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

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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 swim-

ming 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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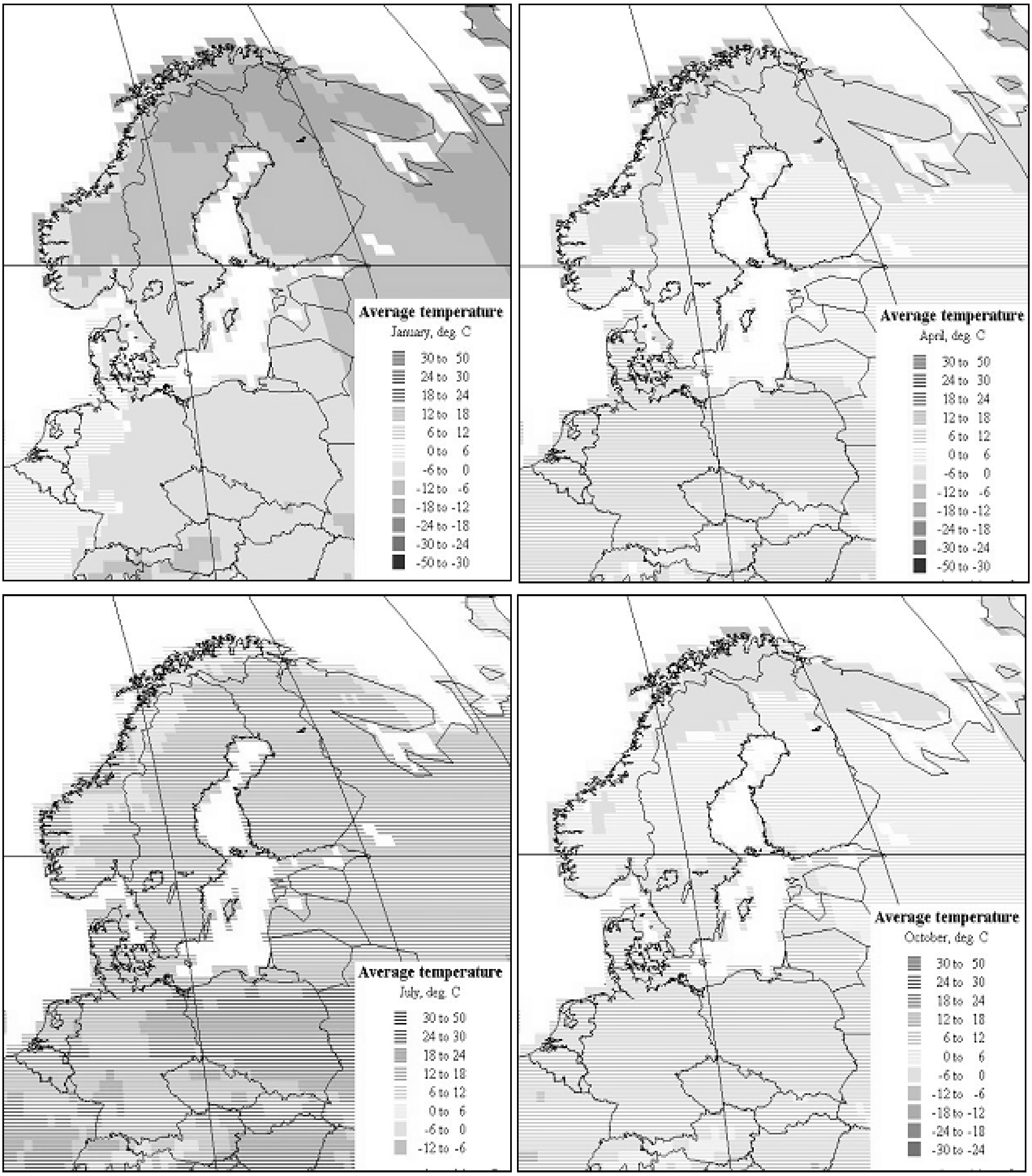


Figure 1. Average temperatures in January, April, July and October (based on data from Leemanns and Cramer, 1998).

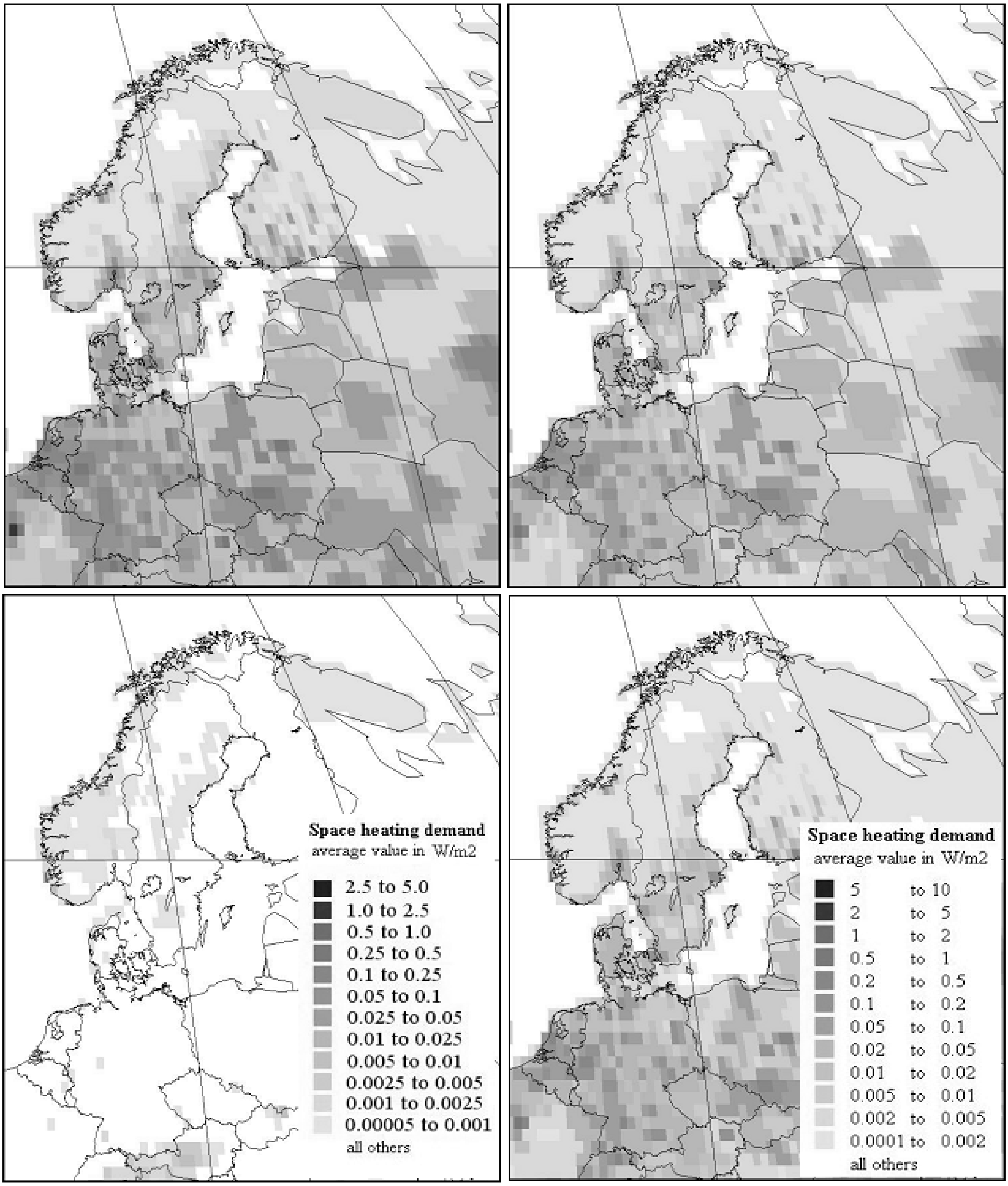


Figure 2. Average end-use space heating demand in January, April (top: left, right), July and October (bottom: left, right), for highest-efficiency scenario (left-hand scale for all four maps) or the unregulated-efficiency scenario (right-hand scale for all four maps).

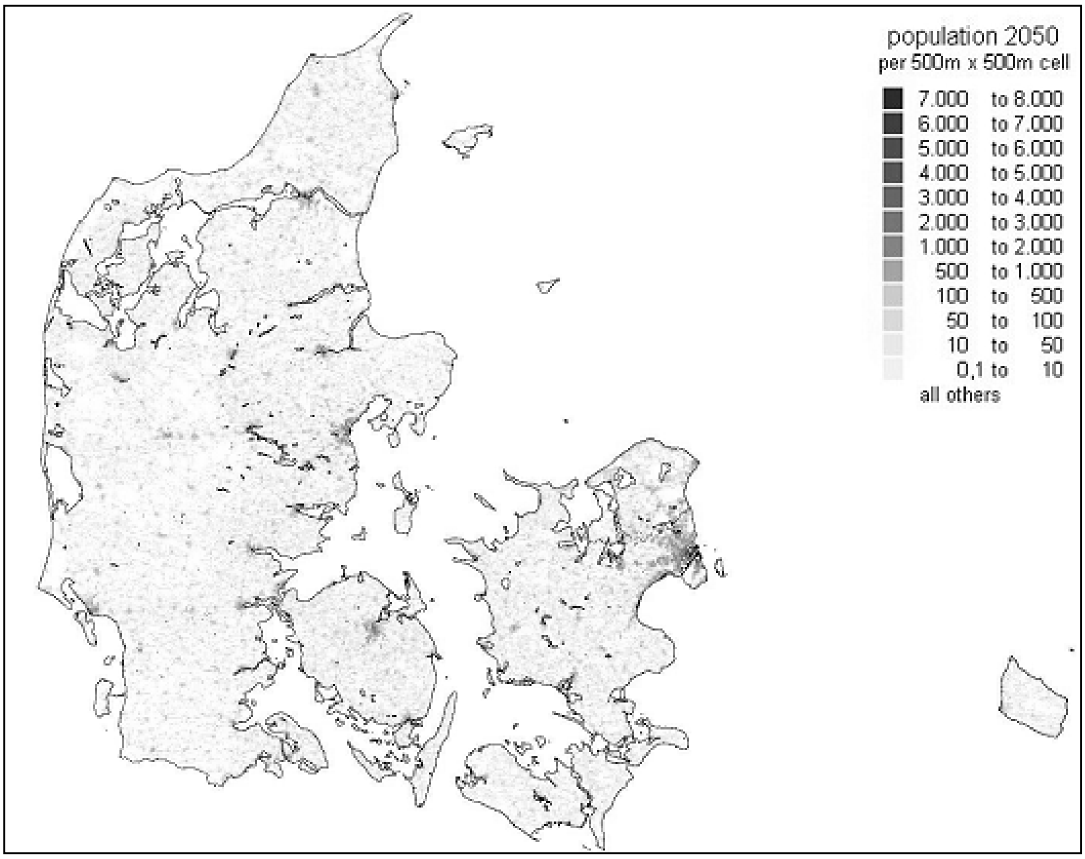
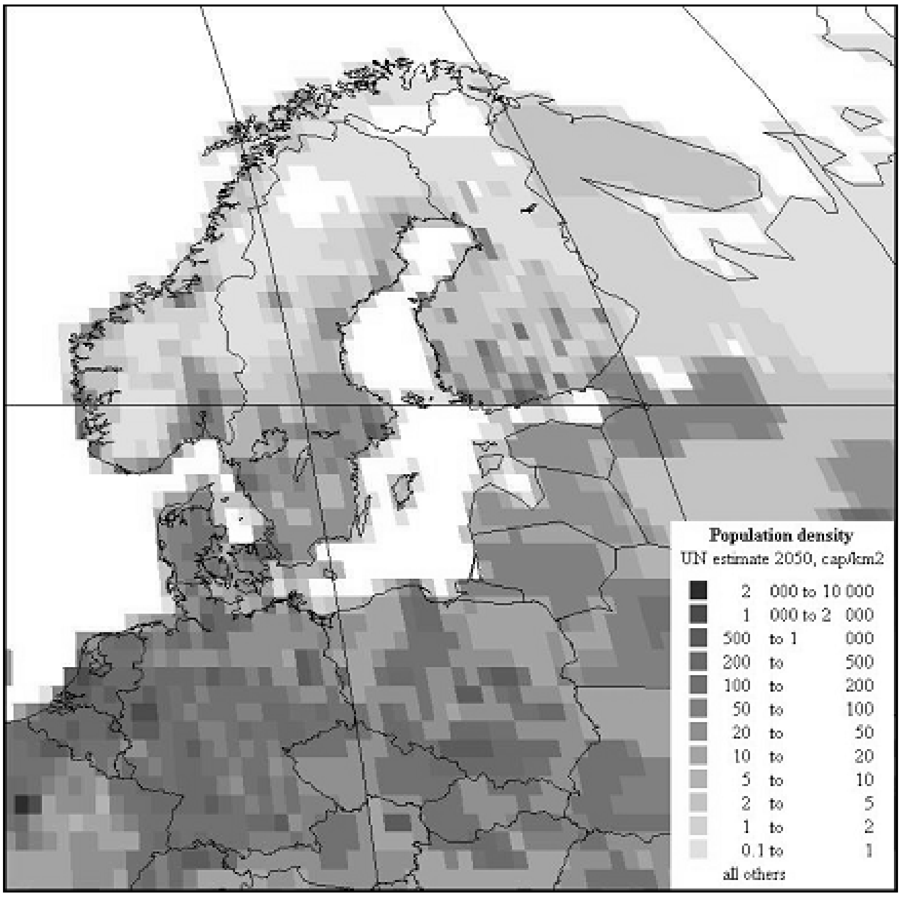


Figure 3. Above (a) : Danish population density assumed in 2060 (number of people per 500 m × 500 m unit cell; Sørensen et al., 2001). Below (b): North European population density assumed in 2060 (number of people per km^2; Sørensen *et al.*, 1999).



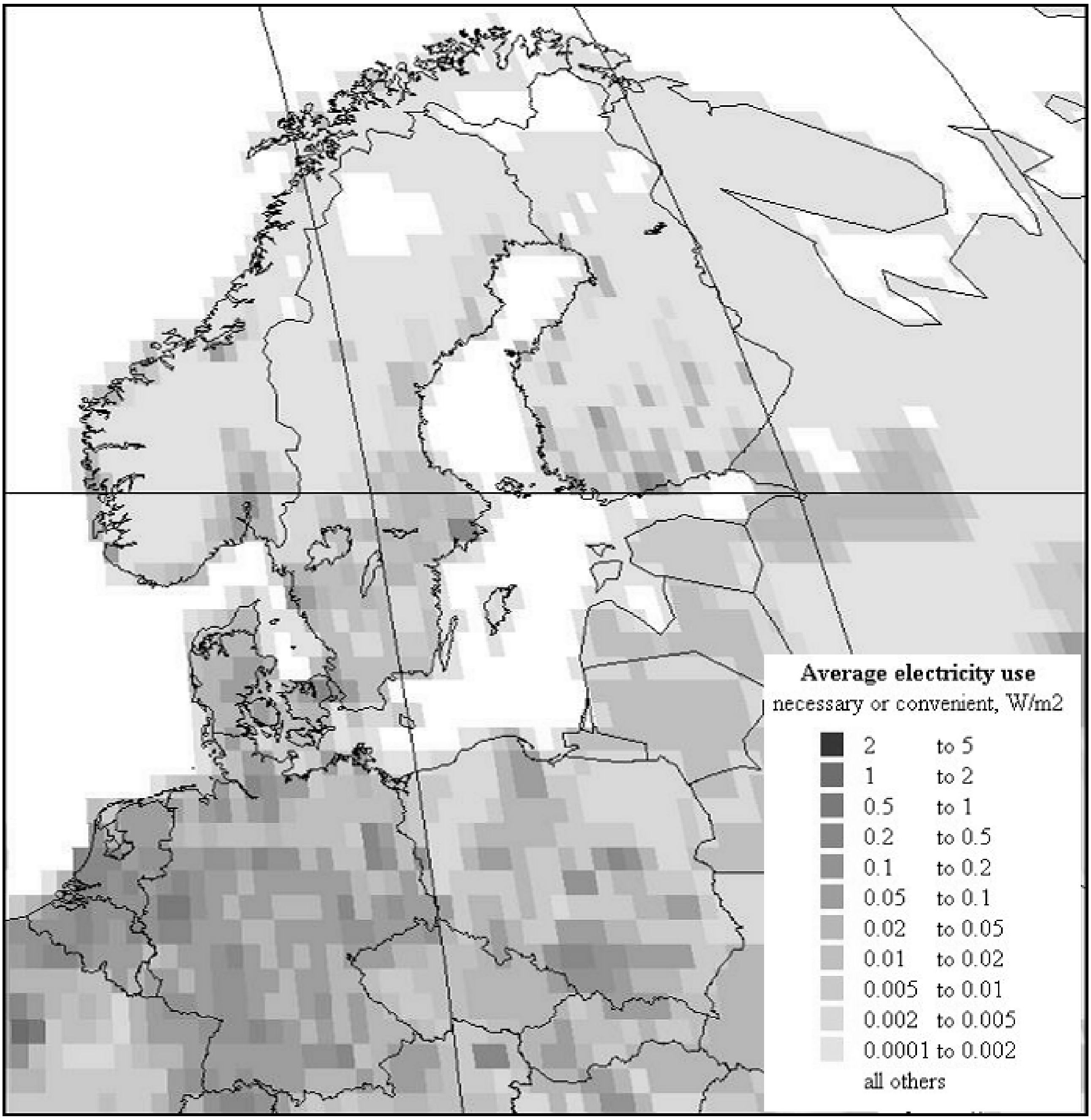
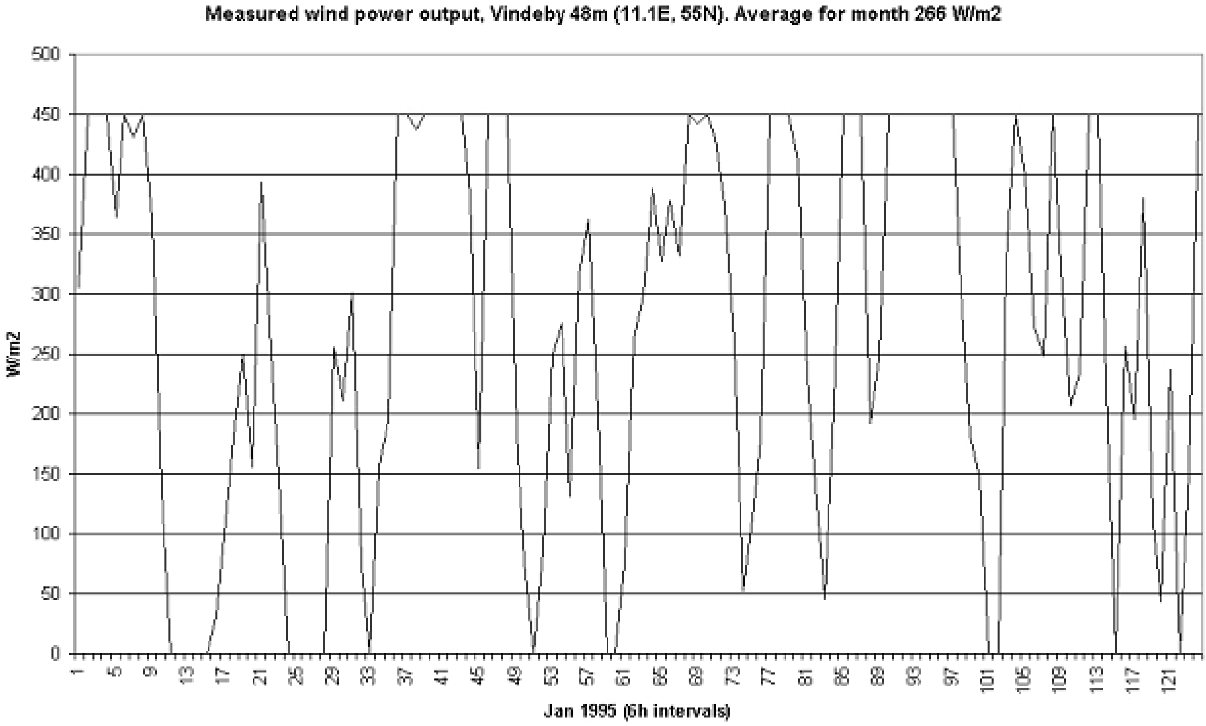


Figure 4. End-use electricity demand in 2060 for the highest-efficiency scenario. Included are both unsubstitutional electricity and electricity used for convenience (e.g. for dishwashers, industrial furnaces).



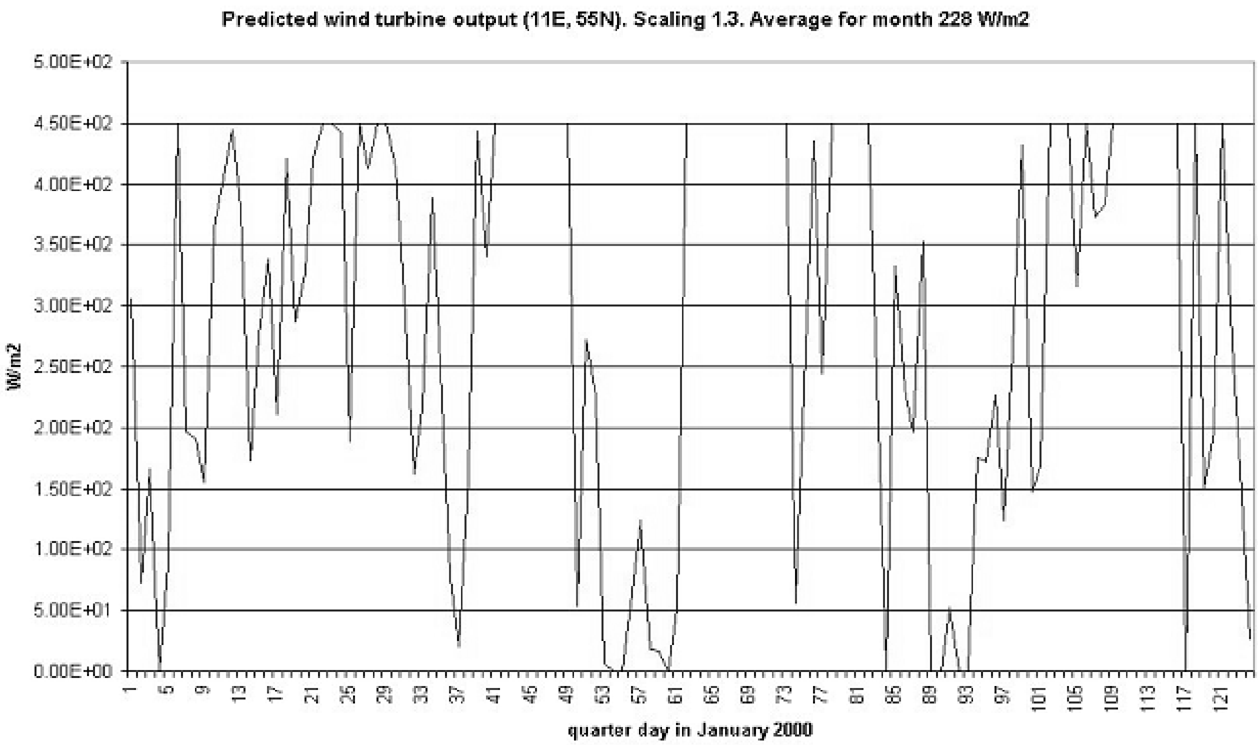
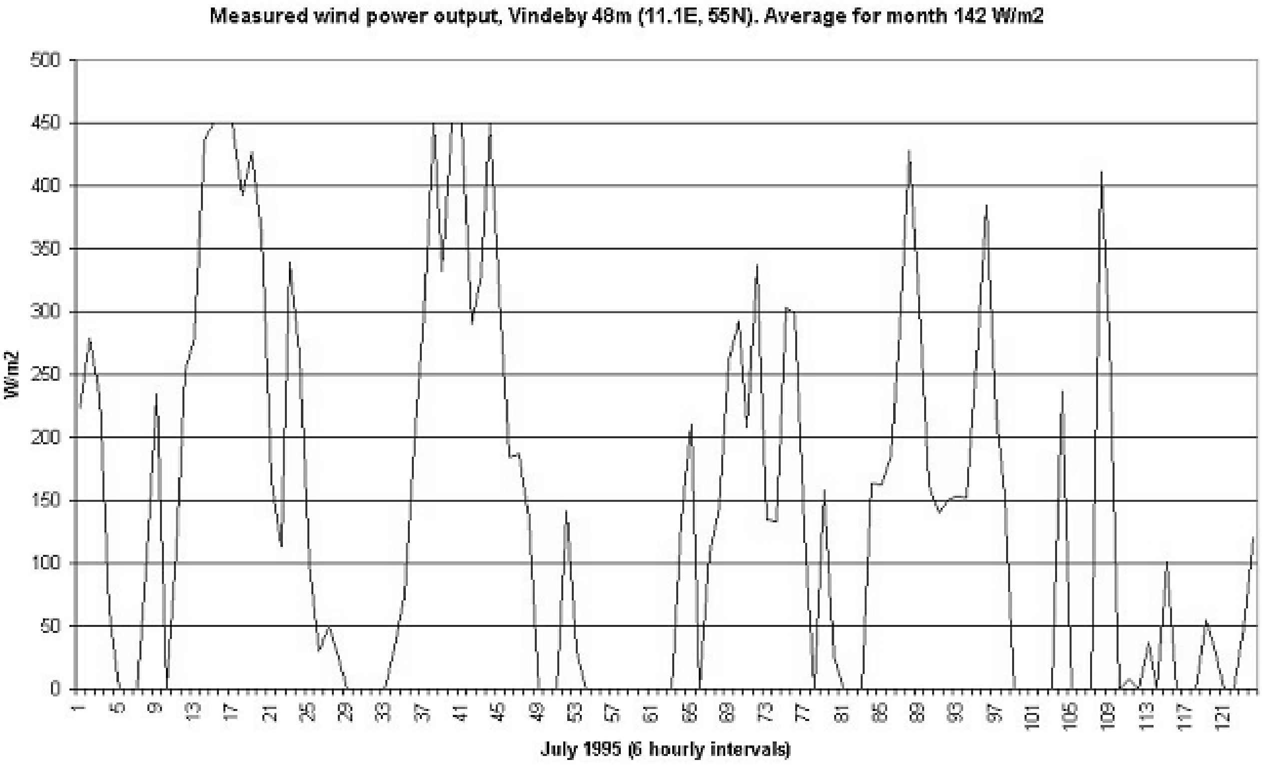


Figure 5. Measured time series of wind power output at the off-shore Danish location Vindeby during January 1995 (top) and corresponding power calculated from scatterometer blended data for January 2000 (bottom). The time resolution is 6 hours (Sørensen, 2006).



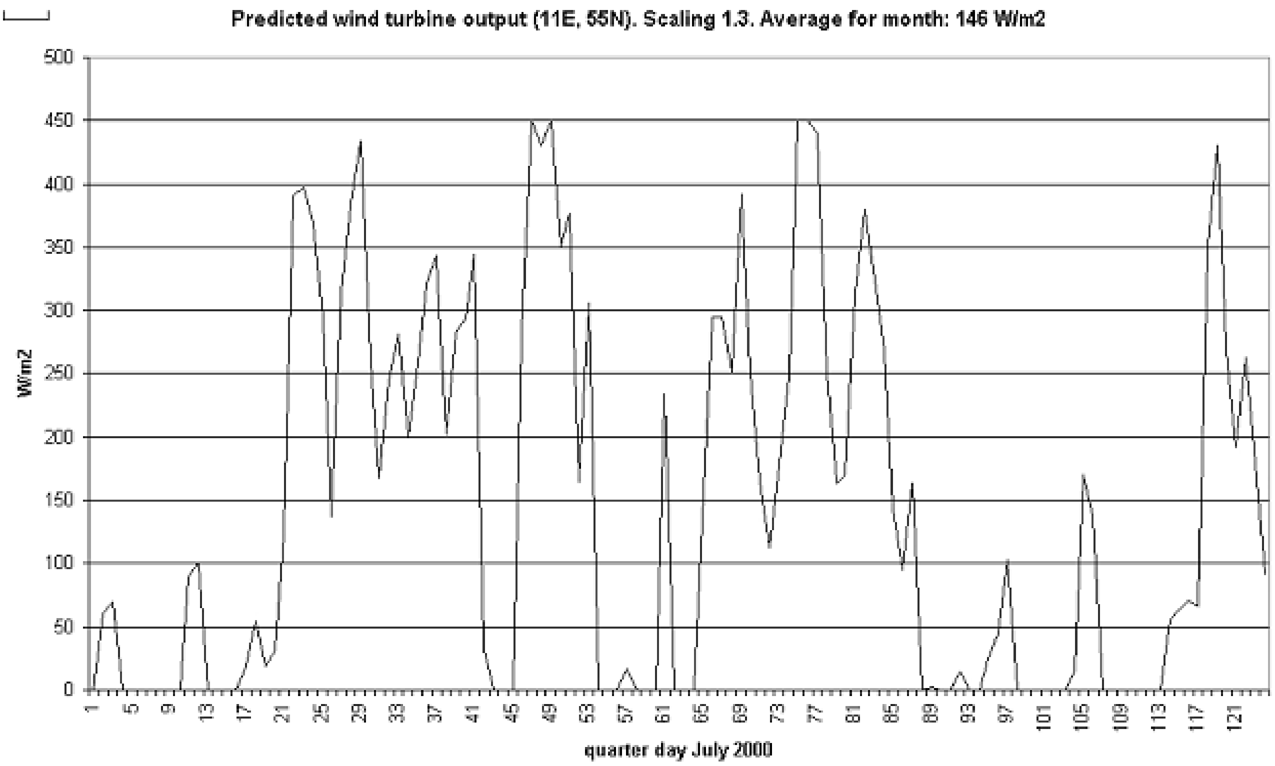
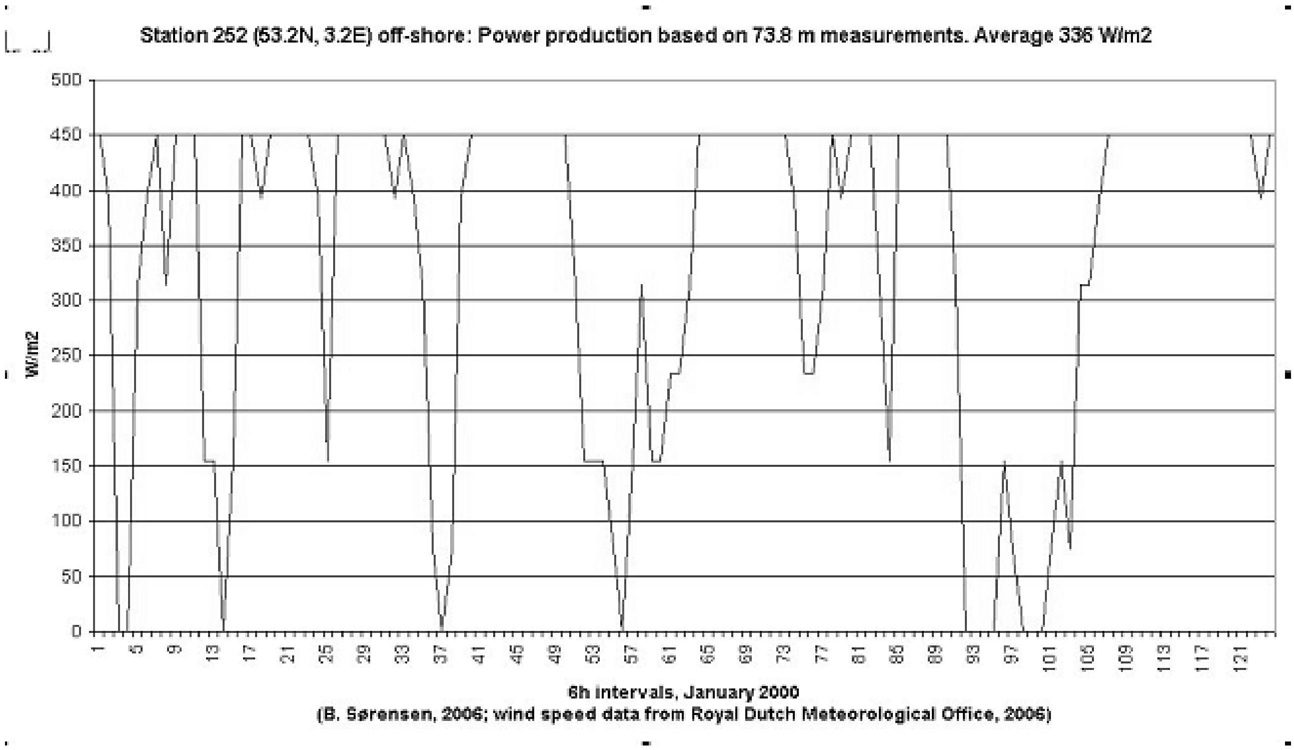


Figure 6. Measured time series of wind power output at the off-shore Danish location Vindeby during July 1995 (top) and corresponding power calculated from scatterometer blended data for July 2000 (bottom). The time resolution is 6 hours (Sørensen, 2006).



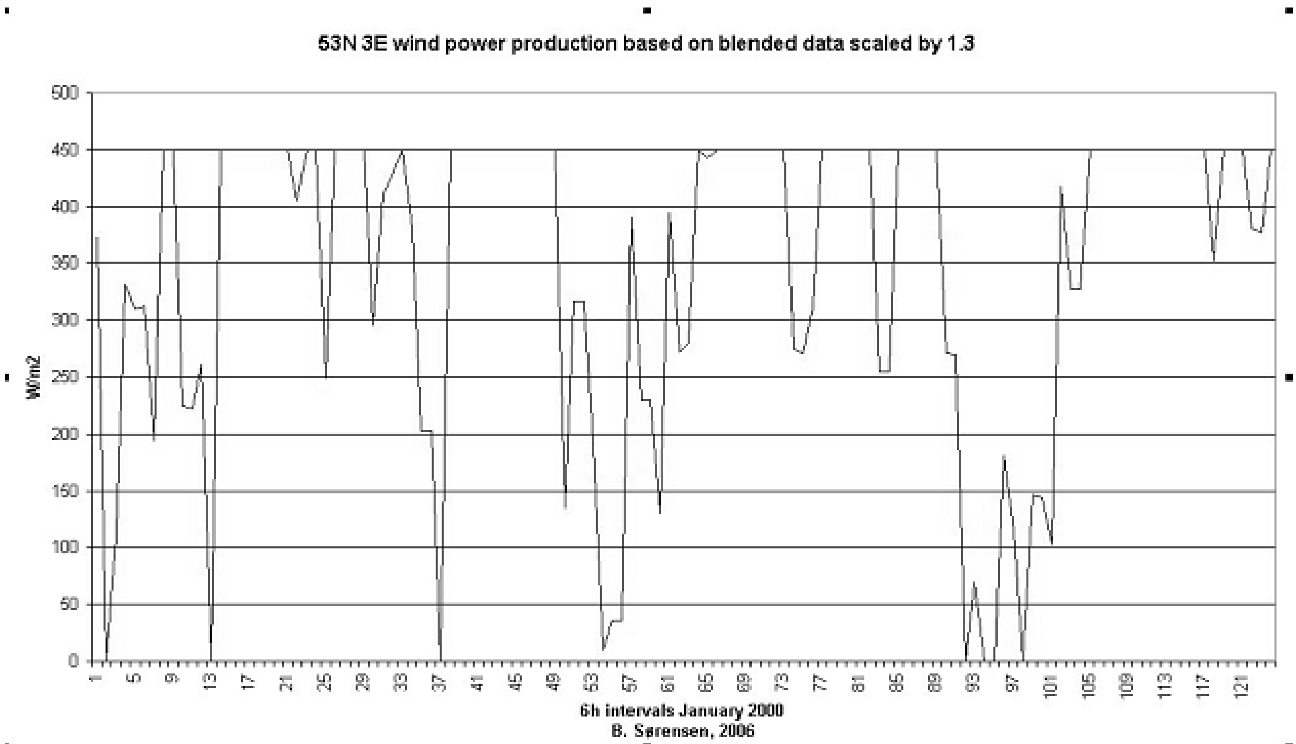


Figure 7. Measured time series of wind power output at the off-shore Dutch location Station XX during January 2000 (top; KNMI 2006) and corresponding power calculated from scatterometer blended data for (bottom). The time resolution is 6 hours (Sørensen, 2006).

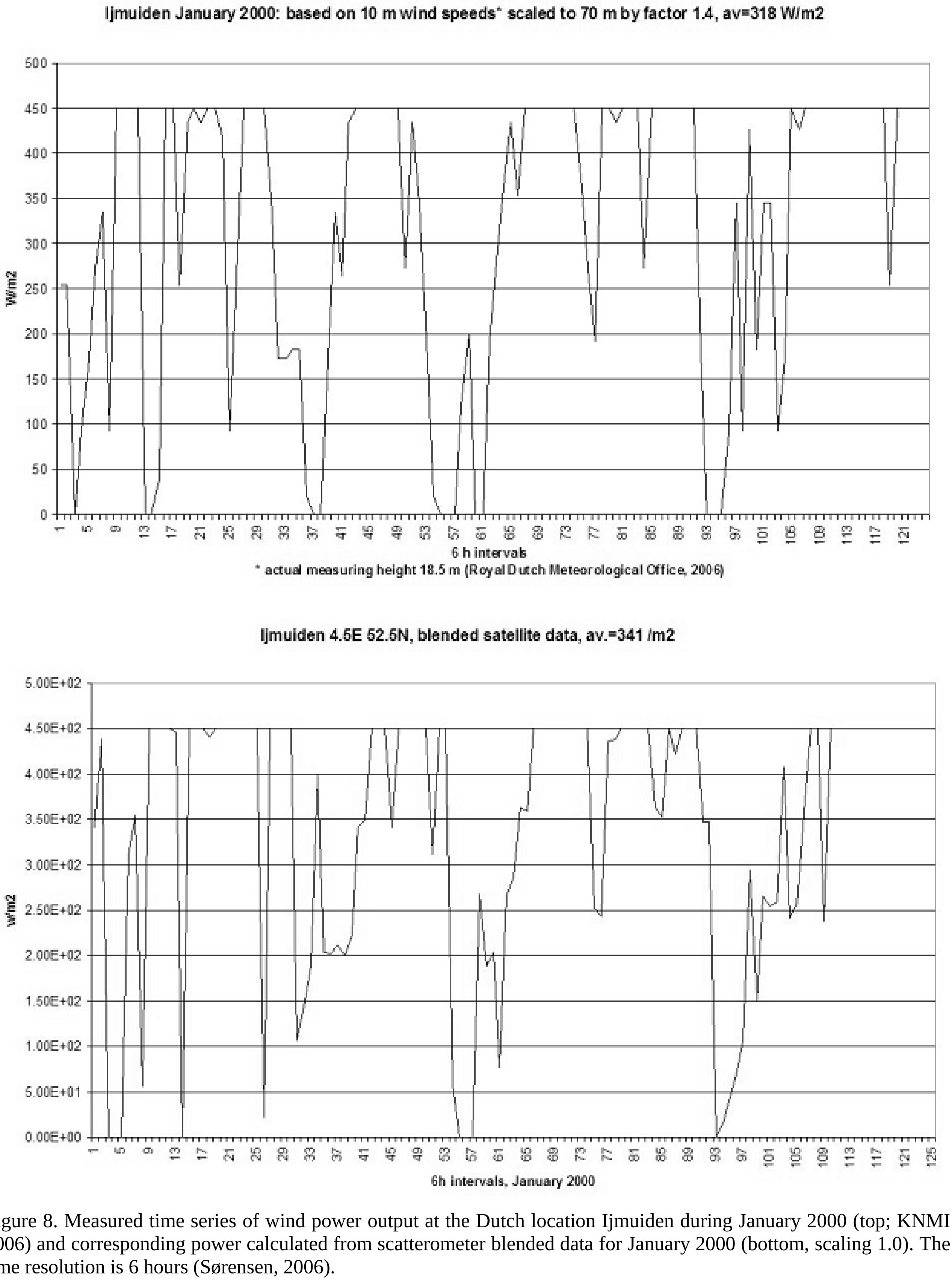
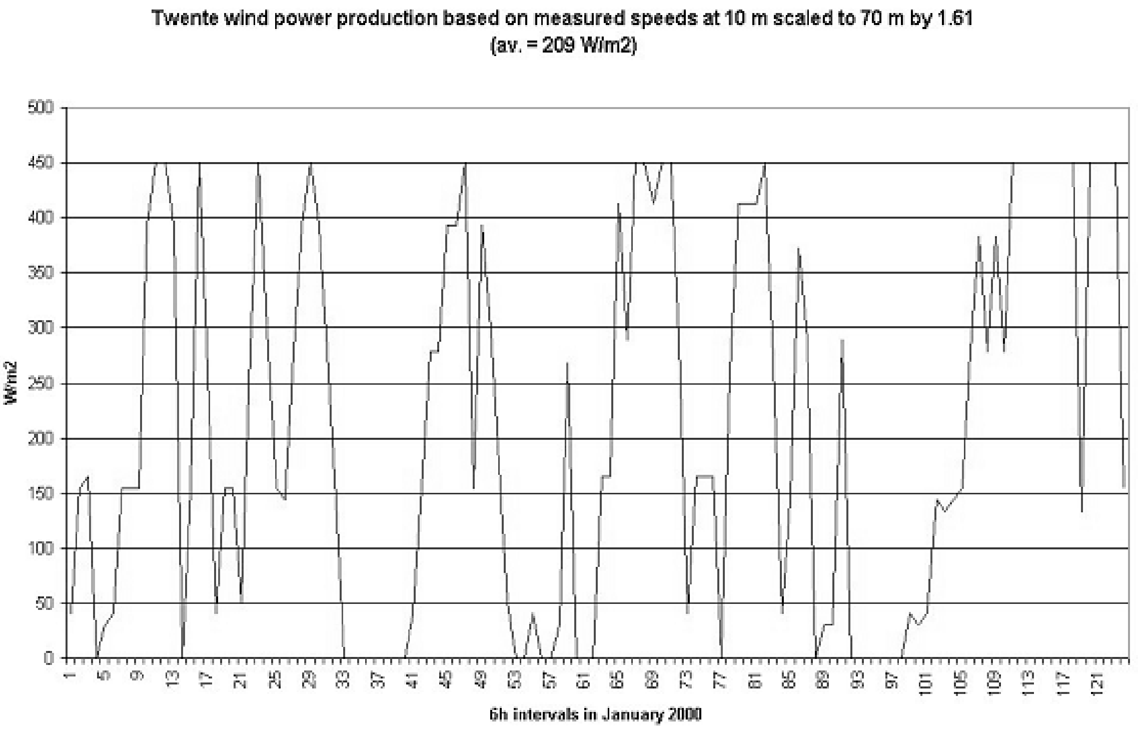


Figure 8. Measured time series of wind power output at the Dutch location Ijmuiden during January 2000 (top; KNMI 2006) and corresponding power calculated from scatterometer blended data for January 2000 (bottom, scaling 1.0). The time resolution is 6 hours (Sørensen, 2006).



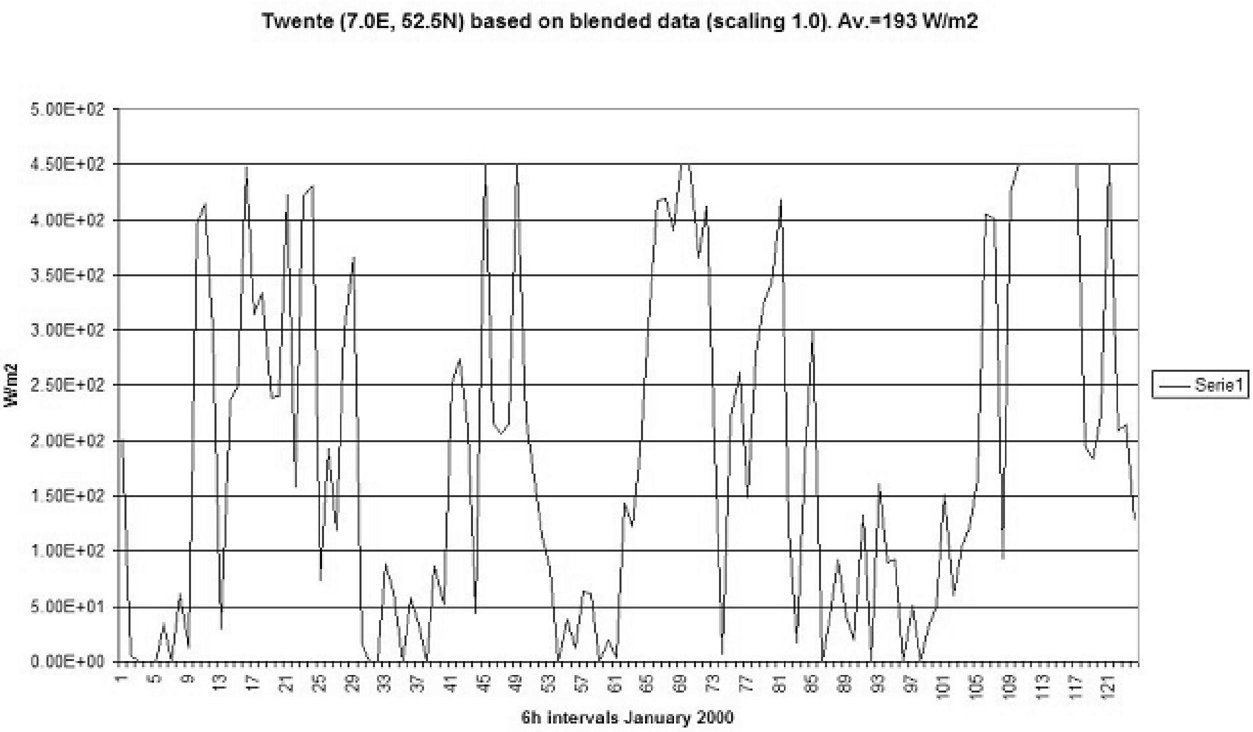


Figure 9. Measured time series of wind power output at the Dutch location Twente during January 2000 (top; KNMI 2006) and corresponding power calculated from scatterometer blended data for January 2000 (bottom). The time resolution is 6 hours (Sørensen, 2006).

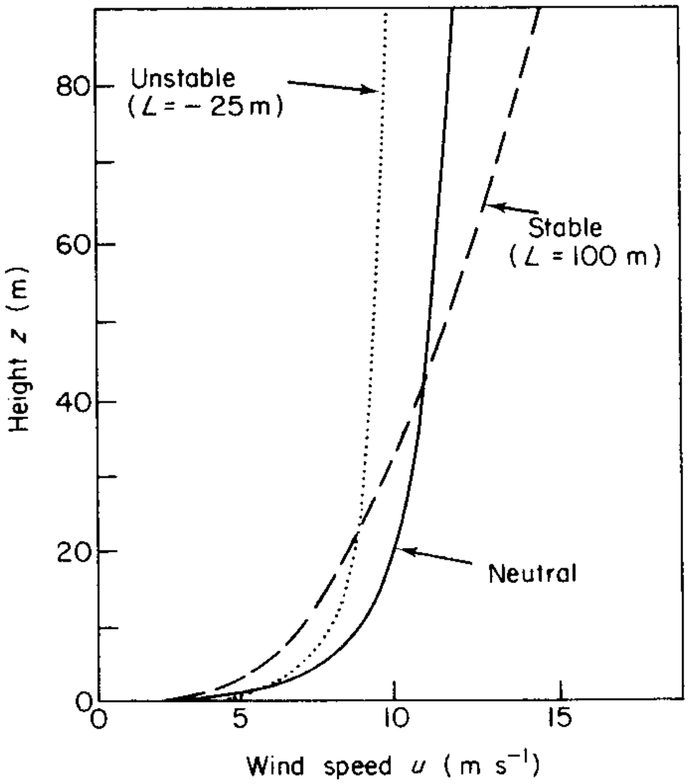


Figure 10. Wind speed profiles for three types of atmospheric stability. The parameter *L* used to describe the non-neutral curves is called the Monin-Obukhov length (from Sørensen, 2004).

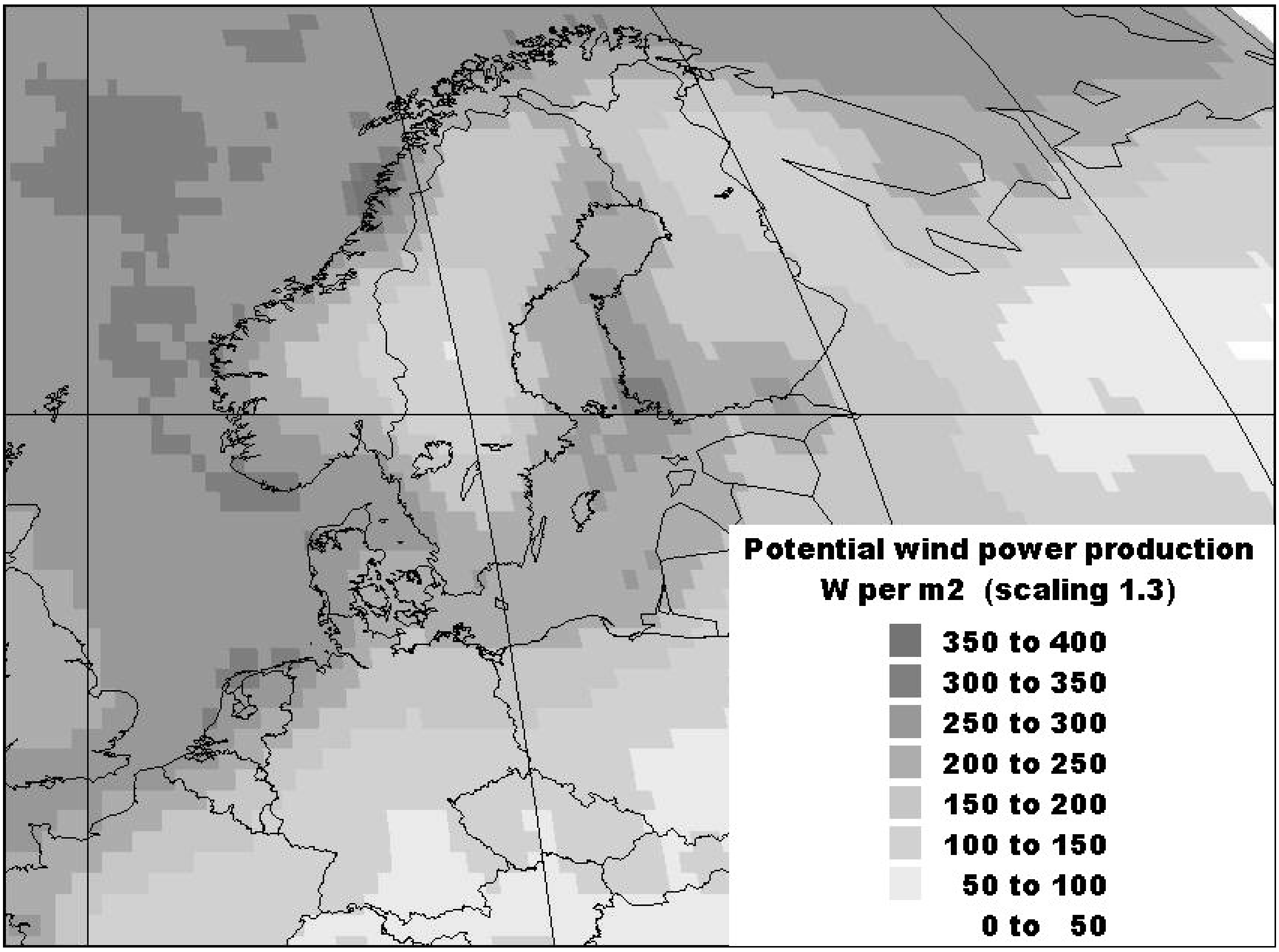


Figure 11. Map of wind resources in Northern Europe, based on blended data model with a scaling factor of 1.3 and a power conversion curve typical of current wind turbines (Sørensen, 2006). The unit is annual average watts per m^2 of swept turbine area

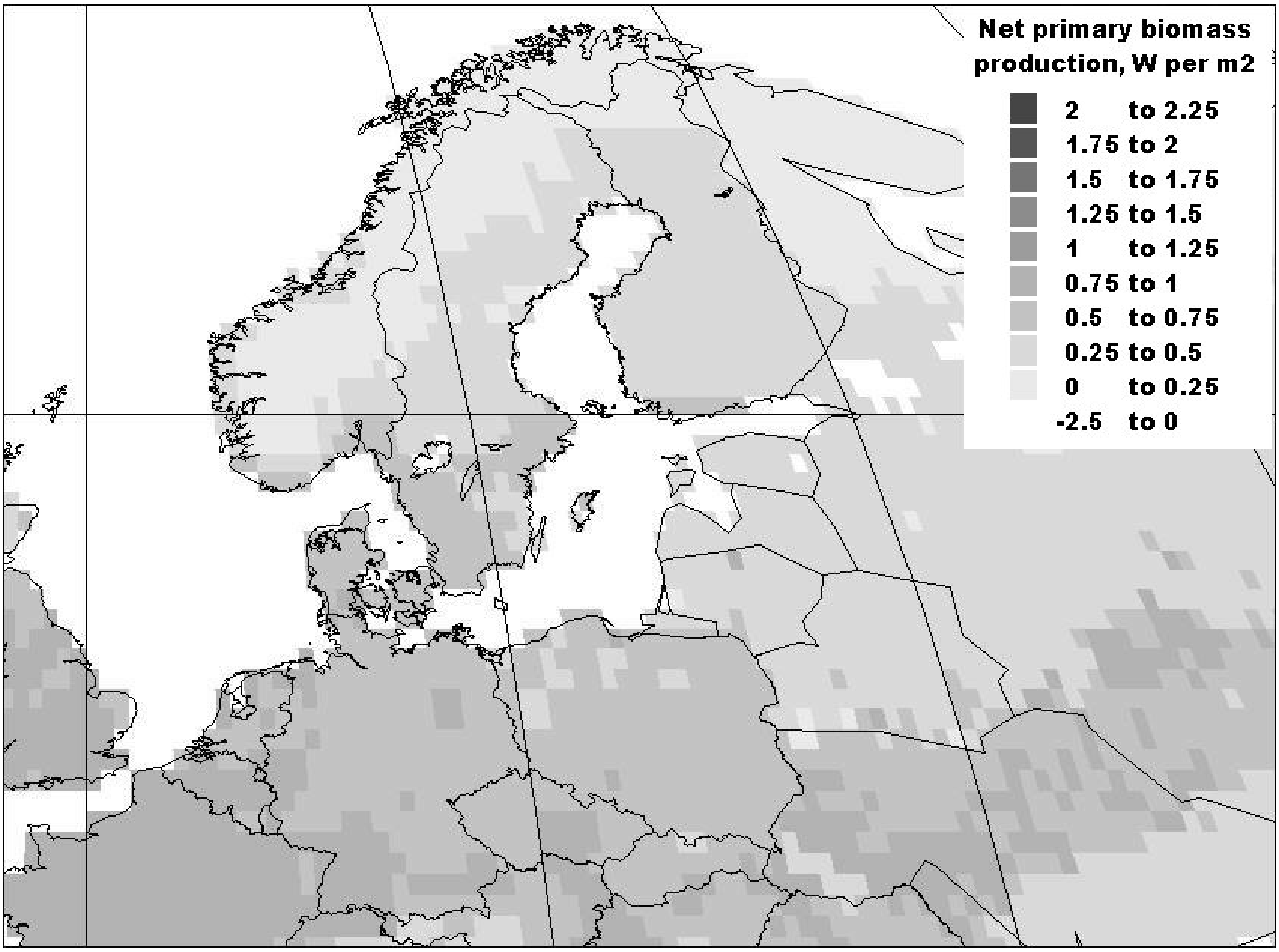


Figure 12. Potential net biomass production in Northern Europe, based on the model described in Sørensen (2004). The unit is W per m^2 of land.

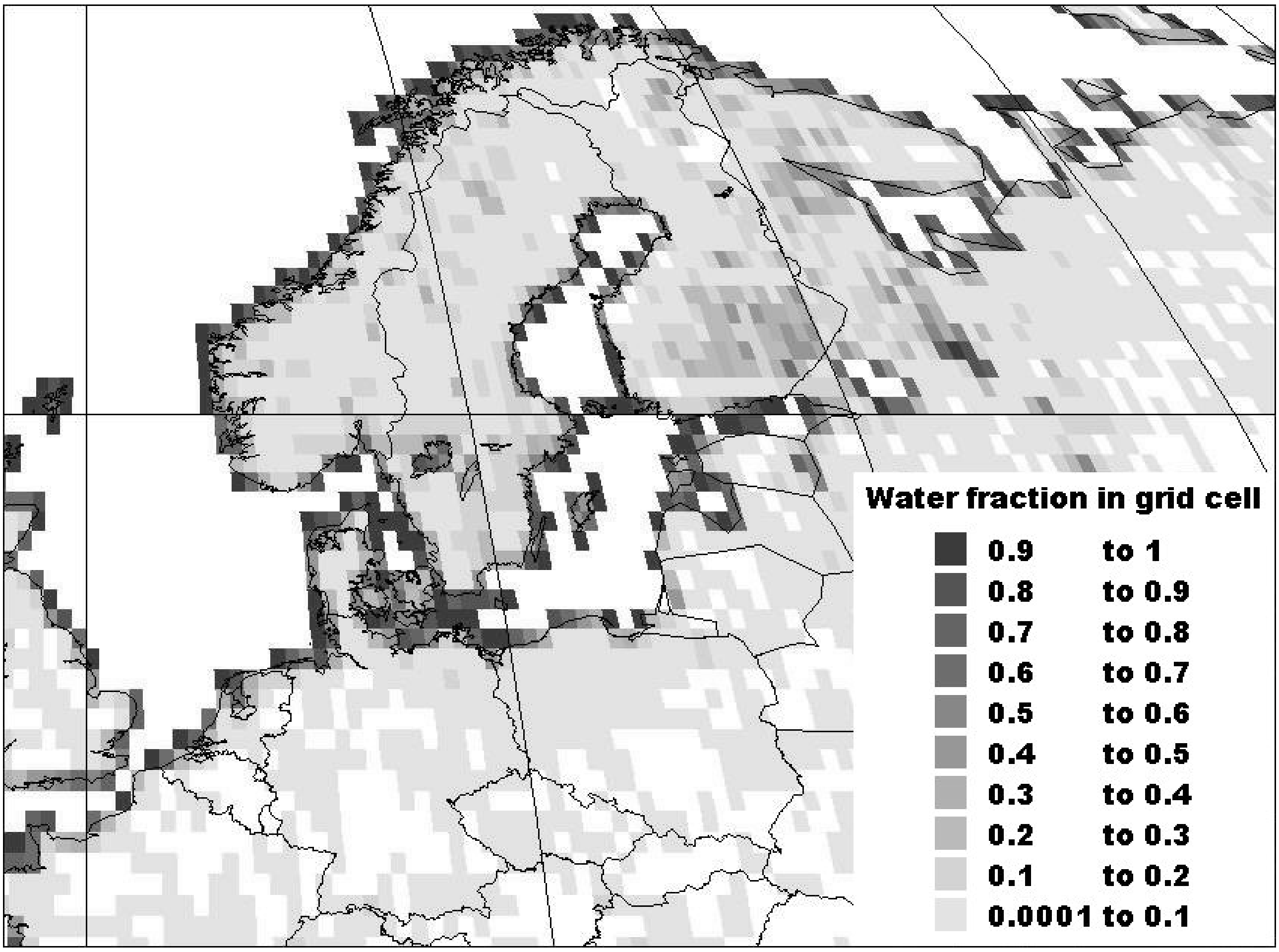


Figure 13. The water fraction of each cell in the model geographical grid. Inland values contain lakes, rivers and other streams, while off-shore values basically indicate the areas of up to 20 km from the coastline, which potentially could be utilised for aquaculture.