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The intelligent energy system for tomorrow

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The intelligent energy system for tomorrow

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Summary

In a future energy system non-fossil fuels have taken the lead, end-use technologies are highly efficient and closely interlinked to supply through intelligent energy systems. Climate change issues, security of supply and economic development need to be pursued concurrently.

This call for flexible and intelligent energy system infrastructures that:

- Effectively accommodate large amounts of fluctuating renewable energy and let the end-user interact with the supply through advanced ICT.
- The second important characteristic is intelligent integration of the entire transport sector.
- The third key area is advanced energy storage facilities in the system and the introduction of super-grids.

The changing global energy scene

The global economy has over the last years faced a number of changes and challenges with the financial crisis, which have significant impacts on almost all countries. At the time of writing this report it is still too early to analyze the full consequences of the crisis and fully grasp the potential impacts, but the attendant issues and their possible solutions are emerging. The crisis comes after a decade of unprecedented economic growth in many countries including most of the major economies. Globalization and free market economy have been dominant and the crisis now seems to bring back focus on the role of government and policy in almost all countries and economic sectors.

The economic recession may be seen as short term relief with regard to GHG emissions for many countries, but

> **Statement by the World Energy Council**
> WEC members feel that the energy sector short and longer term challenges centre on:
> • The security of supply and predictable energy demand,
> • The sustainability of current energy policies,
> • Alleviating the energy poverty experienced by
> more than two billion inhabitants of our planet.
> "These challenges remain while the world is in recession, in fact the recession in many ways exacerbates the issues in the long term; but in other ways it also provides new opportunities for us to reconsider our energy policies."

does not change any of the fundamental concerns. The statement by the World Energy Council [1] is a clear indication that many energy industries share this view.

On the climate side recent scientific findings show that due to the growth in the last decade, GHG concentrations in the atmosphere have been building up faster than even the most pessimistic scenario predicted by the Intergovernmental Panel on Climate Change (IPCC) and consequently the climate change impacts are occurring faster and are more significant than was predicted. See information from the Global Carbon Project[2] in the box below.

> **Atmospheric CO_2 growth**
> Annual mean growth rate of atmospheric CO_2 was 2.2 ppm per year in 2007 (up from 1.8 ppm in 2006), and above the 2.0 ppm average for the period 2000-2007. The average annual mean growth rate for the previous 20 years was about 1.5 ppm per year. This increase brought the atmospheric CO_2 concentration to 383 ppm in 2007, 37% above the concentration at the start of the industrial revolution (about 280 ppm in 1750)

The concept of *energy security* is traditionally directly linked with energy supply. Securing stable supply is a major political concern and a challenge facing both developed and developing economies since prolonged disruptions would create serious economic and basic functionality problems for most societies. Stability of energy demand is evidently a concern seen from the energy supplier side and will affect investment decisions at that level, but in this section the focus is mainly on the supply side of energy security.
The US administration is focused on both energy security and climate change issues. The EU concerns on energy security are very much oriented towards increasing reliance on supplies coming from Russia. Experiences from the last couple of years illustrate the vulnerability of energy supply dependency at the political level. For the large developing economies like China and India there has, especially for China, been a marked shift in the interest in securing stable foreign supply and China has been strengthening links with a large number of fossil fuel producing countries around the world with a special focus on Africa. On the energy demand security side Russia and other fossil energy resource suppliers are increasingly raising concerns about the need for stability of demand reflecting the importance the fuel exports constitute for their economies.

As presented in Figure 1from the IPCC Fourth Assessment[3] it is clear that for the electricity sector the business as usual (BaU) projection is going to be strong growth mainly based on fossil fuels. But with wide scale application of energy efficiency measures both on in power plants and demand sides combined with increased utilization of esp. renewable energy sources it is technically feasible, although at increased cost, to reduce emissions in 2030 by almost 50% compared to the present situation, instead of a projected BaU increase of more than 50%. Such reduction will evidently require strong political will and support from both private consumers and industries around the world, as well as stringent and permanent regulation. But as stated by both the IPCC[3] and the Stern Report[4] the cost of this action is manageable in comparison to the cost of inaction.

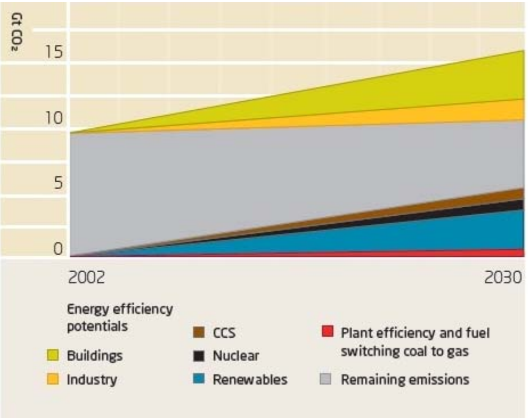


Figure 1: Potential for 50% emission reductions from the electricity sector worldwide.

Renewable energy sources, which at one time occupied an almost insignificant niche, are gradually expanding their role in global energy supply. Today's energy system is the result of decisions taken over more than a century. This long-term development is reflected in the structure of the energy system, which in most cases was developed according to basic engineering requirements: energy is produced to meet the needs of consumers.

There is still an evident gap between the positive developments in renewable energy and the needed expansion illustrated by the IPCC[3] and it is clearly urgent to take major policy action by both OECD countries and the large emitting developing countries to accelerate the already positive trends.

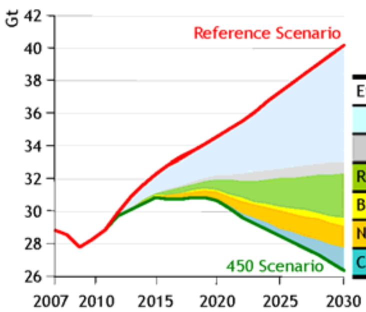
The EU has as part of its action on climate change agreed on an initial reduction of emissions by 20% in 2020. This was specifically combined with a parallel target for renewable energy also at 20% by 2020, including a specific provision for a minimum of 10% biofuels in transport to ensure that targets are not only addressed in electricity and heating. China has similarly set a target of increasing renewable energy use from the present 10% to 20% of the total energy consumption by 2030 to meet the increasing demand and reduce the greenhouse effect. The US administration is similarly moving on both energy efficiency and renewables

The power system is currently undergoing fundamental structural changes. The causes of this include not only the rapidly increasing amount of fluctuating renewable energy that is being connected to the system, but also the use of new types of production and end-use technologies[5].

Large scale application of renewable sources in the electricity supply will require a marked change in transmission and distribution systems. Although renewable energy technologies cannot be discussed en bloc e.g., hydro has a completely different supply profile than wind, it is clear that the level of variability will increase and introduce some degrees of uncertainty compared with fossil systems, which will require more flexible systems. Dealing with the increased variability requires flexible back-up and increase of the general robustness of existing systems with for instance gas turbines representing a flexible back up option now, while further into the future it is the expectation that storage technologies will improve sufficiently to become an integral part of the electricity system.

As stated by the World Energy Council[6]: To develop the so-called climate-friendly technologies, investment into research, development and deployment of new technologies is needed. Consequently, the most important task for any regulatory framework is to provide sufficient incentives for investment leading to the replacement of old and carbon-intense processes by more efficient, low-carbon technologies.

In World Energy Outlook 2009[7] it is highlighted that many different initiatives are needed simultaneously in order to bring down the emissions from the reference scenario to the desired 450 ppm scenario.



	Abatement ($Mt\ CO_2$)		Investment ($2008 billion)	
	2020	2030	2010-2020	2021-2030
Efficiency	2 517	7 880	1 999	5 586
End-use	*2 284*	*7 145*	*1 933*	*5 551*
Power plants	*233*	*735*	*66*	*35*
Renewables	680	2 741	527	2 260
Biofuels	57	429	27	378
Nuclear	493	1 380	125	491
CCS	102	1 410	56	646

Figure 2: Efficiency measures account for two-thirds of the 3.8 Gt of abatement in 2020, with renewables contributing close to one-fifth.

Link between supply and end-use, self-sufficient houses and industry and the transport sector is of paramount importance. In future energy systems with high emphasis on efficiency improvements in both industry and private households changing demand patterns are going to generate new challenges to system operators and utilities. The customers are becoming increasingly independent as they in long periods can be self-sufficient with energy and in other short periods of time are expecting the system to supply all their needs e.g., during cold winter nights or during peak periods in industrial production. Future low energy houses or even *plusenergy houses* could be taken as examples. These houses are built with high insulation standards and equipped with appliances with best efficiency standards. Furthermore, such a house may be producing some of its limited need for electricity and heat by solar collectors, fuel cells etc. Hence, the need for buying external supply of energy is limited to selected periods of time.

Challenges for the system at the introduction of high shares of renewable energy

Energy systems can be made more robust by decentralizing both power generation and control. The planning and operation of large interconnected power systems take place over a broad range of time scales, except the very shortest which are relevant at DSO level (minutes and below).The main difficulties are caused by the variability and limited predictability of power from renewable sources such as wind, photovoltaics (PV) and waves.

The lifetimes of power system components such as generating plants and transmission lines are in the range of 20–60 years. Construction takes 2–10 years, including planning procedures, which especially in the case of transmission lines can be very prolonged. The decision to build a power plant or transmission line therefore requires cash flow and socioeconomic benefits to be estimated many years ahead. These estimations involve scenarios for the future development of key parameters such as CO_2 permit prices and fossil fuel prices. In turn, it is important to estimate the future capacities and locations of renewable energy generating plants with fluctuating outputs, because they will influence power prices.

Taking wind power as an example, expected production is bid into day-ahead power markets. Bidding prices for wind power are low because the short-term marginal production costs of wind turbines are very low. In areas with large amounts of wind power, such as western Denmark[8], this lowers the day-ahead power prices to the point where wind displaces conventional production from the day-ahead market.

The large-scale introduction of fluctuating renewable energy will therefore produce market conditions which favour flexible power plants with lower investment costs than traditional base-load plants such as nuclear power.

Intra-day rescheduling can either take place through intraday markets or be organized by the TSOs. It is important to create incentives for traders to take part in intra-day rescheduling, because if they do not, the entire difference between the day-ahead production and consumption plans will have to be regulated within the operating hour – and the system may not have enough flexibility to achieve this.

Stability is essential to any energy system that is to operate satisfactorily and serve its customers adequately. Stability is a particular concern in electric power systems, which are very vulnerable if they are not properly prepared for system disturbances. Stability is essential if we are to maintain the existing high standard of electricity supply in modern power systems, with the minimum number and duration of blackouts and disturbances.

There are several reasons why power systems are particularly vulnerable. First of all, they require voltages and frequencies to remain within narrow margins, and units will trip if the limits are exceeded. Furthermore, the transmission and distribution grids suffer frequent disturbances because their huge areas create a high risk of lightning strikes and damage to overhead lines.

When renewable energy sources replace large central power plants, the inertia of the power system often falls. Fixed speed wind turbines with directly connected generators do contribute inertia, but the inertia is typically less than in conventional power plants of the same capacity. Standard variable speed wind turbines do not contribute to the power system inertia, because their rotational speeds are independent of frequency, neither does solar power (PV), simply because there is no rotating mass to provide the inertia. Due to the relatively low share of installed PV capacity this is not likely to be an issue in near future. The net effect depends on the technology used to connect wind turbines to the grid, and the number of conventional power plants that are switched off as a result. In good wind conditions, wind turbines will replace more conventional power plants, and total inertia is likely to fall.

Inertia can only prevent the frequency from falling too fast immediately after the loss of a generating unit. As the frequency changes, the speed governors in the power plants are needed to re-establish the rotor speed and consequently the frequency. Figure 3 shows this recovery process graphically: the frequency begins to drop because a power plant trips out at time t=10s. In the beginning, this is almost a linear drop, with a slope that is determined by the inertia, but as the frequency decreases, the governors respond and increase it again at t=12–15s. At t=40s , the governors have stabilized the frequency again, though still below its nominal value.

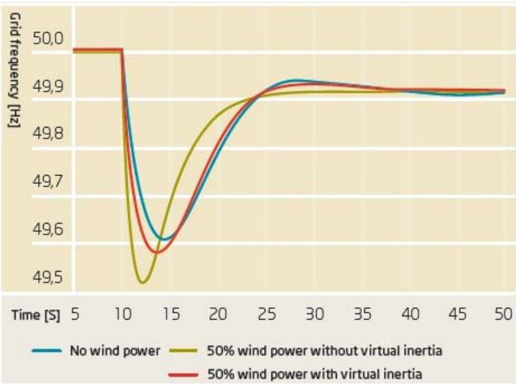


Figure 3: Simulated frequency response to loss of 5% of generation, with (a) no wind power, (b) 50% wind power without virtual inertia, and (c) 50% wind power with virtual inertia. The simulations are done with a simple pu. power system model, including governor and prime mover (turbine) dynamics of conventional generation, and dynamic wind turbine models.

When renewable generation supplants conventional central generation units with speed governors, the associated automatic frequency dependent reserves also need to be replaced. In interconnected systems, this is often not a big task, because the frequency dependent reserves are shared between the interconnected areas.

Negative reserves are generation that can be down-regulated when the frequency is too high. Negative reserves can be provided by wind turbines that down-regulate temporarily when the frequency increases. This may be a good solution, because the wind power is only down-regulated temporarily while the frequency is too high, and therefore the associated amount of lost wind power is fairly small.

Wind turbines can also provide positive reserves if they run continuously in down-regulated mode. This is a much more costly solution, however, because down-regulation continuously wastes power that could otherwise be sold. Still, in systems with very large amounts of wind power, it may be economic to provide positive reserves from wind power when wind speeds are high and electricity prices low or negative.

A more promising source of positive primary reserves is demand response. Since the frequency will normally only be low for periods of 15 minutes or so, until new fast accessible capacity (regulating power) can be brought online, equipment such as refrigerators, freezers and air conditioners can generally be switched off without significant loss of service.

The planned development of offshore wind power in northern Europe is very ambitious. Experience with large offshore wind farms in Denmark has shown that concentrating wind turbines in relatively small areas causes power fluctuations to increase significantly[9].

The infrastructure of the future intelligent energy system should support the provision of ancillary services from sources other than the central power plants. This is because the economic operation of future power systems will reduce the capacity of central power plants to remain online especially in periods with high wind speeds and low electricity consumption. Ancillary services provided by wind power plants and other renewable resources will become increasingly important as the penetration of renewable energy increases.

Characteristics of the intelligent energy system

With very high proportions of renewable energy, power balancing becomes a huge challenge. This includes not only new and reinforced transmission lines between regions and new flexible generating plants, but also the use of existing resources distributed across the power system. Though the power system has a vital role to play in the intelligent energy system, district heating and natural gas are important as well.

The predominant renewable energy resources in Denmark and northern Europe are wind power and in general, solutions based on electricity are characterized by high energy efficiency and flexibility in the use of renewable energy.

It is necessary to have reserve capacity available to provide extra regulating power at short notice. The larger the proportion of fluctuating electricity generation, the greater the need for reserves to cover periods when there is no wind and the need to handle excess electricity production when the wind is strong.

A mix of distributed energy resources is needed to allow system balancing and provide flexibility in the electricity system. Electric vehicles, electric heating, heat pumps, heat storage and small-scale distributed generation, such as fuel-cell-based microCHP, are promising options.

Information and Control Technology (ICT) will be very important to the successful integration of renewables. The benefits of distributed power systems include increased reliability of, improved power quality, the ability to defer investment in extending the grid, and greater energy efficiency e.g. through better use of waste heat. Of these drivers, reliability of service is one of the most important. More and more consumers need uninterrupted power supplies. The rapidly increasing capabilities, and falling costs of ICT open the way to two-way communication with end-users, making this one of the most important enabling technologies for the future power system.

A system based on a high proportion of renewable energy will depend on a number of support technologies that include energy storage and load management, in order to deal with the fluctuating power from renewables such as wind turbines. Such a system, in addition to the obvious benefit of providing a cleaner environment, has the advantage that it is easy to add generating capacity as required, using local energy resources. The cost of such expansion is predictable over the life cycle of the generating plant, regardless of the price fluctuations and shortages that may affect fossil fuels in the future.

One storage or flexibility option is to increase the interaction between supply and demand in what is often termed intelligent systems. This can take many forms but typically involves advanced metering coupled with end-use devices that can be turned on and off electronically depending on the supply situation in a two way communication with the suppliers. This approach lends itself well to larger cooling and heating systems where demand may be quite time flexible. It may gradually be extended to other areas and appliances as the technologies develop. In the future large fleets of electrical cars could provide storage and with intelligent charging provide flexibility. This will clearly require major and challenging restructuring of the transport sector.

Technologies aimed at ensuring flexibility, including hydrogen, pump storage, large batteries and compressed air energy storage (CAES), are necessary to balance the power system.

There are challenges on both long time scales (hours, days or longer), where both electricity demand and renewable energy supply fluctuate independently (energy management), and on short time scales (minutes to hours) where uncertainty in the prediction of renewable energy supplies leads to imbalance (power regulation and reserve). Large-scale electricity storage would be able to shift demand and supply, helping to provide balance over all time scales, and may therefore play an important role in the future intelligent power system.

Pumped hydro has been in commercial service for a long time in many countries. Compressed air energy storage (CAES)[10] is not yet used to a large extent. Several MW-scale battery systems have been developed. Halfway between conventional batteries and fuel cells are flow batteries. The drawbacks of all large-scale batteries are their large footprints and relatively high prices in terms of both power and storage capacity. However, their very fast response times make them suitable for system services such as frequency support. Using hydrogen as a storage of electrical energy suffer from the fact that storage options for hydrogen are difficult to apply in practice and that the round-trip efficiency for electricity storage via hydrogen is typically well below 50%.

Supergrids based on HVDC (High Voltage Direct Current) technology are very attractive because it offers the controllability needed to allow the network both to transmit wind power and to provide the highway for electricity trade, even between different synchronous zones. Moreover, HVDC offers the possibility of terminating inside onshore AC grids, and thus avoiding onshore reinforcements close to the coast[11].

A planned European offshore Supergrid can allow European countries to transfer energy easily between the grids of participating countries. (See Figure 4) UK, Germany, France, Belgium, Netherlands, Luxembourg, Denmark, Sweden and Ireland signed a Political Declaration in December 2009, launching “The North Seas Countries’ Offshore Grid Initiative” to cooperate on the development of offshore wind infrastructure in the North Sea and Irish Seas[12].

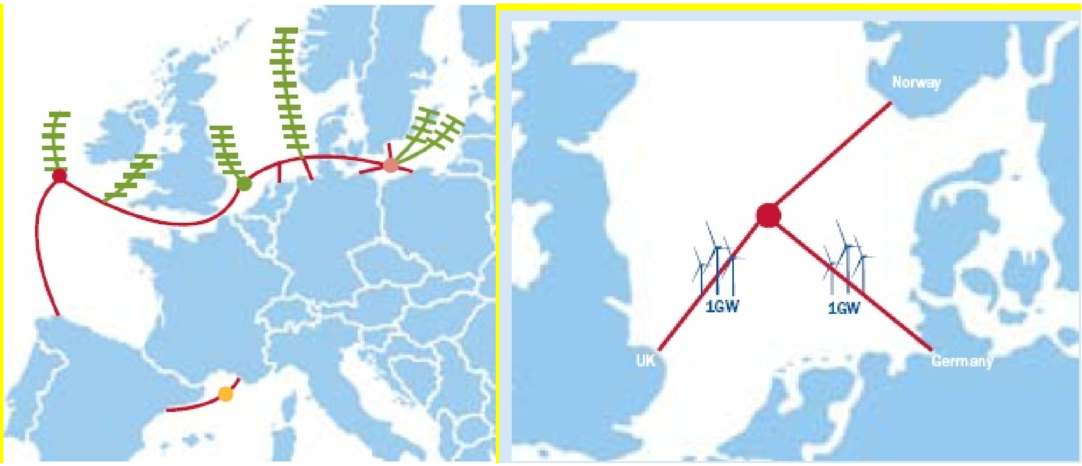


Figure 4: The SuperNode configuration could be a first step for the development of the European Supergrid. It would allow the three-way trading of power between the UK, Norway and Germany, and include two 1 GW offshore wind farms, one in the UK and one in Germany. Depending on the wind farm output at any given time, the capacity for trade would go up to 1 GW between each pair of countries in the combination[13]**.**

Interaction between supply and end use

Homes and businesses could produce electric power and heat using technologies such as fuel cells, photovoltaics, wind turbines, biomass boilers and gasifiers, micro-turbines and internal combustion engines supported by for instance energy storage systems. Excess power would be sold to the grid, and consumers could obtain from the grid power that they did not generate themselves.

The generating technologies and energy sources include wind, solar, micro-hydro, biomass, geothermal energy and wave or tidal power. These share several attributes:

- energy resources that are geographically dispersed and unevenly distributed
- energy resources that are typically intermittent, varying by the hour or the season, and not available on demand
- energy that is typically produced as electricity, rather than some other energy carrier that is easier to store. Exceptions include biomass and hydropower based on reservoirs, and
- in the electricity driven technologies, heat may be a by-product. In the same way, electricity may be a by-product in heat driven technologies.

Up to now, end-users have played only a limited role in system balancing. More active participation of distributed energy resources (DERs) in the balancing process requires the development of suitable technologies for appliances and electric vehicles.

In the future energy system end-users must contribute to maintain balance in the intelligent energy system. The demand must be highest when plenty of wind power is available and prices are low. Besides the electric cars several types of demand, such as heating and cooling equipment controlled by thermostats, can operate in a flexible way. These can be controlled without loss of consumer comfort by installing “smart” electricity meters in houses, businesses and factories, providing two-way communication between suppliers and users, and allowing power-using devices to be turned on and off automatically depending on consumer priorities and the supply situation. This requires communication standards to ensure that the devices connected to the intelligent power system are compatible, and the ability of the system to provide both scalability (large numbers of units) and flexibility (new types of units).

Electricity is traditionally billed at standard rates for each customer, with little effort to adapt consumption to suit varying conditions in the supply system. However, a combination of liberalization of electricity markets, an increase in wind power and new communications technologies have made it possible – and attractive – to develop active demand response.

In many cases, electrical systems can be balanced through delaying the demand for power by minutes or hours, instead of adding extra high-cost generation. Demand response is a voluntary reaction to dynamic electricity prices based on wholesale day-ahead prices or dynamic tariffs, which may include the cost of ancillary services.

Demand response has been demonstrated in practice at full scale[14]. Denmark, however, has only a few examples of demand response apart from demonstration projects.

Developments in ICT have made it possible to calculate, communicate and manage prices dynamically. End-users with interval meters can choose to buy electricity at spot prices. The spot price contract can also be combined with a financial contract, which sets the average electricity price before it is weighted with a demand profile.

Companies who can control the timing of their power demand, e.g., by delaying their usage by two or three hours, can reduce their electricity costs in this way. Examples of electricity use that can be timed to benefit from low power prices are processes involving heating and cooling, batch processes, and pumping in water treatment plants.

Also, some small electricity users – households and small businesses – have meters that can log hourly electricity consumption, allowing these consumers to buy electricity at spot prices. Advanced metering schemes are being developed in European countries like Italy, Sweden, the Netherlands, the UK, France, Germany, Spain, Portugal, Ireland, Finland and Norway[15] as well as in many other countries around the world. Denmark has no mandatory plan to roll out advanced meters, but individual grid companies have decided to do this for nearly half the country's electricity users. Within a few years, all these users will be able to take advantage of dynamic power pricing.

In households, direct electric heating and heat pumps are well-suited to provide demand response, because of the thermal inertia of buildings. In demonstration projects, switching off electric heating for up to three hours has been shown to cause few comfort problems[16].

Several studies have analyzed the value of demand response [17,18]. The fact that hydro power accounts for half of all electricity in the Nordic system means that prices in Norway and Sweden remain quite stable over days and weeks and this reduces the incentive for demand response. Price variation is much larger in Germany, while in Denmark the situation is somewhere in the middle. More wind power is likely to increase the price variation, signalling the need for an active demand side.

Supplying energy for transport via the power grid has several advantages such as increased flexibility through closer links between the power and transport sectors, increased energy efficiency, and the chance to include transport-related greenhouse gas emissions in carbon trading schemes. The transport sector in this respect cover intercontinental sea transport, passenger air transport, private car transport, road based freight transport.

The Danish Case

Since the beginning of 1990s Denmark has considered the problem of Climate Change to be one of the important driving factors behind the Danish energy policy and therefore strong measures for improving energy efficiency and implementing energy conservation measures were adopted alongside with continued efforts to develop and implement carbon-efficient technologies such as cogeneration and wind power. Being a member of The European Union this development is driven both by national and EU policies.

The Danish energy system has three main characteristics:

- Denmark has a very diversified and distributed energy generation based upon three major national grids; the power grid, the district-heating grid and, finally, the natural gas grid. The combined utilisation of these grids has implied that Denmark has a highly efficient supply system with a high share of combined heat and power.
- Renewable energy technologies – especially wind power – play a large and increasingly important role in the Danish energy system. At present 20% of the Danish power needs are supplied by wind power and Denmark is the global front-runner in the development of offshore wind farms. It is envisaged that wind power by 2025 will cover more than half of total power production in Denmark[19].
- Geographically, Denmark is located on the border between the European continent and the Nordic countries, and consequently acts as a kind of "buffer" between the Nordic and the European energy systems. As member of the Nordic power exchange, Nord Pool, Denmark has extensive power trade with Germany but also a considerable transit of power between the continent and the other Nordic countries. Also the Danish natural gas grid connects Sweden with Germany.

As the only country in the EU Denmark is a net exporter of energy. In 2008 production from the Danish oil and natural gas fields in the North Sea exceeded the Danish gross energy consumption by approx. 75 % - that is, Denmark produced 75% more than domestic total energy needs. At the same time Denmark has for a period of more than 20 years succeeded in keeping gross energy consumption at an almost constant level although gross national product in the same time period has increased by more than 80%. (See Figure 5) Thus in general combining the above-mentioned issues imply that Denmark has an energy situation far better off than most countries in the EU.

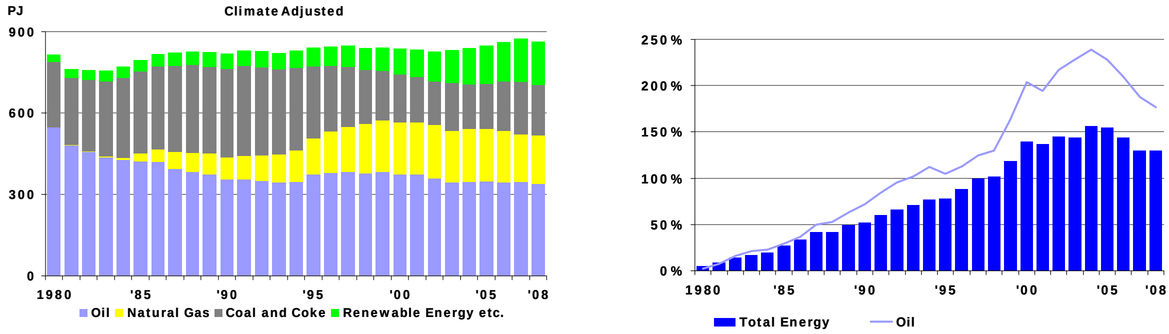


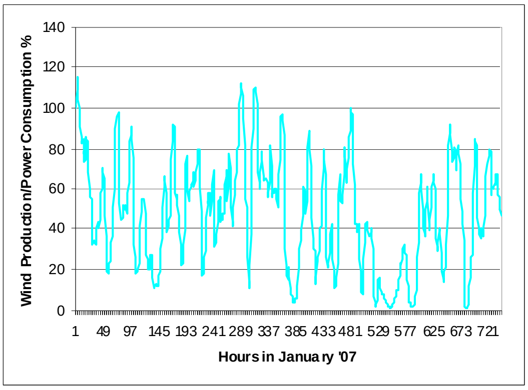
Figure 5: Development of Danish gross energy consumption by fuel (left). The Danish degree of Self-sufficiency (right). Source: Danish Energy Agency.

Nevertheless, also Denmark is facing a number of challenges, some of them in line with the EU in general, some specific for the Danish system:

- Oil and gas production peaked in 2005 and will gradually decrease to a level below domestic consumption, thus increasing the vulnerability of the Danish energy supply. To mitigate the increasing dependency on imported fossil fuel resources, the Danish Government has established the Climate Change Commission with the main responsibility to come up with policy measures to phase out the use of fossil fuels within the next 50 years. These measures will also be vital in the Danish Climate Change policy to reduce Danish emissions of greenhouse gases.
- Combined heat and power production utilised in combination with an extensive district heating system is the corner stone in the highly efficient energy system in Denmark. However, utilising small scale CHP-plants have exploited the heating market to the limits and further expansion potentials are limited.
- Denmark has the highest share of wind power in the world, 20% of total power supplied by wind turbines. Aiming at a higher share integration into the power system requires innovative and advanced solutions.
- As the only sector in Denmark, the transport sector is increasing its use of energy. A major challenge in the future will be to replace fossil fuels in the transport sector by renewable sources.

Thus, new policies are required which - relying to an increasing degree on renewable sources - are going to change the Danish (and European) energy systems radically within the next decades. Energy technologies based on variable sources, especially wind power but to a more limited extent also wave power and photovoltaics, are expected to have a large role to play in the future energy supply. In Denmark wind power is by 2025 expected to supply 50% of Danish electricity consumption implying that occasionally wind power will produce as much as twice the power normally needed in the Danish system. Certainly this is a challenge that not only will require significant changes in the energy system structure, but also necessitates the development of intelligence within the system.

Being a member of the Nordic power exchange, NordPool, comprising Denmark, Sweden, Norway and Finland, Denmark has strong interconnectors to its neighboring countries. This facilitates the integration of wind power where in the Western part of Denmark[20] the share is as high as 25% on average. This implies that from time to time wind power covers more than 100% of the power consumption in Western Denmark (see figure 5). In the latest Energy plan the Danish government plan a doubling of the capacity by 2025 from the present 3100 MW to 6200MW, offshore wind farms contributing substantially to this increase. However, at present the spot market is pressed to the limit when plenty of wind power is in the system (see Figure 6). Therefore a share of 50% of wind power in the Danish power supply will necessitate a much deeper integration of wind power in the energy system.



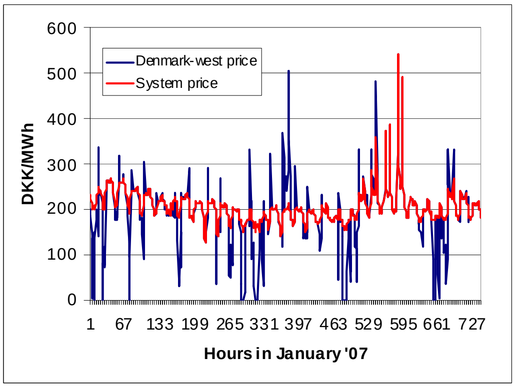


Figure 6: Left: Wind power as percentage of power consumption in Western Denmark and right: Spot prices for the same area and time period.

Energinet.dk together with Vattenfall Europe Transmission are investigating the feasibility of constructing an offshore electricity transmission grid simultaneously linking together the electricity grids of two countries and connecting two countries' offshore wind turbines at Kriegers Flak with the electricity grids on land. Kriegers Flak could become the world's first international offshore wind farm electricity grid with cables for exchanging electricity between Denmark and Germany[21].

The combined utilization of the three grids - the power grid, the district heating grid and the natural gas grid - has implied that Denmark has a highly efficient supply system with a high share of combined heat and power. The future increased production of renewable energy, primarily wind energy, must interact as effectively as possible with these grids to maximise displacement of fossil fuels in the electricity, heat and transport sectors. To achieve this flexibility will be key.

The problems of integrating variable sources interact closely with the long-term development of the power system, including solutions that may benefit not only integration of wind power but also the operation of the total system. The challenges posed by variability are currently receiving considerable attention by Danish research institutions. The combination of having the highest share of wind power and being a small country where demonstrations more readily carried through makes Denmark an attractive place to develop technologies, systems and markets to facilitate large scale deployment of wind power.

Electric vehicles can become a major asset to the Danish energy system and to the vision of integrating larger amounts of renewable energy. The combination of large-scale wind power expansion and increased use of electric vehicles forms a win-win solution for the energy system. EVs can act as storage devices for smoothing power fluctuations from renewable resources, and can provide other services valuable to the reliable operation of the power system. EVs that can discharge to the grid, as well as charging from the grid, are said to have vehicle-to-grid (V2G) capability, otherwise known as intelligent bidirectional charging. By helping to make up shortfalls in conventional generating capacity, V2G could add a great deal of flexibility to the power system

and reduce excess supply of power significantly.

Three possibilities of charging exist:

1. *Simple charging – no intelligent interaction between electric vehicles and the power system.*
2. *Intelligent charging – intelligent interaction between electric vehicles and the power system.*
3. *Intelligent charging and discharging – using the electric vehicle as a storage facility in the power system.*

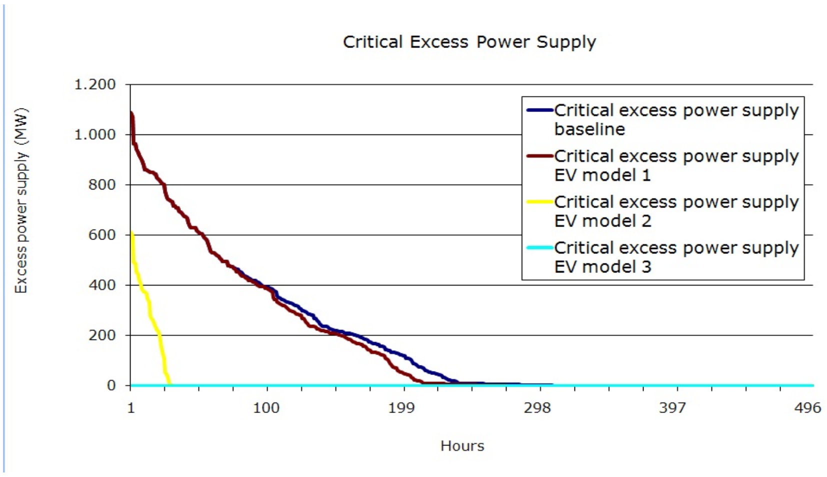


Figure 7: Excess supply of electricity in the three charging cases (see above). Source: Energinet.dk

These three cases have significantly different influences on the Danish power system. This is illustrated in figure 7 where the excess supply of power is shown in all three cases. As shown the intelligent charging case reduces excess supply significantly, while excess supply of power is eliminated in the case where not only charging is intelligent but also the electric vehicle is used as a storage facility in the power system.

There are various solutions to the design of this interaction. At present a number of Danish projects are researching and developing the possibilities of the electric vehicles as an integrated part of the power system:

- **E**lectric vehicles in a **D**istributed and **I**ntegrated market using **S**ustainable energy and **O**pen **N**etworks (Edison) was launched last year as a partnership between eight parties, among these the Danish Energy association (project leader), DONG Energy and Risø DTU. The main aim of the project is to develop the infrastructure for electric vehicles, including communication systems for charging

- The Danish company DONG Energy has invested large means in project Better place. The aim of Better Place is to develop the infrastructure and intelligent network to deliver a range of services to drivers, enable widespread adoption of electric vehicles, and optimize energy use. Better Place has operating companies in Israel, Denmark, and Australia.

- ChoosEV is a EV company with the aim to supply electric vehicles, charging stations, financing, management, consulting and environmental optimization in relation to electric vehicles and infrastructure. The Shareholders are the electric utility companies Syd Energi and SEAS-NVE together with the car rental company Sixt.

Summary and main conclusions

The world is facing huge challenges in the long term with regard to energy supply, climate change and security of supply. These challenges are at present deepened by the current financial crisis, which have significant impacts on almost all countries. Climate change issues, security of supply and economic development need to be pursued concurrently.

Today's energy system is the result of decisions taken over more than a century. This long-term development is reflected in the structure of the energy system, which in most cases was developed according to basic engineering requirements: energy is produced to meet the needs of consumers. However, a new supply structure must be developed for a future where non-fossil fuels have taken the lead and have become the dominating supply options and at the same time end-use technologies have become highly efficient and end-use and supply have become closely interlinked through intelligent energy systems. Renewable energy sources, which at one time occupied an almost insignificant niche, must gradually expand their role in this global energy system. Such a future energy system will require a much more flexible energy system, also including the flexibility of the energy consumers.

In the middle of this century flexible and intelligent energy system infrastructures shall first of all be able to:

- Effectively accommodate large amounts of fluctuating renewable energy and let the end-user interact with the supply through advanced ICT.
- The second important characteristic is intelligent integration of the transport sector, i.e. intercontinental sea transport, passenger air transport, private car transport and road based freight transport.
- The third key area is advanced energy storage facilities in the system and the introduction of super-grids.

Denmark has the highest share of wind power in the world, 20% of total power supplied by wind turbines. Aiming at a higher share e.g. 50% integration into the power system requires innovative and advanced solutions. As the only sector in Denmark, the transport sector is increasing its use of energy. A major challenge in the future will be to replace fossil fuels in the transport sector by renewable sources by the introduction of electrical cars, biofuels and synthetic fuels based on non-fossil sources. Thus, new policies are required which going to change the Danish (and European) energy systems radically within the next decades.

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