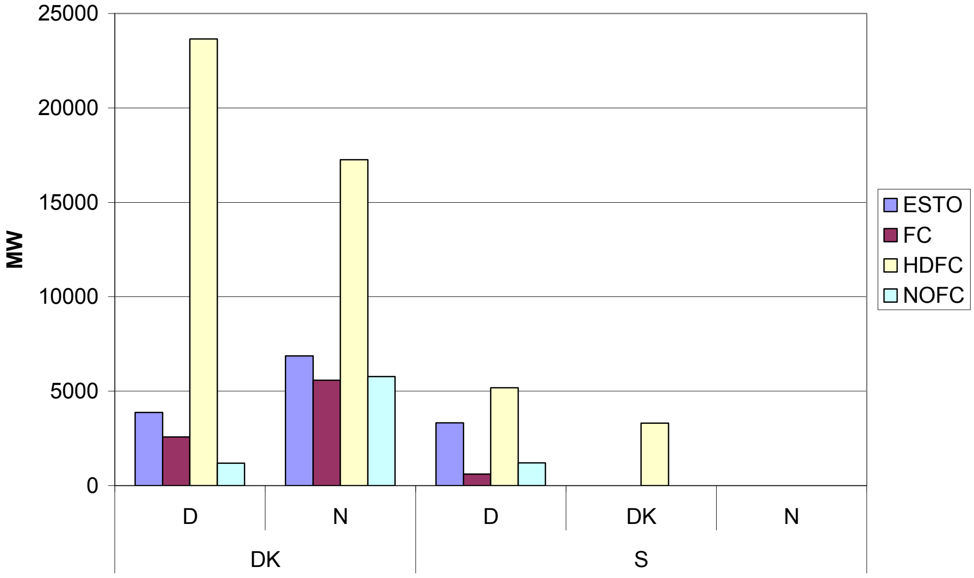

Figure 23 Investment in transmission capacity between the country given in the bottom row and the country in the row above in the figure in MW.

Figure 22 shows that the main transmission of power is hydropower from Norway to Denmark and continuing into Germany supplemented by Danish wind power production. This can also be seen from *Figure 23* showing that the biggest investments in transmission capacities are between Germany and Denmark, and Denmark and Norway. The transmission capacities between Denmark-Sweden and Sweden-Germany are also increased in order to export hydropower from Sweden to Germany.

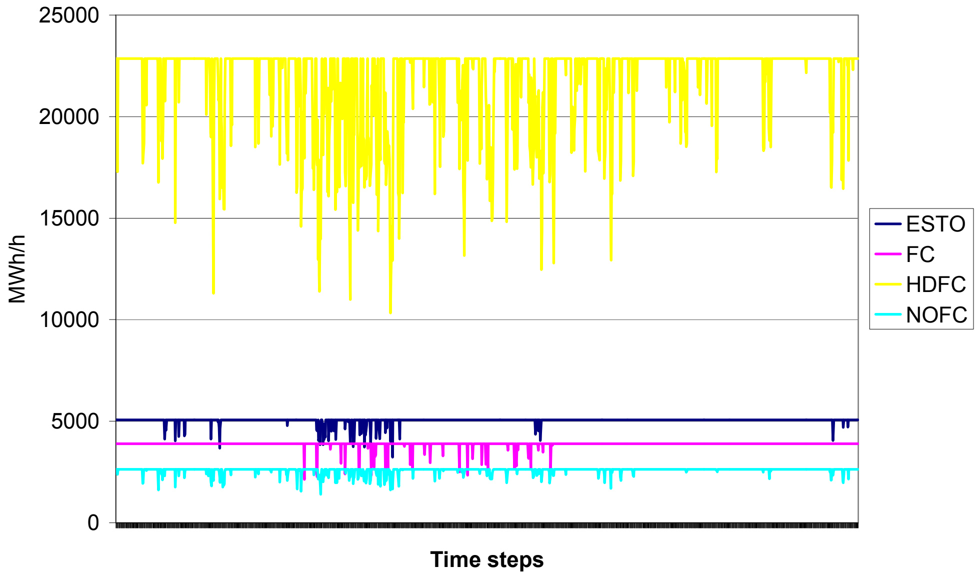

Figure 24 The power export from Denmark to Germany in each time step during the year in each scenario.

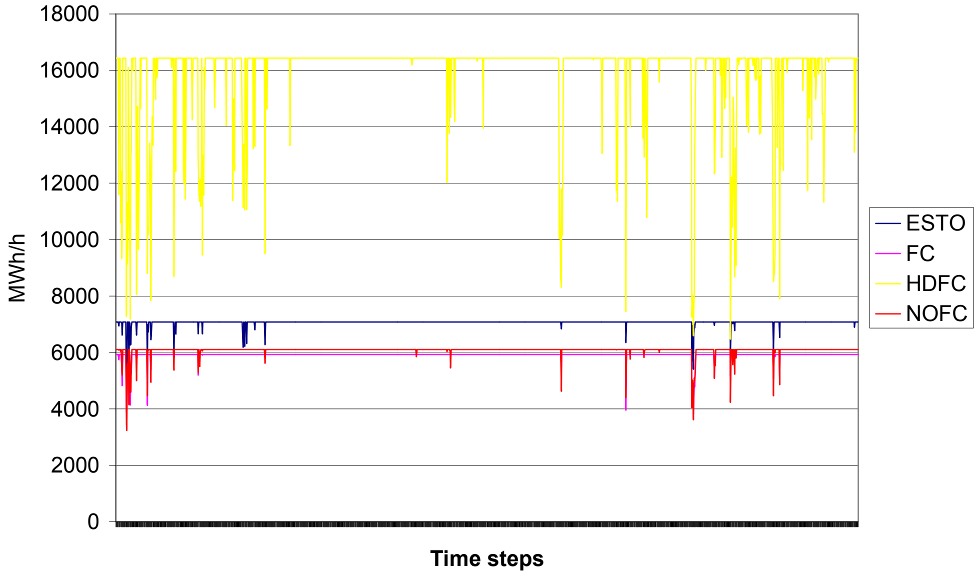

Figure 25 The power export from Norway to Denmark in each time step during the year in each scenario.

Figure 24 shows that the transmission lines between Denmark and Germany are heavily utilised to power import into Germany, and *Figure 25* shows the same between Norway and Denmark. It can be observed that the transmission lines become less utilised in HDFC compared to the other scenarios, because of a larger need for transmitting the variable wind power production in HDFC compared to the other scenarios.

Table 12 Annual usage of biomass. The biomas used for production of liquid biofuels is subtracted both from the usage numbers and the resource numbers.

	ESTO	FC	HDFC	NOFC
Biomass usage [PJ]	4692	4921	6567	4753
Biomass usage relatively to resource [%]	71	75	100	72
Biomass usage D [PJ]	4427	4920	6556	4749
Biomass usage D relatively to resource [%]	67	75	100	72
Biomass import into D [PJ]	3885	4378	6014	4207

Table 12 shows that all available biomass is used in HDFC and 71-75% in the other scenarios. Germany uses the biomass in all scenarios expect ESTO where a small amount is used in the Scandinavian countries. This results in a large biomass import into Germany.

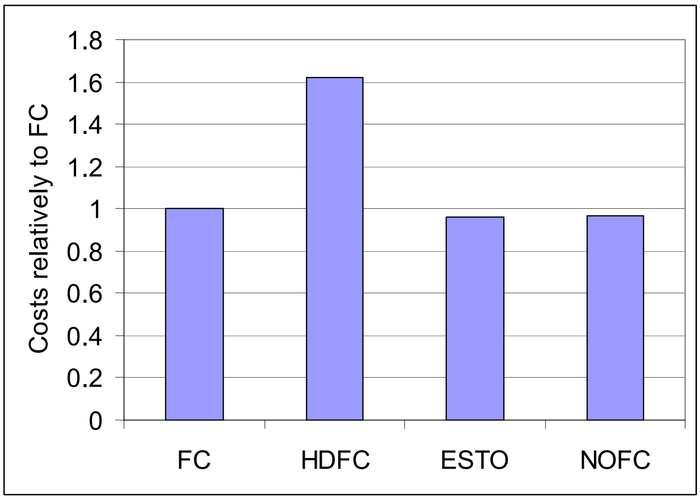

Figure 26 The annual sum of the fuel costs, variable operation and maintenance costs and investment costs in each scenario expressed relatively to the costs of FC. The total costs of FC was 41.4 billion Euros.

Figure 26 shows the annual sum of the costs elements included in the model relatively to FC. Apart from HDFC, the cost differences between scenarios are small with ESTO and NOFC being respectively 3.8% and 3.1% cheaper than FC.

1.4.3 Conclusions

The study of the all renewable energy scenarios for the energy, heat and transport sectors in Germany and the Scandinavian countries in 2060 showed that under the assumptions made, it is feasible to fulfil the energy demands with renewable energy sources coming from within the countries. Furthermore a doubling of the electricity and heat demand relatively to the base case could be covered with renewable energy sources. Germany is the big consumer of energy relatively to the Scandinavian countries, so there is a large import of electricity into Germany coming from hydropower in Norway and Sweden and wind power from mainly Denmark, and a large import of biomass from the forests of Sweden, Finland and Norway. The need for electricity imports into Germany leads to a significant increase in the transmission capacities between Norway and Denmark, and between Denmark and Germany.

Germany uses solar panels and CHP plants using biomass to produce heat, where as the Scandinavian countries use electricity in heat pumps.

The variability of wind power production was handled by varying the hydropower production and the production on CHP plants using biomass, by power transmission, by varying the heat production in electric heat boilers, and by varying the production of hydrogen in electrolysis plants in combination with hydrogen storage. Investment in hydrogen storage capacity corresponded to 1.2% of annual wind power production in the scenarios without a hydrogen demand from the transport sector (ESTO and NOFC), and approximately 4% in the scenarios with a hydrogen demand from the transport sector, i.e. only a small fraction of the wind energy production was needed to be stored as hydrogen. Even the scenarios without a demand for hydrogen from the transport sector, ESTO and NOFC, saw investments in hydrogen storage due to the need for flexibility provided by the ability to store hydrogen. The storage capacities of the electricity storages provided by plug-in hybrid electric vehicles in ESTO were too small to make hydrogen storage superfluous.

The direct conversion of biomass to hydrogen was not used under the economic assumptions made in that the model preferred conversion of biomass to electricity and then to hydrogen. Heat pumps were used to provide the bulk of the heat production in the Scandinavian countries with electric heat boilers more being used to provide flexibility.

Both the sceanario with successful introduction of fuel cell technologies, FC, and the scenarios without fuel cells, NOFC and ESTO, were able to handle the variability of wind power production. The differences between FC and NOFC/ESTO were mainly that FC needed a significantly larger hydrogen storage. Furthermore NOFC/ESTO had approximately 3-4% lower total costs compared to FC.

5 Transport extensions of Balmorel

This chapter documents extensions of Balmorel that has been initiated in this project but has not been completed during this project. The model extensions will be finalised in future projects already underway.

1.5 Inclusion of transport in Balmorel

The purpose of extending Balmorel with a model of the transport sector is to enable analysis of:

- The economic and technical consequences of introducing a possibility for using electrical power in the transport sector either directly in electric vehicles (EVs) and plug-in hybrids (PIHs) or indirectly by production of hydrogen or other transport fuels. Especially the consequences for power systems with a high share of wind power are studied.
- The economic and technical consequences of having vehicle to grid technologies in the power system i.e. EVs and PIHs with the ability of feeding power into the power grid.
- The competition between different vehicle technologies when the investment costs and fuel costs of the vehicles and the benefits for the power systems are taken into account.
- The competition between using biomass resources for power production or for production of transport fuels.

Only road transport is treated and the implementation focuses on plug-in vehicles divided according to their propulsion system: electric vehicles, plug-in parallel hybrid vehicles, plug-in seriel hybrid vehicles, plug-in fuel cell vehicles. Vehicles not plugged-in are treated on a very aggregate level only characterized by their fuel type, annual driving distance, and their energy consumption per vehicle kilometer.

1.6 Terminologi

- Accessory loads: energy consuming equipment in the vehicle not directly involved in the propulsion of the vehicle such as compressors, pumps and fans used to heat, cool and ventilate the passenger compartment, lights, audio equipment, power steering and power braking.
- Engine: the combustion engine (otto or diesel) in the vehicle.
- Fuel cell: the fuel cell in the vehicle.
- Motor: the electrical motor in the vehicle.
- Power bus: the power electronics in the vehicle inverting and converting AC/DC and DC/AC and directing power to the sub-systems.
- On-board storage: the electricity storage on-board a vehicle.
- Plug-in vehicles: electric vehicles (EVs), plug-in fuel cell vehicles (PIFCVs), plug-in parallel hybrid electric vehicles (PIPHEVs), plug-in seriel hybrid electric vehicles (PISHEVs).
- Propulsion system: a certain configuration of engine, motor, on-board storage and plug-in capability.
- Transport service: person transport delivered by cars or goods transport delivered by trucks.
- Vehicle group: group of vehicles having the same propulsion system and delivering the same transport service.
- Vehicle technology: a vehicle characterised by the transport service it delivers, the type of propulsion system, the fuel and a specific set of technical and economical parameters.

1.7 Assumptions

- Energy consumption of a vehicle technology is divided into energy consumption by accessory loads and energy consumption used to propel the vehicle. The accessory loads are assumed to get electrical power from the power bus in the vehicle, whereas the propulsion power is delivered from an electrical motor or/and from an engine. Both the propulsion power and the energy consumption of accessory loads are assumed to be proportional to the vehicle kilometer driven in a time step.

- Regenerated braking energy in the vehicles is going into the on-board electricity storage. It is assumed proportional to the number of kilometers driven in each time step.
- Transport patterns treated with average values i.e. statistical data describing transport patterns assumed known making it possible to extract average values.
- Aggregation of vehicles into vehicle technologies (e.g. only a limited number of types of electric cars used to represent all types of electric cars).
- Aggregation of grid-vehicle interactions: the vehicles are aggregated into vehicle groups when modelling the loading of on-board storage from the grid and the power delivered to the grid from the vehicles. This also implies that the on-board storage is treated on vehicle group level.
- Loading of storage from grid and power from vehicle groups to grid dependant on number of vehicles plugged-in.
- Constant size of electricity storage on-board vehicle group as seen from the power system i.e. not dependant on vehicles plugged-in. This assumption is buildt on the observation that during a short time period e.g. 24 hours all passenger cars will be plugged in, so the storage capacity of all cars observed with a daily time resolution will be available for the power system. As the size of the storage capacity is mostly relevant when it comes to storing electricity for longer time periods e.g. several days, the assumption about treating the storage as constant seems good.
- CO2 emissions taken into account.
- Other environmental impacts (e.g. local vehicle pollutants) taken into account with one vehicle technology dependant externality cost figure assumed proportional to the vehicle fuel consumption.
- All modeled electrical power flows in a vehicle involves conversion (either AC/DC or DC/AC) except the power flow from the fuel cell to the electricity storage, so an average inverter loss is allocated to all power flows.

1.8 In data to transport model

- Vehicle technology data:
    - Average efficiencies during the driving pattern experienced by the vehicle:
        - Engine, fuel cell, motor, generator, on-board storage, power bus
        - Costs: investment, yearly operation and maintenance exclusive fuel costs
    - Capacities:
        - Engine, fuel cell, motor, on-board storage (size, unloading, loading)
    - Average energy consumption during the driving pattern experienced by the vehicle (proportional to vehicle kilometre in time step):
        - Consumption of accessory loads
        - Consumption mechanical propulsion power at driving wheel
        - Mechanical energy regenerated when braking
        - Average energy consumption of vehicle (for non plug-ins)
- Vehicle utilisation data:
    - Annual driving of vehicle technology
    - Average utilisation of vehicle technology (persons or tons)
- Transport pattern data:
    - Driving pattern: share of annual driving done in time step
    - Plug-in pattern: share of vehicles plugged into the power grid at a certain time step

  - Each vehicle technology associated with a certain driving pattern and plug-in pattern
- Transport demand data: the yearly demand for each transport service.

1.9 Equations

Sets:
a: area
DP: driving pattern
f: fuels
r: region
PP: plug-in pattern
p: type of propulsion system (plug-in hybrid, electric vehicle)
t: time step
v: vehicle technology
x: type of transport service (person transport, transport of goods)

Parameters:
AnnDriv(v): the annual driving of a vehicle of type x and propulsion system type p [km].
BrakEng(v): Proportionality factor converting number of kilometres driven in a time step to amount of braking energy of the vehicle in that time step [MWh/vehicle km].
CapEng(v): the capacity of the vehicles engine [MW]
CapGridCon(v): the capacity of the grid connection used by the vehicles [MW].
CapMot(v): the capacity of the vehicles electrical motor [MW]
CapSto(v): the capacity of the onboard electricity storage [MWh].
CapStoLoad(v): the loading capacity of the onboard electricity storage [MW].
CapStoUnload(v): the unloading capacity of the onboard electricity storage [MW].
ConsAcc(v): proportionality factor expressing the energy consumption of acessories [MWh/vehicle km].
ConsProp(v): proportionality factor expressing the energy consumption of the propulsion [MWh/vehicle km].
ConsVeh(v): the specific fuel consumption of the vehicle [MWh/vehicle km].
CO2Emis(f): the CO2 emission connected to fuel f [tons CO2/MWh fuel].
CO2Price: the price of CO2 emission permits [Euro/ton CO2]
DrivPat(DP,t): the share of the annual driving delivered in t.
EffInv(p): the efficiency of the AC/DC inverter converting power from the grid.
EffMot(v): the average efficiency of the electrical motor.
EffPB(v): the average efficiency of the power bus (inverter).
EffSto(v): the average efficiency of the electricity storage during a charging/recharging cycle.
FuelPrice(f): the fuel price of fuel f [Euro/MWh fuel]
MaxSto(v): the maximum storage level of onboard electricity storage.
MinSto(v): the minimum storage level of onboard electricity storage.
PlugInRatio(PP,t): the share of vehicles connected to the power grid in t.

Variables:
FromGrid(x,p,a,t): Power from the grid [MWh].
LoadStoEng(v,t): Loading of on-board electricity storage coming from vehicle engines belongin to vehicle technology v [MWh].
NumVeh(a,v): number of vehicles of a certain type, includes new investments
OutEngGen(v,t): Output from the vehicle engine going to the generator [MWh].
OutEngProp(v,t): Mechanical output from the vehicle engine going directly to propulsion of the vehicle [MWh].
S(x,p,a,t): storage content of all vehicles in time step t [MWh].
ToGrid(x,p,a,t): power going back to the grid from the vehicles [MWh].
UnloadSto(v,t): unloading of the electricity storage onboard vehicles (only applies for EVs and PISHEVs [MWh].
UnloadStoProp(v,t): unloading of the electricity storage onboard vehicles going to propulsion (only PIPHEVs) [MWh].

UnloadStoOth(v,t): unloading of the electricity storage onboard vehicles not going to propulsion (only PIPHEVs) [MWh].

1.9.1 Demand for transport services

For now only person transport with cars and goods transport with trucks are included. The inclusion of other types of transport services is only an issue about data availability and data collection. Each vehicle technology is characterised by an annual driving distance and an average utilisation factor.

$$\sum_{a,v}\left(NumVeh(a,v)*AnnDriv(v)*VehCapUtil(v)\right)=TrpDemand(r,x)\ (1)$$

1.9.2 Electric vehicles

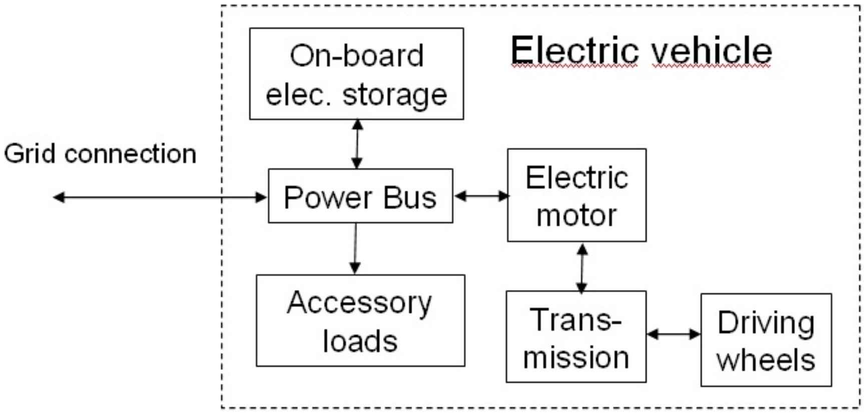

Figure 27 Propulsion system configuration of electric vehicles.

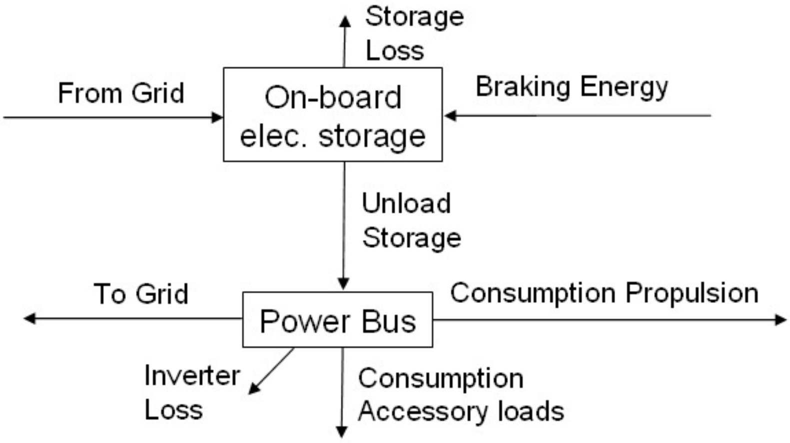

Figure 28 Power flows model of electric vehicles.

Figure 27 and Figure 28 shows respectively the configuration of the propulsion system in an electric vehicle and the translation into the power flow model used in this work. The power flow model reflects the assumption about the braking energy going into the on-board storage. Only sub-systems with more than one in-going or one-outgoing power flow are shown, because subsystems with only one in-going and out-going power flow (e.g. the electrical motor) just invokes a scaling by the average efficiency of the sub-system.

Balance equation for electricity storage:
The electricity storage can be charged from the grid. The charging/discharging losses are modelled as being proportional to the unloading of the electricity storage, i.e.:

$$StoLoss(v,t)=UnloadSto(v,t)*(1/EffSto(v)-1)$$

Storage Level at beginning of t+1 equal to storage level at beginning of t + Charging from grid + charging from braking energy – unloading:

$$S(x,p,a,t+1) = S(x,p,a,t) + FromGrid(x,p,a,t) * EffInv(p)$$
$$+ \sum_{v\in x,p} \begin{pmatrix} EffInv(v) * NumVeh(a,v) * AnnDriv(v) * BrakEng(v) * \\ \sum_{DP\in v} DrivPat(DP,t) \end{pmatrix} \quad (2)$$
$$- \sum_{v\in x,p} \left(UnloadSto(v,t) / EffSto(v) \right)$$

Balance equation for power bus:
Power to grid +Consumption accessory loads + Consumption propulsion power = Energy from storage:

$$ToGrid(x,p,a,t) + \sum_{v\in x,p} \begin{pmatrix} NumVeh(a,v) * AnnDriv(v) * \sum_{DP\in v} DrivPat(DP,t) \\ * \begin{pmatrix} ConsAcc(v) \\ + ConsProp(v) / \left(EffMot(v) * EffTrans(v) \right) \end{pmatrix} \end{pmatrix} \quad (3)$$
$$= \sum_{v\in x,p} \left(UnloadSto(v,t) * EffPB(v) \right)$$

Minimum and maximum storage level onboard vehicles:

$$\sum_{v\in x,p} \left(NumVeh(a,v) * CapSto(v) * MinSto(v) \right) \le S(x,p,a,t)$$
$$\le \sum_{v\in x,p} \left(NumVeh(a,v) * CapSto(v) * MaxSto(v) \right) \quad (4)$$

Power from grid depends on the number of vehicles plugged in:

$$FromGrid(x,p,a,t) \le PlugInRatio(x,p,a,t) * \sum_{v\in x,p} \left(NumVeh(a,v) * CapGridCon(v) \right)$$

(5)

Power to grid depends on the number of vehicles plugged in:

$$ToGrid(x,p,a,t) \le PlugInRatio(x,p,a,t) * \sum_{v\in x,p} \left(NumVeh(a,v) * CapGridCon(v) \right)$$

(6)

Loading of on-board storage restricted:

$$FromGrid(x,p,a,t) * EffInv(p)$$
$$+ \sum_{v\in x,p} \begin{pmatrix} EffInv(v) * EffMot(v) * EffTrans(v) * NumVeh(a,v) * AnnDriv(v) \\ * BrakEng(v) * \sum_{DP\in v} DrivPat(DP,t) \end{pmatrix} \quad (7)$$
$$\le \sum_{v\in x,p} \left(NumVeh(a,v) * CapLoadSto(v) \right)$$

Unloading of on-board storage restricted:

$$UnloadSto(v,t) \leq CapUnloadSto(v) \quad (8)$$

Propulsion power from electric motor restricted:

$$AnnDriv(v) * \sum_{DP \in v} DrivPat(DP,t) * ConsProp(v) / \left(EffMot(v) * EffTrans(v) \right) \leq CapMot(v) \quad (9)$$

1.9.3 Plug-in parallel hybrid vehicles

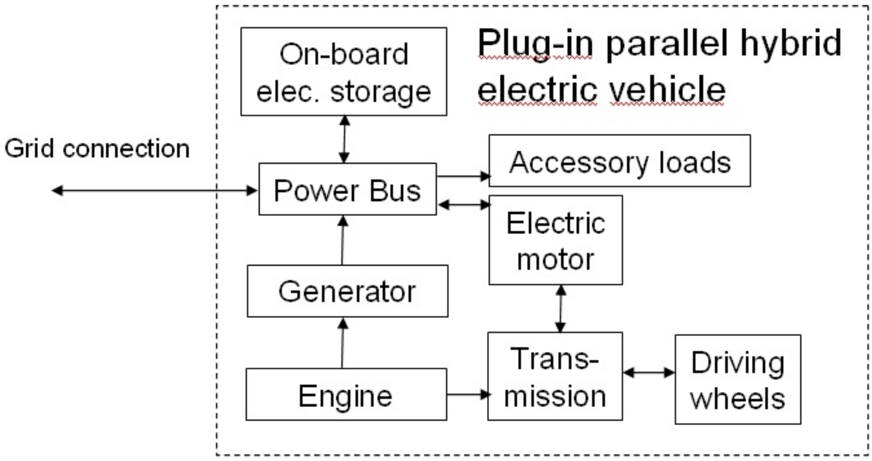

Figure 29 Propulsion system configuration of plug-in parallel hybrid electric vehicles.

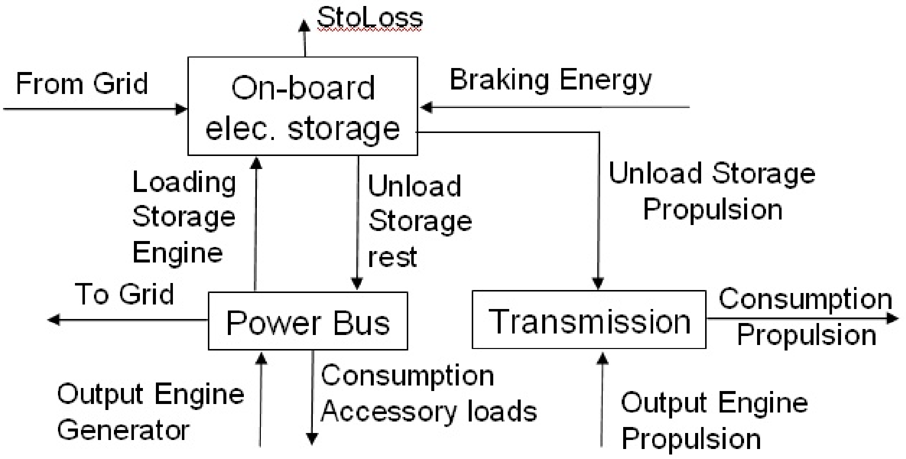

Figure 30 Power flows model of plug-in parallel hybrid electric vehicles.

The inverter loss has not been shown in the power flow model of PIHEVs shown in Figure 30..

Balance equation for electricity storage:
The electricity storage can be charged from the grid or from the engine. The charging/discharging losses are modelled as being proportional to the unloading of the electricity storage.
Storage Level at beginning of t+1 equal to storage level at beginning of t + Charging from grid + charging from braking energy+ Charging from engine – unloading:

$$
\begin{aligned}
&S(x,p,a,t+1)=S(x,p,a,t)+\mathit{FromGrid}\,(x,p,a,t)*\mathit{EffInv}\,(p)\\
&+\sum_{v\in x,p}\left(\mathit{LoadStoEng}\,(v,t)+\mathit{NumVeh}\,(a,v)*\begin{pmatrix}\mathit{EffInv}\,(v)*\mathit{AnnDriv}\,(v)\\ *\,\mathit{BrakEng}\,(v)*\sum_{DP\in v}\mathit{DrivPat}\,(DP,t)\end{pmatrix}\right)\\
&-\sum_{v\in x,p}\left(\left(\mathit{UnloadStoRest}\,(v,t)+\mathit{UnloadStoProp}\,(v,t)\right)/\,\mathit{EffSto}\,(v)\right)
\end{aligned}
$$

(10)

Balance equation power bus:

Power to grid +Consumption accessory loads + Load storage from engine= Output engine to generator + Unloading storage not going to propulsion:

$$
\begin{aligned}
&\mathit{ToGrid}(x,p,a,t)+\\
&\sum_{v\in x,p}\left(\mathit{LoadStoEng}(v,t)+\mathit{NumVeh}(a,v)*\left(\mathit{AnnDriv}(v)*\sum_{DP\in v}\mathit{DrivPat}(DP,t)*\mathit{ConsAcc}(v)\right)\right)\\
&=\sum_{v\in x,p}\left(\mathit{OutEngGen}(v,t)*\mathit{EffGen}(v)*\mathit{EffInv}(v)+\mathit{UnloadStoRest}(v,t)*\mathit{EffInv}(v)\right)
\end{aligned}
$$

(11)

Balance equation transmission:

Unloading storage to propulsion + Output engine to propulsion = Consumption propulsion

$$
\begin{aligned}
&\sum_{v\in x,p}\left(\begin{pmatrix}\mathit{UnLoadStoProp}(v,t)*\mathit{EffInv}(v)*\mathit{EffMot}(v)+\\ \mathit{OutEngProp}(v,t)\end{pmatrix}*\mathit{EffTrans}(v)\right)\\
&=\sum_{v\in x,p}\left(\mathit{NumVeh}(a,v)*\mathit{AnnDriv}(v)*\sum_{DP\in v}\mathit{DrivPat}(DP,t)*\mathit{ConsProp}(v)\right)
\end{aligned}
\qquad (12)
$$

Maximum engine output restricted by capacity:

$$\mathit{OutEngGen}(v,t)+\mathit{OutEngProp}(v,t)\leq \mathit{CapEng}(v)\ (13)$$

Loading of on-board storage restricted:

Power from grid + braking power + loading storage from engine lower than loading capacity storage

$$
\begin{aligned}
&\mathit{FromGrid}(x,p,a,t)*\mathit{EffInv}(p)\\
&+\sum_{v\in x,p}\left(\mathit{LoadStoEng}(v,t)+\mathit{NumVeh}(a,v)\begin{pmatrix}\mathit{EffInv}(v)*\mathit{AnnDriv}(v)\\ *\,\mathit{BrakEng}(v)*\sum_{DP\in v}\mathit{DrivPat}(DP,t)\end{pmatrix}\right)\\
&\leq\sum_{v\in x,p}\left(\mathit{NumVeh}(a,v)*\mathit{CapLoadSto}(v)\right)
\end{aligned}
$$

(14)

Unloading of on-board storage restricted:

$$\mathit{UnloadStoOth}(v,t)+\mathit{UnloadStoProp}(v,t)\leq \mathit{CapUnloadSto}(v)\ (15)$$

Furthermore equations (4), (5) and (6) also apply for plug-in parallel hybrid vehicles.

1.9.4 Plug-in seriel plug-in hybrid vehicles including fuel cell vehicles

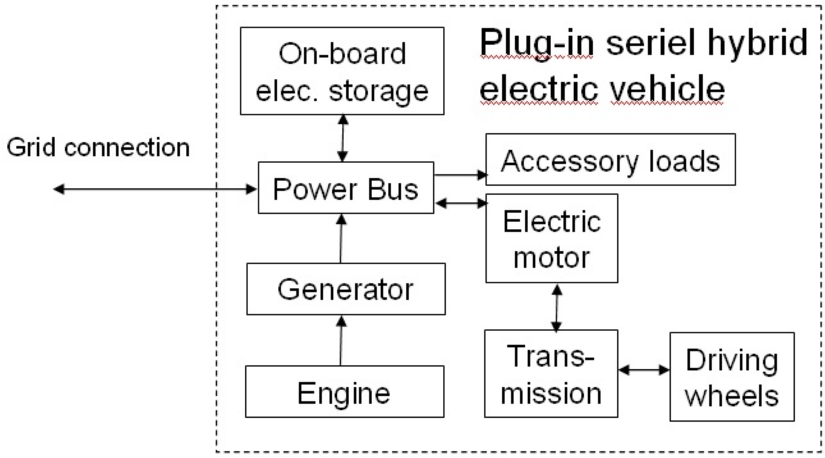

Figure 31 Propulsion system configuration of plug-in seriel hybrid electric vehicles.

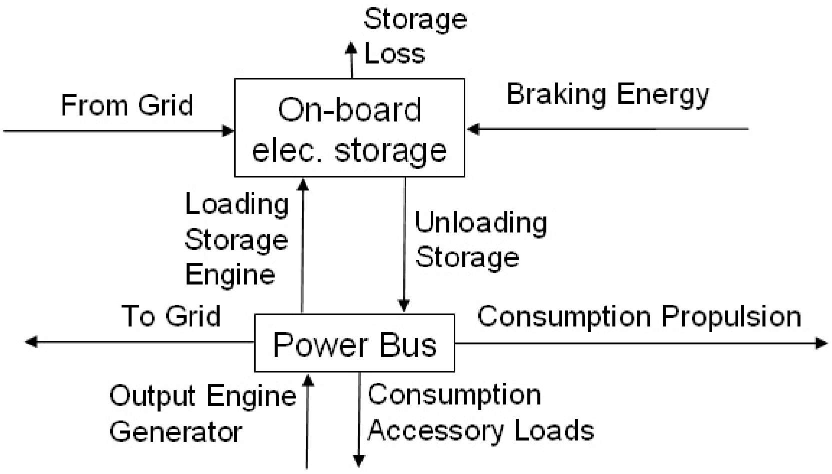

Figure 32 Power flows model of plug-in seriel hybrid electric vehicles.

Balance equation for electricity storage:

$$S(x,p,a,t+1) = S(x,p,a,t) + FromGrid(x,p,a,t) * EffInv(p)$$

$$+\sum_{v\in x,p}\left(LoadStoEng(v,t) + NumVeh(a,v) * \begin{pmatrix} EffInv(v) * AnnDriv(v) \\ * BrakEng(v) * \sum_{DP\in v} DrivPat(DP,t) \end{pmatrix}\right)$$

$$-\sum_{v\in x,p}\left(UnloadSto(v,t) / EffSto(v)\right)$$

(16)

Balance equation power bus:

Power to grid +Consumption accessory loads + Consumption propulsion + Load storage from engine= Output engine generator + Energy from storage:

$$
\begin{aligned}
&ToGrid(x,p,a,t)+\\
&\sum_{v\in x,p}\left(LoadStoEng(v,t)+NumVeh(a,v)*\begin{pmatrix}AnnDriv(v)*\sum_{DP\in v}DrivPat(DP,t)*\\(ConsAcc(v)+ConsProp(v)/EffMot)\end{pmatrix}\right)\\
&=\sum_{v\in x,p}\left(OutEngGen(v,t)*EffGen(v)*EffPB(v)+UnloadSto(v,t)*EffPB(v)\right)
\end{aligned}
$$

(17)

Furthermore equations (13) with *OutEngProp(v,t)=0,* (4), (5), (6), (8) and (14) also applies for plug-in seriel hybrid vehicles.

1.9.5 Plug-in fuel cell vehicle

The same equations applies as for PISHEVs by replacing *OutEngGen(v,t)* with *OutFC(v,t)* and setting *EffGen(v) =1.*

1.9.6 Non plug-in vehicles

Irrespective of vehicles without a plug-in capability being conventional, hybrid electric or electric, the model only takes into account their yearly fuel consumption and yearly transport service delivered.

1.9.7 Additions to objective function

The additions to the objective function for plug-in hybrid electric vehicles consist of fuel costs and CO2 costs of vehicles:

$$
\sum_{a,t}\sum_{\substack{v\in TRPSER\\ v\in PRPSYS}}\begin{pmatrix}(FuelPrice(f)+CO2Price*CO2Emis(f))*\\(OutEngRest(v,t)+OutEngProp(v,t))/EffEng(v)\end{pmatrix}\quad(18)
$$

The additions to the objective function for non plug-in vehicles consist of fuel costs and CO2 costs of vehicles:

$$
\sum_{a}\sum_{v}\begin{pmatrix}(FuelPrice(f)+CO2Price*CO2Emis(f))*NumVeh(a,v)\\ *AnnDriv(v)*ConsVeh(v)\end{pmatrix}(19)
$$

1.9.8 Addition to electricity balance equation

Addition electricity balance equation:

$$
\sum_{a\in R(a)}\sum_{x,p}\left(ToGrid(x,p,a,t)-FromGrid(x,p,a,t)\right)(20)
$$

1.9.9 Addition to hydrogen balance equation

The fuel consumption of hydrogen from vehicles are included in the energy balance equation for hydrogen.

1.10 Specification of vehicle technology

A vehicle technology is characterised by the fields given in Table 13.

Name in Balmorel	Description
VHDTYPE	Type of transport service delivered from the vehicle (person or goods transport)
VHDPROPTYPE	Type of propulsion system
VHDFUEL	Fuel type
VHDINVCOST	Investment cost (Euro/Vehicle)
VHDOMCOST	Yearly operation and maintenance costs exlusive fuel costs (Euro/Vehicle)
VHDEFF	'Fuel consumption of vehicle (GJ/Vehicle km)

VHDLIFETIME	The economical life time (Years)
VHDFROMYEAR	The first year where the technology is available
VHCAPENGINE	The capacity of the engine in the vehicle (kW)
VHCAPMOTOR	The capacity of the electrical motor in the vehicle (kW)
VHCAPELESTO	The capacity of the electricity storage in the vehicle (kWh)
VHCAPELECLHD	The loading capacity of the vehicle (minimum of capacity of grid connection and loading capacity of electricity storage) (kW)
VHCAPELECUNLHD	The unloading capacity of the vehicle (minimum of capacity of grid connection and unloading capacity of electricity storage) (kW)
VHELECLOSS	The loss connected to the loading/unloading of a storage, here expressed as proportional to the loading
VHDMINELECSTO	The minimum storage level of the electricity storage as a fraction of the storage capacity (MWh)
VHDEFFPB	The efficiency of the power bus that converts power on-board the vehicle
VHDEFFMOT	The efficiency of the electrical motor on-board the vehicle
VHDEFFGEN	The efficiency of the generator converting the mechanical power output from the engine to electrical power
VHDEFFTRANS	The efficiency of the transmission from the engine and/or electric motor to the driving wheels

Table 13 Vehicle parameters used to specify a vehicle technology.

1.11 Specification of vehicle utilization

In stead of specifying the vehicle utilization on vehicle technology level, it has been chosen to aggregate vehicle technologies into vehicle groups having the same propulsion system and delivering the same transport service. For each vehicle group the following is used to characterize the utilisation pattern:

Name in Balmorel	**Description**
VHANNDRIV(Y,TRPSER,PRPSYS)	The annual driving of a vehicle (km/vehicle)
VHCAPUTIL(Y,TRPSER,PRPSYS)	The utilisation of the capacity (personkm/vehiclekm or Tonskm/vehiclekm)
IDRIVPAT(DP,S,T)	The share of the annual driving delivered in time step t.
IPLUGINPAT(PP,S,T)	The share of vehicles connected to the power grid in time step t

Table 14 Vehicle group parameters used to specify the average utilization of a vehicle group.

References

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Appendix*

Technology catalogue for hydrogen/storage/trade study 2005-7

The earlier hydrogen project (Sørensen *et al.*, 2001) contained a technology catalogue for all the technologies of relevance to that project. Here, we revisit the most important technologies used in the current hydrogen scenarios in order to determine, if the development during the intermediary years have changed the outlook for performance, time frames or price expectations. A number of new database entries are added. As regards the technologies for using fossil fuels in a transition period, we refer to the Technology Catalogue of the Danish Energy Agency (DDoE, 2005).

1 Electricity production technologies

1.1 Wind power

The technology consists of a three-bladed horizontal-axis rotor and a nacelle-integrated generator using either synchronous or asynchronous technology with various inverter and transmission options. Different numbers of gear-steps are in use, including gear-less constructions relying entirely on inverter functionality. Also for tower and foundation (particularly for off-shore operation), there are several concepts in use (Sørensen, 2004; Koenemann and Ristau, 2006). Estimates of cost and life cycle impacts are based on Morthorst and Chandler (2004) and Sørensen (2004; 2005). Typically, off-shore installations have the higher equipment and O&M costs and the higher production performance (in the range given), while land-based installations are in the lower equipment and O&M cost and production range, the latter depending strongly on the specific site characteristics. No precise distinction is made, because the cost for land-based turbines is highly dependent on the cost of land (influenced by the character of simultaneous uses of the land), and that at sea on foundation depths (and type of bottom sediments, an issue more important e.g. for Norway than for Denmark). A more detailed evaluation would separate rated power and energy production components of the operational costs.

Table 1. Electricity production by wind turbines

	Current	2015-2020	2050+	unit
Rated unit capacity	1-3	3-10	3-10	MW
Rotor diameter	60-120	100-140	100-160	m
Swept area	2000-11000	10000-15000	10000-20000	m^2
Hub height	70-160	80-160	100-180	m
Lifetime	20-25	25	25	y
Coefficient of performance*	0.30/0.46	0.3-0.5	0.3-0.5	
Environmental impacts (LCA)**	0.006	0.004	0.001	∈/kWh
Equipment costs (installed)	1.0-1.5	1.0-1.5	1.0	∈/W_{rated}
Operational cost (levelised over 20y)	0.25/0.36	0.2-0.3	0.2	∈/W_{rated}
Implied direct power cost	0.03-0.04	0.025-0.035	0.02-0.03	∈/kWh

* Average power production as fraction of rated power (depends on location and design choice, current value quoted for a good Danish on-shore/off-shore site with typical new turbines from Sørensen; 2005).
** Currently dominated by externalities of fossil fuels used in manufacture. A high cost of greenhouse warming impacts has been used (Sørensen, 2004). Noise impacts are included but visual impacts not quantified. Year-2000 ∈'s used.

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* Contribution from RUC to Comparative assessment project, written by Bent Sørensen, 2006.

1.2 Other power-from-renewable-sources technologies

Use of photovoltaic power in the scenarios is modest, and the cost is expected to remain (under Nordic conditions) considerably above that of wind power. The reason for a certain marked penetration in the northern regions is the existence of special niche markets, such as remote buildings (e.g. vacation houses) with high grid connection costs or only summer usage.

Biomass technologies currently provide fuel for power production at costs not too far from those of fossil fuels. However, in the longer perspective, the most likely application of the finite biomass resources is expected to be in the transportation sector, because of limited substitution options for mobile fuels. For this reason, biomass will be treated under biofuels, where a range of technologies may be of interest for the scenario construction, notably as competitors for hydrogen.

Geothermal energy is not considered for power production, because Iceland is the only Nordic country with such resources of any significance, and Iceland is not included in the scenarios.

Hydropower is a major component of the Nordic system, today as well as in the scenarios for the future. Generally, the generation cost has historically been low in the Nordic countries, and particularly in Norway. However, environmental costs, particularly of flooding land areas of high natural and recreational value has effectively stopped any further expansion of the Nordic hydro system. For this reason, capital cost estimates for new plants are not relevant, and the cost of providing hydro power from existing installations are not in a market-oriented model determined by the original investments, but rather on market parameters (demand versus the annual wetness-depending filling of reservoirs), plus of course operational costs. The lower limit implied on the level of hydropower costs is in this light of the order of 0.01 €/kWh, while the actual sales price can be much higher. The project uses actual prices from the Nordic power market.

2 Heat production technologies

Particularly in Denmark and Finland, combined power and heat production currently provides a large share of the heat demand. An important question for the scenario construction is, if the future renewable energy mix will allow a similar coupling of heat and power technologies, and if such a coupling will remain desirable.

Useful co-produced heat does not emerge from wind turbines or to any appreciable extent from hydro turbines. However, a number of the conversion processes mentioned below (electricity to hydrogen or vice versa, biomass to hydrogen, etc.) will have associated heat production, which will be discussed in the survey of the respective sections.

Solar thermal collectors may be used to produce heat, but under Nordic conditions, such production peeks during summer and is thus anticorrelated with overall heat demand. The hot water demand during summer would in many cases be small enough to be derivable from any decentralised energy equipment, or from centralised energy conversion through district heating lines. The expectation is thus that solar thermal energy will remain a niche market, mainly for remote applications (although the present penetration includes city dwellings, where older boiler units have extremely poor part-load efficiencies during summer and therefore provide solar energy with a more favourable economy if their use allows the boilers to be shut down). Solar thermal energy is not explicitly included in the present scenarios.

Biomass is currently used to generate heat, notable in highly polluting stoves (not to mention open fireplaces). The contribution of this practice to negative air quality is so much out of proportion with its energy contribution, that a total ban on such uses must be forthcoming. Larger-scale heat generation by biomass combustion has smaller emissions, but far from negligible ones. It is therefore envisaged, that only the above-mentioned co-produced heat from converting biomass to biofuels will be included in the scenarios.

The discussion of scenario implementation needs to consider the use of heat generation technologies in an interim period, and to discuss the most favourable way of coping with diminishing heat demands, caused both by the advanced in building heat-loss prevention and by the altered power-to-heat generation rations of a future, renewable energy-based energy systems.

3 Fuel production technologies

3.1 Hydrogen production

The most important routes to hydrogen production are from fossil fuels, from electricity or from biomass. Additional options that have been assessed but not significantly developed include direct production by solar light (using organic or inorganic devices) and thermal decomposition of water that may become interesting if nuclear breeder reactors operating at temperatures above 1000°C become developed. The full spectrum of possibilities is described in detail by Sørensen (2005). Here the current technologies of steam reforming and electrolysis are used as reference sheets for discussing the emerging technologies for electrochemical and biochemical (or bio thermal) production of hydrogen. Current steam reforming costs are taken from Topsoe (2006).

Table 2. Hydrogen production by steam reforming of methane (main constituent in natural gas).

	Current	2015-2020	2050+	unit
Rated unit capacity*	10-1000	0.0001-1000	0.0001-1000	MW
Lifetime	10-20	20	20	y
Conversion efficiency	0.6-0.85	0.3-0 .85	0.3-0.85	
Environmental impacts (LCA)		0.004	0.001	∈/kWh
Equipment costs (installed)	0.7	0.5-5.0	0.5-5.0	∈/W_{rated}
Fuel cost	0.012	0.02	0.04	∈/kWh
Operational cost (levelised over 20y)	0.5-1.0	0.3-1.0	0.3-1.0	∈/W_{rated}
Implied conversion cost	0.03-0.04	0.025-0.035	0.02-0.03	∈/kWh

* Concepts other than conventional convective reforming (typically up to 50 MW units) include reformers based on partial oxidation, autothermal or dry reforming, and with use of tubular or membrane-separated compartments. Because some of these technologies do not rely on large heat exchangers, unit size is less of an issue and even equipment for mobile technologies has been developed, down to rucksack or laptop size (Sørensen, 2005).

Of particular interest for wind-based power systems is the production of hydrogen from electricity. This is typically done by use of a fuel cell in reverse mode of operation. The conventional technology uses alkaline fuel cells (often just called electrolysers or alkaline electrolysers), but all types of fuel cells can in principle be used.

Table 3. Hydrogen production from electricity by alkaline electrolysis.

	Current *	2015-2020	2050+	unit
Rated unit capacity	1	1-50	1-50	MW
Lifetime	15	18	20	y
Conversion efficiency	0.7-0.75	0.8	0.9	
Environmental impacts (LCA)	small	small	small	∈/kWh
Equipment costs (size dependent)	0.2-1.4	0.2	0.18	∈/W_{rated}
Operational cost	0.006-0.042	0.006	0.0054	∈/W_{rated}/y
Electricity cost	0.07	0.06	0.05	∈/kWh of H_2
Implied conversion cost **	0.075-0.10	0.065	0.054	∈/kWh

* DDoE (2005)

** Assuming operation for 40% of the year.

3.2 Production of biofuels

Biomass can be used to produce liquid or gaseous fuels such as methanol, ethanol, biodiesel, biogas or hydrogen. Current production is based on the biomass products offering the lowest fuel production costs (e.g. sugar-to-ethanol, soybean- or rapeseed-to-methyl esters). These feedstocks are typically in competition with food production, and a sustainable production of biofuels is assumed to shift the feedstock to biomass residues. They are several times more abundant by weight than the grains or seeds (allowing a higher level of biofuel production) and their energy use does not preclude current applications, as it is possible to return most of the nutrient and soil-conditioning content to the agricultural land. Similarly, wood products (used for methanol production) would in a sustainable mode derive from forest management residues rather than from wood products that could be used in the paper and pulp industries and for construction or furniture.

Table 4. Biodiesel production based on biomass residues from agriculture.

	Current *	2015-2020	2050+	unit
Rated unit capacity	10-1000	10-1000	1-1000	MW
Lifetime	10-20	20	20	y
Conversion efficiency	~0.5	0.5	0.5	
Environmental impacts (LCA) #	modest	modest	modest	∈/kWh
Biomass cost **	170	<50	<50	∈/ton
Process fuels cost ***	~20	15	10	∈/ton
Credit for byproducts ***	~150	50	50	∈/ton
Total cost of biofuels produced ****	0.04-0.065	0.07	0.05	∈/kWh

* Current feedstock in Europe is not residues but mainly rapeseed, in the USA mainly soybean.

** Current European rapeseed prices (UFOP, 2006). Future prices pertain to non-food biomass residues.

*** Adapted from Shapouri (2003). Current byproducts are in the USA mainly soymeal.

**** The higher current quote for Europe is ab factory, with a cost around 0.088 ∈/kWh at filling stations (tax exempt in Germany, UFOP, 2006). For US soybean-based biodiesel, the retail cost is 0.047 ∈/kWh (MI & IFQC, 2006). Cost has so far declined with time, but future biofuel production is assumed based on the more complex technologies relevant for non-food biomass residues as feedstock.

\# Compared to fossil diesel, 50-70% less CO and HS, 10% more NO_x if not retained. Impacts have not been monetised (Sheehan *et al.*, 1998; EPA, 2002; McCormick *et al.*, 2003).

Table 5. Gaseous fuel production from biomass residues (methane, gen-gas, hydrogen)

	Current	2015-2020	2050+	unit
Rated unit capacity	0.001-1000	0.001-1000	0.001-1000	MW
Lifetime	10-20	20	20	y
Conversion efficiency (methane, producer gas)	0.35-0.6	0.65	0.65	
Conversion efficiency (hydrogen, pipeline gas)	0.3-0.45	0.5	0.55	
Environmental impacts (LCA)	-0.02*	~0	~0	∈/kWh
Biomass residues cost **	0.02-0.03	0.02	0.02	∈/kWh
Plant capital costs (methane, producer gas)	2.5 **	2.2	2	∈/W_{rated}
Plant capital cost (hydrogen, pipeline gas)	4	3.5	3	∈/W_{rated}
O&M	0.25 **	0.2	0.15	∈/ W_{rated}/y
Total cost of methane produced ***	0.04-0.14**	0.04-0.08	0.03-0.07	∈/kWh

* The negative value is due to avoided methane leaks to the atmosphere, causing warming (Sørensen, 2004; 2006).

** The high value of total cost is based on the Ribe biogas plant, the low on the Vegger plant, both in Denmark. The biomass composition appears to have a substantial influence on yields (Sørensen, 2004).

*** With hydrogen as an end-product, the cost is some 50% higher, even considering revenues from side products.

In all cases, the sustainable technologies (sometimes termed "2nd-generation technologies) would have a cost some 10-40% higher than that of using food products or wood (Sørensen, 2004). Biogas (methane) production is currently often used for electricity production, but could serve the transportation sector just as natural gas is in many countries used in vehicles. Production of hydrogen from biomass (through fermentation, gasification or pyrolysis) is possible but either involves additional process steps or specific hydrogen producing cultures with smaller yields (Gavala *et al.*, 2006; Sørensen, 2006) and thus with additional cost, because the simpler biofuels can equally well be used in the transportation sector and do not have to wait for fuel cell technologies to become viable.

Table 6. Ethanol production based on biomass residues from agriculture or forestry.

	Current *	2015-2020	2050+	unit
Rated unit capacity	10-1000	0.001-1000	0.001-1000	MW
Lifetime	10-20	20	20	y
Conversion efficiency	0.3-0.5	0.3-0.6	0.4-0.7	
Environmental impacts (LCA)	some	some	some	∈/kWh
Feedstock cost **	70	<100	<100	∈/ton
Credit for byproducts **	40	15	10	∈/ton
Cost of ethanol produced **	0.046	0.088	0.05	∈/kWh

* Currently based on fermentation of sugars (and in the USA animal fats) with distillation used to separate alcohol and water. In the future based on lignocellulose from corn stover or other straw residues with use of enzymatic liquefaction and saccharification preceding fermentation (Jørgensen *et al.*, 2006) ,and with membrane separation.

** Current: Shapouri, H. (2003). Future cost based on residues: Dansk Landbrug (2006).

Table 7. Methanol production based on biomass residues from forestry.

	Current *	2015-2020	2050+	unit
Rated unit capacity	10-1000	0.001-1000	0.001-1000	MW
Lifetime	10-20	20	20	y
Conversion efficiency	0.4-0.5	0.4-0.55	0.45-0.6	
Environmental impacts (LCA)	some	some	some	∈/kWh
Biomass residues cost **	0.02-0.03	0.02	0.02	∈/kWh
Plant capital cost (hydrogen, pipeline gas)	2.5	3.	2.5	∈/W_{rated}
O&M	0.2	0.2	0.15	∈/ W_{rated}/y
Methanol production cost	0.043	0.08	0.05	∈/kWh

* Currently produced from natural gas (price from www.methanex.com).

4 Energy storage technologies

Due to the decentralised nature of many renewable energy systems, the attachment to a common transmission/distribution system will in most cases smooth any short-term fluctuations. Only in case of stand-alone systems will there be a need for handling short-time variations, e.g. by condensors or small batteries in case of electricity-producing systems.

For the Danish energy system, the most relevant type of storage will be for handling variations in wind production relative to demand (possibly in conjunction with use of trade arrangements to handle the problem). The earlier study (Sørensen *et al.*, 2001) demonstrated that the required storage capacity needed to smooth the effect of passing weather front systems affecting wind speeds would be no more than three weeks of average demand. Seasonal storage was found necessary only for systems primarily depending on photovoltaic energy, which is not considered in the present study.

Among the types of storage known to be suitable for such intermediate length storage in connection with stationary energy supply systems are compressed gases such as air or hydrogen (preferably using underground caverns to reduce cost), physcial/chemical storage (in compounds such as hydrides or using reversible chemical reactions), hydro reservoirs (in countries possessing them) and perhaps advanced low-cost utility-scale batteries.

For mobile energy systems, compressed energy storage is using containers, and few useable alternatives are available (liquefied hydrogen storage has problems of loss of hydrogen, active coal and metal hydrides are heavy and too slowly responding for most automotive applications, and so on). For small mobile systems, such as laptops and video camaras, advanced batteries are the currently preferred storage type, with methanol containers plus fuel cells as a possible future option.

Below, the hydrogen storage options under investigation in the present work are analysed, together with a few competing options.

4.1 Large-scale hydrogen storage

The geology of Denmark allows underground storage of gases in either up-bending aquifers or domes of salt intrusion. Both are in use for storage of natural gas and are expected to be capable of hydrogen storage at a suitable pressure (Sørensen, 2005). Similar formations are also in use for compressed air storage (Sørensen, 2004). In other countries without the soft underground from glacier deposits characterising Denmark, the alternative of caverns excavated in rock is possible, albeit at a higher cost. In the case of salt dome caverns, the salt is flushed out of a cylindrical volume over a period of 2-3 years before installing the cannisters holding the gas to be stored. The efficiencies given in Table 8 assume an input of hydrogen made from surplus electricity but includes only the hydrogen in and out operations. For efficiencies of electricity-to-hydrogen, hydrogen transmission and hydrogen-to-electricity conversion (if hydrogen is not used directly) one is referred to the relevant Tables.

Table 8. Hydrogen storage at a pressure of 5-10 MPa in underground caverns (rock, salt domes or aquifers, the cost figures are for salt domes).

	Current	2015-2020	2050+	unit
Rated unit capacity	0.5-5	0.5-10	0.5-20	PJ
Lifetime	30+	30+	30+	y
Cycle efficiency	0.8	0.9	0.9	
Environmental impacts (LCA)	small	small	small	∈/kWh
Excavation costs (salt flushing)	20*	10	8	∈/GJ_{rated}
Plant capital cost	30**	20	16	∈/GJ_{rated}
O&M	1.5	1	1	∈/ GJ_{rated}/y
Cost of hydrogen storage for 3 weeks***	0.46	0.35	0.3	∈/$\text{GJ}_{\text{stored}}$

* A. Hauge Petersen (DONG), private comm.
** Padró, Putsche (1999).
*** Assuming that the store is in use some 40% of the year.

4.2 Small-scale hydrogen storage

Hydrogen in flasks at a pressure level of 20-30 MPa is a standard commodity. In the USA, efforts are made to introduce a new standard of pressures around 75 MPa, due to the amount of hydrogen required in US-style heavy passenger cars with fuel cell propulsion systems, in order to achieve an acceptable range between fillings. Cost figures are given in Table 9.

4.3 Selected competing storage technologies

Hydro reservoirs already part of electricity-producing systems (e.g. in Norway) can be used as a “store” nearly without cost, by regulating water flow through the hydro turbines according to deficits and surplusses in e.g. the wind power for which storage is desired. Reservoir levels are hardly affected in large reservoirs, and turbine capacity is usually so generous that the extra generation does not require new investments. The only problem may occur in cases of high wind power production, where the minimum water flow in some of the hydro systems may be difficult to maintain. In a hydro-dominated system such as the Nordic one it should be possible to handle this through management of the production rate of all the installations in the system. It is thus considered that the main cost of such “storage” is the fee for system management. This shifts the problem to one of power trade conditions, which is a commercial rather than a technology-driven problem. It is therefore very difficult to assess the possible technical limit for using the hydro system in a mode of smoothing renewable energy flows. It might be possible by flow management and additional hydro turbine capacity to accomodate considerably higher levels of renewable energy smoothing than is effectuatted today. A guideline for estimating the range would be from total system minimum flow limit to maximum turbine capacity, with the difference between average hydro production and that corresponding to minimum flow constituting the maximum import of surplus wind energy, and the difference between maximum hydro producton and the average production as the maximum export of power in case of deficient wind production. If the power exchange system were working rationally, the cost of selling/buying would increase dramatically, when these two limits are approached.

Table 9. Hydrogen storage at a pressure of 20-30 MPa in portable pressure flasks.

	Current	2015-2020	2050+	unit
Refilling plant capacity	~1	1-100	1-100	GJ
Lifetime	10-15	15	15	y
Cycle efficiency	0.88	0.89	0.90	
Environmental impacts (LCA) **	small	small	small	∈/kWh
Plant capital cost	4*	3	3	∈/MJ$_{rated}$
O&M	0.4	0.3	1´0.3	∈/ MJ$_{rated}$/y
Cost of refilling hydrogen storage flask***	1	1	1	∈/MJ

* Lipman, Deluchi (1996)

** Cf. Sørensen (2005), Chapter 6.2.5 for components of net energy analysis.

*** Excluding cost of hydrogen

In regions without reservoir-based hydropower, but with suited topology, pumped hydro can be used. The cost is higher than for reservoir management types of storage, but comparable to the compressed air option mentioned below (0.5 ∈/W$_{rated}$ plus the cost of the hydro turbine installation; DDoE, 2005).

Table 10. Compressed air storage of surplus electricity.

	Current *	2015-2020	2050+	unit
Rated unit capacity	10-1000	10-1000	10-1000	MW
Lifetime	30	30	30	y
Cycle efficiency **	0.4-0.55	0.5-0.6	0.6	
Environmental impacts (LCA) ***	some	some	some	∈/kWh
Plant capital cost (size dependent) #	0.67-0.67	0.3-0.6	0.25-0.5	∈/W$_{rated}$
O&M (size dependent) #	0.01-0.02	0.008-0.015	0.006-0.01	∈/ W$_{rated}$/y
Cost of storage (3 weeks) ##	0.27-0.5	0.25-0.4	0.25-0.3	∈/kWh

* The current mode of operation typically uses fuel to compress the air and electricity is produced during peek hours at an overall fuel-to-power efficiency that is some 70% of the one for conventional power plants (Sørensen, 2004).

** The higher value assumes heat recuperation (Sørensen, 2004).

*** Emissions of NO_x (15 g/GJ fuel), CH4 and N2O are given in DDoE (2005).

Based on DDoE (2005).

Assuming that the store is in use 40% of the year.

Whereas utility-adapted batteries and metal or advanced hydrides are too far from the marketplace to warrant future cost estimates, the alternative of compressed air storage with regeneration of electricity in a gas turbine has for some time been in limited use. Typical data are presented in Table 10.

Using methanol as a “hydrogen store” for automotive applications was actively studied 5-10 years ago. The methanol production cost is discussed in section 4 above. Remaining costs are those of an onboard reformer for generation of hydrogen (regeneration if the methanol was originally produced from hydrogen), plus a simple methanol container (similar to current gasoline tanks). As mentioned, the direct use of methanol in the transportation sector appears to be a more realistic alternative, leaving the cost of methanol production from surplus electricity and raw materials as the main cost item.

5 Infrastructure technologies

5.1 Electricity infrastructure

The siting of wind turbines (on- or off-shore) is different from the siting of fossil fuel-based power plants depending on availability of cooking water and harbours for coal delivery. As a result, the overall design of the electricity transmission systems is changing and will further change along the path to the scenario futures studied in this project. It has been customary for quoting costs of wind parks to include the additional transmission costs, although the same has not traditionally been the case for fossil plants (and it would in any case be difficult to say what the basis of comparison should be – in the wind case it is simply taken as the existing transmission network. The key electricity grid implications of the renewable energy based system considered here is that the transmission capacity may change in some regions: It may increase due to occasional excess wind power having to be transmitted to hydrogen production plants or to international markets, and it may decrease due to possible better match between sites of production and of electricity use. The latter effect is presumably small (because wind power installations no longer are highly decentralised), but the former could require considerable transmission grid reinforcement efforts. On the other hand, the largest wind power excesses are naturally expected in situations of low demand (e.g. at night), where there would be unused transmission capacity at disposal. Because maximum wind turbine output is 3-4 times average output, while minimum load is only about half the average load, the net result will be a requirement for more transmission capacity. However, due to the international electricity markets being formed and growing in importance, offering not only power exchange between neighbouring countries but also some continental exchange, it is likely (and indeed planned) to increase transmission capacity for reasons not connected to the renewable energy introduction. As a result, it would seem reasonable to burden the wind system only with part of the cost of expanding transmission. The costs of AC underwater cables or corresponding DC lines with thyristor transformers are quoted as around 2 euro per kW per km (see Sørensen, 2004).

Also the local distribution infrastructure may be influenced by the types of technology considered in the present project. If surplus power transformation into hydrogen is taking place decentralised, the distribution network may also have to be reinforced to accommodate the surges caused by excess wind power. Also here, the exact requirement is difficult to assess, because the distribution network has traditionally been built to considerable overcapacity, due to past visions of dramatically increasing energy use. The combined effect of more efficient equipment at the end-user and increasing use of power-demanding equipment may imply low- or no-growth power demands, leaving the surplus distribution capacity for system uses in the case of a decentralised hydrogen-producing scenario.

5.2 Heat infrastructure

The more efficient system envisaged in the scenarios will produce less heat waste, and the heat demand will continue to decline as a result of efficiency measures at the end-users. As a result, establishment of new district heating areas is not seen as economically viable, and the use of the existing ones may decline in importance. The lines may attain a new role in redistributing heat between local buildings, in the case of decentralised heat and power production by building-integrated fuel cells, and should in any case be capable of sustaining their O&M costs. If fuel cell combined production is made centrally, the heat would continue to be used in district heating lines where they exist, and expansion of the transmission and distribution system may be considered. Danish experience is that with a source of heat that would otherwise be wasted, heat transmission of some 30 km can be made economically viable, at least in a social context with regard to the choice of depreciation rate and time.

5.3 Hydrogen infrastructure

The transmission of hydrogen through pipelines is similar to transport of natural gas. The upgrading necessary has been discussed in Sørensen *et al.* (2001). Typical costs of establishing dedicated hydrogen pipelines are in the USA 625000 US$/km (Sørensen, 2005) or some 32 euro/km per TJ/y flow capacity.

Transport of hydrogen by use of containers on trucks, rail or ships currently favours ship transport when possible, at a cost of some 25 US$/GJ or 3 US$/kg (1999-prices, cf. Sørensen, 2005). Transport in liquid form works out to a cost similar to the one given above for pipeline transport, while use of pressurised containers entails a doubling of cost (Sørensen *et al.*, 2001). On the other hand, the efficiency of liquefying hydrogen is only 85%, supplementary refrigeration energy is needed and evaporation losses may cause environmental concern.

The distribution of hydrogen to the end-user involves conversion of filing stations for automotive applications (say filling onboard containers at 30 MPa), or development of a one-car filling station concept for transferring hydrogen to individual cars in private garages, e.g. from a two-way fuel cell installation within the building. Other transfers may be to and from local metal or other hydride stores. The costs of these infrastructure components vary but all take advantage of the substantial number of more or less identical installations. For hydrogen filling stations, of which several hundred pilot plants are currently in operation across the world, the cost of a substantial replacement of current gasoline filling stations has been estimated to equal one year's O&M cost for the current system, or adding 10% (some 0.1 euro/kg) to the cost of hydrogen (Sørensen, 2005). For individual filling station in garages, the cost of hydrogen may increase by 50-100%. The experience from compressed natural gas filling stations available in many parts of the world is relevant for hydrogen filling despite obvious differences.

Alternatives of filling stations based on liquid hydrogen tanks or from hydride or carbon stores are discussed in Sørensen *et al.* (2001) and Sørensen (2005). They do not play a major role in the present scenarios.

5.4 Infrastructure components for alternative fuels

Liquid fuels such as ethanol and methanol may be distributed in much the same was as gasoline and diesel, just as biogas resembles natural gas and can be handled in the same way. There are differences between the biofuels and the fossil ones in terms of toxicity and similar properties, but relative to e.g. hydrogen as a new fuel, the changes required appear very minor (Sørensen, 2005), and so are the prospective distribution costs relative to that of the present infrastructure.

6 Fuel conversion technologies

Due to the emerging nature of fuel cell technologies and some of the other technologies invoked in the present visions of future energy systems, statements about future costs are highly uncertain and would probably best have been avoided, if they were not essential to the scenarios of the present project. To resolve this problem, the costs quoted here are rather to be viewed as target costs that are seen as required for the marketplace penetration of the technologies involved. Although they mostly originate from key industry representatives, one should not forget that the present phase is one of early R&D involving both proper industry expenditures but also massive injection of public funding. The competition for such money requires a balance in applications between optimism and realism, and different parts of the world have different traditions regarding the level of optimism that is considered proper for an industry trying to obtain the privilege of spending substantial amounts of taxpayers' money in the interest of future revenues to the company, justified by promises of job-creation or job-preservation – and in the energy case also by the promise of national supply continuity and security.

6.1 Large-scale power (and associated heat) from hydrogen

Two kinds of technology for hydrogen power or CPH production are considered in the scenarios: Combustion technologies using e.g. gas turbines and fuel cell technologies, where the SOFC technology appears most promising for utility-scale applications. Both technologies may be used without utilisation of associated heat, with a slight increase in efficiency.

Table 11. SOFC fuel cell plant.

	Current *	2015-2020 ###	2050+ ###	unit
Rated unit electric capacity #	1-10000	10-1000	10-1000	kW
Lifetime	2	5	10	y
Electric efficiency	0.5-0.6	0.6-0.65	0.65-0.7	
Upstart time required at cold start	10-20	10-20	10-20	h
Environmental impacts (LCA) **	some	some	some	∈/kWh
Plant capital cost #	10	1	0.5	∈/W_{rated}
O&M	0.05-0.1	0.05-0.07	0.03	∈/ W_{rated}/y
Fixed cost of plant ***	0.9	0.045	0.013	∈/kWh of electricity
Fuel cost (H_2 by electrolysis)	0.1	0.065	0.054	∈/kWh of fuel
Sale of heat for district heating, if feasible	0.03	0.03	0.03	∈/kWh of heat
Cost of power produced ***	1.0	0.11	0.067	∈/kWh of electricity

* Sørensen (2005). Due to the high operating temperature, heat exports can be made available at high temperature, suited e.g. for industrial users. For home users, this is not an advantage.

** Metal contamination of wastewater streams, decommissioning wastes difficult to handle (Sørensen, 2005).

*** Assuming a capacity factor of 65%, typical of alrge centralised plants, excluding cost of fuel (see Tables 2 and 3) and credit for heat sales. For the lower utilisation expected in decentralised applications, the cost is correspondingly higher but so is also the lifetime. Pilot installations are likely to use and reform fossil fuels.

The cost figures assume a capacity of 200 kW or higher. The low-capacity installations under development for home applications will have considerably higher costs, due to temperature and safety requirements.

Replacement of fuel cell stacks is assumed to account for 70% of cost. The auxiliary equipment may have a lifetime of 15 years.

DDoE (2005).

Table 12. Gas turbine power plant using H_2 as fuel.

	Current *	2015-2020	2050+	unit
Rated unit electric capacity	0.003-400	0.003-400	0.003-400	MW
Lifetime (size-dependent)	8-30	10-30	10-30	y
Electric efficiency (size-dependent)	0.3-0.6	0.3-0.6	0.3-0.6	
Upstart time required at cold start	1-10	1-10	1-10	minutes
Environmental impacts (LCA)	some	some	some	∈/kWh
Plant capital cost (size-dependent)	0.35-1.0	0.35-0.8	0.35-0.6	∈/W_{rated}
O&M (size-dependent)	0.0025-0.0055	0.0025-0.005	0.0025-0.005	∈/ kWh electricity
Fuel cost (H_2 by electrolysis)	0.1	0.065	0.054	∈/kWh of fuel
Sale of heat for district heating, if feasible	0.03	0.03	0.03	∈/kWh of heat
Cost of power produced (size-dependent)	0.11-0.2	0.07-0.15	0.055-0.12	∈/kWh of electricity

* DDoE (2005).. Again O&M costs could be separated into an energy and a rated power component.

6.2 Small-scale power (and associated heat) from hydrogen

Two technologies for small-scale use of hydrogen to produce electricity (and associated heat) are considered. One is the PEM fuel cell currently under development for automotive applications, and the other is its application for building-integrated CPH-systems. As detailed in the previous study (Sørensen *et al.*, 2001), the stationary systems would preferably be reversible fuel cells capable of both producing hydrogen for parked cars or for storage from surplus electricity delivered through the distribution system, and electricity with associated heat for the demands of the building. In principle, all types of fuel cells can be used reversibly. However, the low-temperature systems are by many manufacturers considered most practical for decentralised use, and the R&D suggests interesting developments in the direction of increased efficiency for hydrogen production (cf. the discussion in Sørensen, 2005). Long upstart times for SOFC prevent their use in automotive applications and possibly constitute an obstacle for individual building usage.

Table 13. PEM fuel cell system for stationary use.

	Current *	2015-2020 ###	2050+ ###	unit
Rated unit electric capacity #	1-250	1-1000	1-10000	kW
Lifetime	2	5	10	y
Electric efficiency	0.3-0.5	0.45-0.55	0.5-0.6	
Upstart time required at cold start	<1	<1	<1	minute
Environmental impacts (LCA) **	small	small	small	∈/kWh
Plant capital cost #	10	1.0	0.4	∈/W_{rated}
O&M	0.05-0.1	0.07	0.03	∈/ W_{rated}/y
Fixed cost of plant ***	0.9	0.03	0.007	∈/kWh of electricity
Fuel cost (H_2 by electrolysis) *	0.09-0.15	0.065	0.054	∈/kWh of fuel
Sale of heat for district heating, if feasible	0.03	0.03	0.03	∈/kWh of heat
Cost of power produced ***	1.0	0.1	0.06	∈/kWh of electricity

* EU Hydrogen and Fuel Cell Technology Platform, DS, SRA (2005a; 2005b); DDoE (2005); Sørensen (2005). Some current systems use hydrogen based on natural gas, but costs are here based on hydrogen from surplus electricity.

** Preliminary LCA evaluations exist. Catalyst recycling is important (Sørensen, 2005).

*** Excluding cost of fuel (see Tables 2 and 3) and credit for heat sales. Assuming a capacity factor of 0.67. For lower utilisation, the cost is higher but so is also the lifetime in years. For household systems, a capacity factor over 0.5 probably requires load management.

The cost figure for 2020 is the target for stationary use (over 400 000 units sold; lifetime 40000 h) (EU H_2 & FC Technology Platform, DS, 2005a). The 2050 market has increased by a further factor of 10.

Replacement of fuel cell stacks is assumed to account for 70% of cost. The auxiliary equipment may have a lifetime of 20-25 years.

Current target lifetime in terms of operating hours is 40000 for stationary systems.

Table 14. PEM fuel cell system for automotive use.

	Current *	2015-2020 ###	2050+ ###	unit
Rated unit electric capacity #	1-250	1-1000	1-10000	kW
Lifetime	2	5	10	y
Electric efficiency	0.3-0.5	0.45-0.55	0.5-0.6	
Upstart time required at cold start	<1	<1	<1	minute
Environmental impacts (LCA) **	small	small	small	∈/kWh
Plant capital cost #	10	0.05	0.04	∈/W_{rated}
O&M	0.05-0.1	0.05	0.03	∈/ W_{rated}/y
Fixed cost of plant ***	5	0.01	0.004	∈/kWh of electricity
Fuel cost (H_2 by electrolysis) *	0.09-0.15	0.065	0.054	∈/kWh of fuel
Cost of power produced ***	5.1	0.075	0.06	∈/kWh of electricity

* EU Hydrogen and Fuel Cell Technology Platform, DS, SRA (2005a; 2005b); DDoE (2005); Sørensen (2005). Some current systems use hydrogen based on natural gas, but costs are here based on hydrogen from surplus electricity.

** Preliminary LCA evaluations exist. Catalyst recycling is important (Sørensen, 2005).

*** Excluding cost of fuel (see Tables 2 and 3) and credit for heat sales, assuming a capacity factor of 0.12 (which may be generous, cf. Sørensen, 2005). For lower utilisation, the cost is higher but so is also the lifetime in years.

The cost figure for 2020 is the target for automotive applications (over 1 million units sold, lifetime 5000 h). The 2050 market has increased by a further factor of 10.

Replacement of fuel cell stacks is assumed to account for 70% of cost. The auxiliary equipment may have a lifetime of 20-25 years.

Current target lifetime in terms of operating hours is 5000.

Table 15. PEM fuel cell system for small-scale portable use.

	Current *	2015-2020 ##	2050+ ##	unit
Rated unit electric capacity #	1-50	1-200	0.5-500	W
Lifetime	2	5	10	y
Electric efficiency	0.05-0.2	0.1-0.2	0.1-0.3	
Fuel canister capacity	12-20	20-30	20-100	h
Environmental impacts (LCA) **	small	small	small	∈/kWh
Plant capital cost #	1-2	0.05-1	0.04-0.05	∈/W_{rated}
O&M	0.02	0.02	0.02	∈/ W_{rated}/y
Fixed cost of plant ***	0.9	0.02	0.005	∈/kWh of electricity
Fuel cost (methanol canister) *	0.3	0.2	0.1	∈/kWh of fuel
Cost of power produced ***	1.3	0.22	0.11	∈/kWh of electricity

* EU Hydrogen and Fuel Cell Technology Platform, DS, SRA (2005a; 2005b); DDoE (2005); Sørensen (2005). "Current" is here taken as the projection for 2008-2010. Initial methanol cost is based on production from fossil fuels.

** Preliminary LCA evaluations exist. Catalyst recycling is important (Sørensen, 2005).

*** Excluding cost of fuel (see Tables 2 and 3) and credit for heat sales, assuming a capacity factor of 0.1. For lower utilisation, the cost is higher but so is also the lifetime in years.

The natural flow DMFC is much simpler than the PEM fuel cells used e.g. in transportation. The alternative PEM systems (high-power but few operating hours), aimed at emergency or rucksack power, typically in the range of 50-500 W, are projected already by 1010 to reach a price of 0.5 ∈/W_{rated} (EU H_2 & FC Technology Platform, DS, 2005a). The 2050 market has increased by a further factor of 10.

Current lifetime specification for a portable DMFC in terms of operating hours is 500 h.

6.3 Other uses of hydrogen

Hydrogen use in industry may increase in importance if hydrogen becomes established as an energy carrier. However, the types of use are expected to be similar to those of today and no particular analysis has been made.

6.4 Power from biofuels

Biofuels can be used to generate electricity, in conventional boilers or in reforming, high-temperature fuel cells. Technology data can be found elsewhere and corrected for the capacity factor relevant for using this option to handle the fluctuations of renewable energy sources such as wind.

6.5 Other uses of biofuels

Biofuels need not be restricted to use in the transportation sector, although the limits on renewable production would probably make such a restriction meaningful. The present scenarios do not envisage other uses of buifuels.

6.6 Electricity-to-heat conversion technologies

As the present scenarios typically have abundant electricity production (due to a large wind component), and little co-produced heat (except from fuel cells, and also here smaller than for presently used, less efficient conversion technologies). At the same time, heat usage, e.g. for space conditioning, is expected to decline, due to the continued improvement in building standards as regards heat losses, but it is unlikely to disappear. Therefore, the system may have a need for converting electricity to heat, a process which would be wasteful unless a heat pump is used. Only where district heating lines are available, may it be contemplated to use heat pumps in central facilities. In the rest of the heating market, individual building-integrated heat pumps are the natural choice. The cold reservoir of the heat pump may be air, water or soil, with air as the poorest solution for conditions in the Nordic region. Use of water is limited by availability (say presence of a frost-free stream or intermittent waste water from household activities) and although soil seems the best solution, the cost of establishing heat exchange tubes in frost-free depths is higher than that of air-to-air, air-to water, water-to-water or water-to-air heat exchangers. The heat pump compressor in all cases uses electricity, which is the only energy input to which a cost is assigned.

Table x. Heat pump using ambient air, waste water or soil as its low-temperature reservoir.

	Current	2015-2020	2050+	unit
Rated unit capacity (heat output)	1-100000	1-100000	1-100000	kW
Lifetime	15-25	20-25	20-30	y
Coefficient of performance	3-4.2	3.2-4.2	3.5-4.2	
Environmental impacts (LCA)	small	some	some	∈/kWh
Capital cost of installed system *	0.6-1.8	0.4-1	0.3-0.6	∈/W$_{\text{rated output}}$
O&M (size dependent) *	0.001-0.006	0.001-0.004	0.001-0.003	∈/ W$_{\text{rated}}$/y
Fixed cost of conversion (per unit of heat) **	0.03-0.09	0.02-0.05	0.01-0.03	∈/kWh
Cost of electricity used (per unit of heat output) #	0.014	0.011	0.008	∈/kWh

* DDoE (2005) quotes costs for installations of 200 kW to 100 MW. The upper cost value used is obtained from actual household systems rated at about 1 kW

** System assumed in use 20% of year at rated power. The fixed cost doubles if the usage time fraction is only 10%.

Quoted for an average COP of 3.6 and a price of (wind) power declining from 0.05 to 0.03 ∈/kWh (untaxed).

7 End-use technologies

No detailed technology catalogue of end-user equipment is made here. The assumptions regarding technical potential are the same as in the previous study (Sørensen *et al.*, 2001), but the actual development is as much a question of political initiatives and consumer preferences, both depending on both value systems and external conditions, as described in Part I of this report and underlying each scenario construct.

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