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Risø Energy Report 4

The Future Energy System
– Distributed Production and Use

Edited by Hans Larsen and Leif Sønderberg Petersen

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1 Preface

The coming decades will bring big changes in energy systems throughout the world. The systems are expected to change from central power plants producing electricity and maybe heat for the customers to a combination of central units and a variety of distributed units such as renewable energy technologies or fuel cells. Furthermore the following developments are expected:

- closer link between supply and end-use
- closer link between the various energy carriers distributed through grids such as electricity, heat, natural gas and maybe hydrogen in the future
- increased energy trade across national borders

Risø Energy Report 4 is the fourth in a series of reports covering energy issues at global, regional and national levels. This report covers the future of energy systems over the next 20–30 years. It deals with sustainable energy in general, but pays special attention to system aspects and the distribution of energy through grids such as those used for natural gas, electricity, district heating and hydrogen. The focus is on industrialised countries, but the report also deals with specific points relevant to developing countries, such as isolated energy systems. The transport sector is discussed only in the context of its use of energy supplied through the various grids.

Individual chapters of the report have been written by Risø staff members and leading Danish and international experts. The report is based on internationally recognised scientific material, and is fully referenced and refereed by an international panel of independent experts. Information on current developments is taken from the most up-to-date and authoritative sources available.

Our target groups are colleagues, collaborating partners, customers, funding organisations, the Danish government and international organisations including the European Union, the International Energy Agency and the United Nations.

2

Summary, conclusions and recommendations

HANS LARSEN AND LEIF SØNDERBERG PETERSEN, RISØ NATIONAL LABORATORY, DENMARK

Summary

The world is facing major challenges in providing energy services to meet the future needs of the developed world and the growing needs of developing countries. These challenges are exacerbated by the need to provide energy services with due respect to economic growth, sustainability and security of supply.

Today, the world's energy system is based mainly on oil, gas and coal, which together supply around 80% of our primary energy. Only around 0.5% of primary energy comes from renewable sources such as wind, solar and geothermal. Despite the rapid development of new energy technologies, the world will continue to depend on fossil fuels for several decades to come - and global primary energy demand is forecasted to grow by 60% between 2002 and 2030.

The expected post Kyoto targets call for significant CO_2 reductions, increasing the demand to decouple the energy and transport systems from fossil fuels. There is a strong need for closer links between electricity, heat and other energy carriers, including links to the transport sector.

On a national scale Denmark has three main characteristics. Firstly, it has a diverse and distributed energy system based on the power grid, the district heating grid and the natural gas grid. Secondly, renewable energy, especially wind power, plays an increasingly important role in the Danish energy system. Thirdly, Denmark's geographical location allows it to act as a buffer between the energy systems of the European continent and the Nordic countries.

Energy systems can be made more robust by decentralising both power generation and control. Distributed generation (DG) is characterised by a variety of energy production technologies integrated into the electricity supply system, and the ability of different segments of the grid to operate autonomously. The use of a more distributed power generation system would be an important element in the protection of the consumers against power interruptions and blackouts, whether caused by technical faults, natural disasters or terrorism.

In an electricity supply system containing a large proportion of distributed small-scale generating units, these units need to play their part in providing system services such as stability, security of supply and power quality. This places new requirements for control and regulation on the generating units, the communication links between the units and the system as a whole. It is likely in the future that many consumers will have intelligent energy management systems based on two-way communication with energy suppliers. This will facilitate online pricing and other demand-led methods of balancing supply and demand.

Energy carriers such as hydrogen and ethanol may become important as interface for renewable energy sources to mobile users. About 20% of global primary energy is currently used for transport, and this fraction is increasing.

It is possible to reduce end-use energy consumption by 20-50% over a twenty-year period through efficiency improvements.

Conclusions

Global energy challenges require new long-term solutions, such as future energy systems based on renewable and other non-fossil sources, and more energy efficient end-use. Closer links are required between electricity, heat and other energy carriers, including links to the transport sector and the future use of biofuels and hydrogen. There is also a need for closer links between supply and end-use. A possible and quite promising solution may be to base future energy systems on more distributed production and use. Such a system should have the following characteristics:

- Increased robustness through decentralisation, allowing segments of the grid to be operated autonomously.
- Distributed production combined with intelligent end use.
- New information and communication technologies (ICTs) to provide system control that is distributed, self-organising and self-healing.
- Utilise developments in ITC to create control systems that are distributed and with a higher level of intelligence.
- Exploitation of the potential to reduce end-use energy consumption by 20–50% over a twenty-year period through efficiency improvements such as "passive" houses and new lighting technologies.

Seen as a whole, many of the necessary elements in a development towards distributed systems are available now, the future task lies in combining these elements and implement them in the energy system.

Recommendations

The Danish energy system is to a large extent diversified and distributed and renewable energy technologies play an increasingly important role. This offers the possibility to become an international key player in the development of future energy systems. Danish research

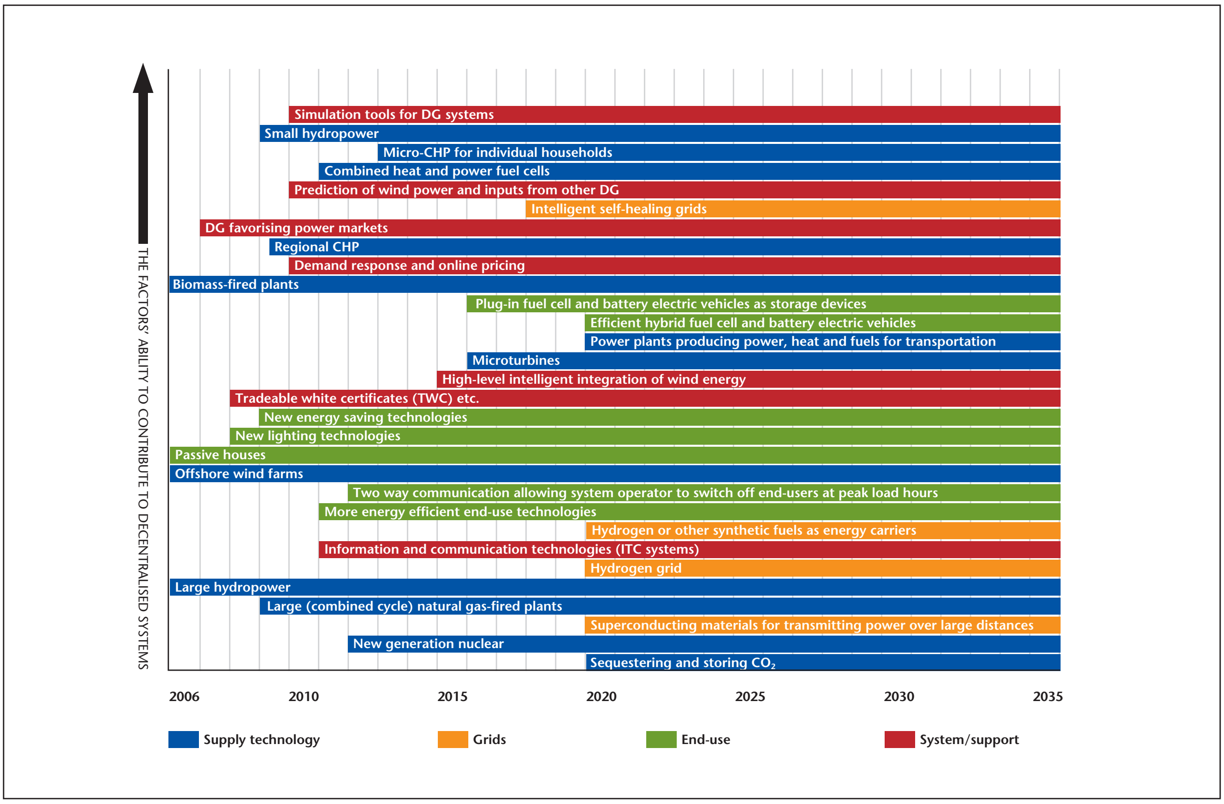

Figure 1: Qualitative estimate of the time frame for introducing factors, systems and technologies contributing to the future energy systems into the market on a commercial scale.

communities and Danish industry have a good basis for becoming a key player world-wide in this development.

A prerequisite is that Danish research should focus on selected technology and system components, and take part in demonstration projects at European and global levels. Another prerequisite is to exploit the unique position of Denmark between the Nordic countries and the rest of Europe.

Denmark has the necessary research and industrial competences to become a key player in the following areas of research and industrial development:

- micro-CHP (combined heat and power) plants based on reversible fuel cells
- future wind power plants
- polymer-based solar cells
- biofuels for the transport sector
- hydrogen technologies (in the long term)
- highly efficient lighting and passive houses
- ICT-based systems for monitoring and control of energy consumption and communication between units
- simulation tools for distributed systems; and
- standards, procedures and techniques for the design, testing and certification of distributed generation systems.

To initiate and speed up the Danish key-player role, investments in R&D and subsequently in demonstration projects are needed to ensure that the technologies and systems are ready for the marketplace in the timeframes required.

To support this development some elements of a future Danish energy policy could be:

- Raising the percentage of renewable energy over the coming decades to make a major contribution. It is particularly important to increase the share of renewable energy in the electricity system and the transport sector.
- Stimulate efficiency improvements by technological developments that have not yet been carried out. In a number of areas, R&D investments can give a high payback.
- Efficiency improvements will be limited if they rely on ordinary market forces. Some efficiency improvements may require regulatory measures. Others may need economic incentives introduced through political action.

Hence, focused R&D combined with suitable regulation and market incentives could allow Denmark to increase its current leadership in sustainable energy systems. We recommend collaboration between politicians, researchers and industry to exploit these opportunities.

3

International trends and scenarios for future energy systems

PER DANNEMAND ANDERSEN AND STEFAN KRÜGER NIELSEN, RISØ NATIONAL LABORATORY, DENMARK

Introduction

In evaluations of long term energy forecasts made in the past the conclusion often is that a large number of the forecasts, projections, predictions and associated policy recommendations turn out to be inaccurate or even mistaken. On the other hand we can learn from errors made in the past and try to avoid these in our present use of forecasts and foresights. In the preface of this report we state that “this report is based on internationally recognised scientific material”. One key observation in a recent evaluation of long term energy forecasts made over the latest 50 years was that *“some of the most egregious forecasting errors have often been made by the smartest people, working for the most prestigious organisations, with the most money”* [6].

The reasons for making long term scenarios are often misunderstood or simplified. Scenarios are often put in three categories: prediction, exploration and anticipation. Predictive scenarios aim at describing the most likely future and generally involve forecasting current trends into the future creating the best possible images of the future. Explorative scenarios aim at describing a number of plausible futures which can be possible, desirable/feared and/or realizable and start out from present trends leading to equally likely futures. Anticipative or normative scenarios are build on the basis of desirable or feared visions about the future. Quite often the long term energy scenarios contain elements of all three approaches. One important lesson learned is that prospective energy studies often reflect the basic values or hopes of the authors. They are not only meant to give the best prediction of the future but also to initiate debate today or even promote visions. Such basic considerations and preconditions are not always clearly stated even in internationally recognised scientific material.

With these challenges in mind, the aim of this chapter is to examine what we can expect of energy sources, technologies and systems in the next global economic cycle and beyond. Specifically, it covers energy demand, energy sources, key energy technologies, and the overall energy system.

Energy and global economic cycles

Energy systems are often seen as one of the main indicators of the global economy. The industrialised economies of the world show two types of economic cycle: short (five to ten years) and long (50–60 years) [1]. Over the past couple of centuries, the same “long waves” have often been noticeable in primary energy sources, energy systems and technological innovations as well as in the economy as a whole [7]. See Figure 2.

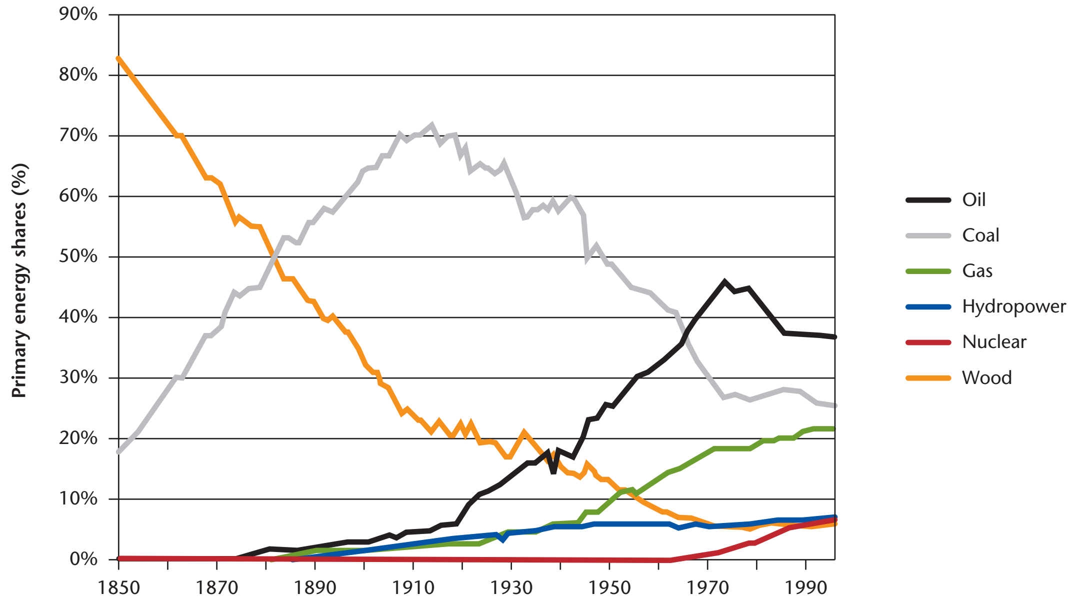

Figure 2: Global primary energy use 1850-1995. Source Grübler, 1998.

Before the Industrial Revolution, wood was the main source of energy. Industrialisation followed the invention of the coal-powered steam engine, which was used in factories and mobile applications such as trains and ships. For two cycles of the world economy the icons were coal, steam engines and steel production.

The next cycle came with the transition from coal to oil as the main source of energy. This was accompanied by new energy system technologies such as the electricity supply system and the road transport system, the latter featuring vehicles powered by internal combustion engines. We are now said to be between the fourth and fifth long waves of the world economy, with the latest period of decline characterised, if not created, by the oil embargoes of the 1970s. According to this theory, the world economy should now be heading towards a period of more stable growth in the decades to come. Also following this theory the world economy goes from a phase characterised by product innovations in existing industries and the creation of new industries to a phase characterised by process innovation in existing industries and in basic sectors such as the energy sector. This indicates that the new energy technologies introduced to the energy sector over the last 20 years (wind turbines, micro gas turbines, fuel cells, information and communication technologies, etc.) will massively be integrated in the energy sector in the decades to come. This will lead to industrial learning and the move down the learning curve for these technologies. On the other hand we can generally expect fewer completely new energy innovations in the decades to come.

Energy demand

Global energy demand has risen substantially over the last two centuries and is expected to grow in the decades to come. But among the world's nations there are large variations in energy service levels, energy demand and energy production systems due to differences in economies, geographic conditions, technological trajectories and lifestyles. Energy demand depends on the level of industrialisation and the types of industries in the countries concerned, as well as on geographically-defined heating needs and individual lifestyle choices: diet, number and types of electrical appliances and vehicles, dwelling sizes, commuting distances, transport systems and so on. Per-capita energy demand is currently especially low in developing countries, but this will change. The International Energy Agency (IEA) projects that developing countries will account for two-thirds of the increase in global energy demand in the coming decades.

Primary energy sources

The world's energy system is currently based mainly on oil, gas and coal, which together provide around 80% of primary energy. Biomass and waste account for 12%, nuclear power 7%, hydropower 2%, and only around 0.5% comes from other renewable energy sources such as wind, solar and geothermal [2].

Different internationally recognised organisations present various forecasts for the future consumption. The IEA forecasts in a so-called *reference scenario* that consumption of primary energy will grow by more than 60% in the period 2002–2030 (Figure 3). Fossil fuels are expected to account for some 85% of this increase.

Energy scenario studies often concentrate on the future of nuclear energy and fossil fuels: coal, oil and natural gas, plus the longer-term prospects of producing oil from tar sands and extracting natural gas trapped in hydrates beneath the oceans. Fossil fuels and nuclear energy both

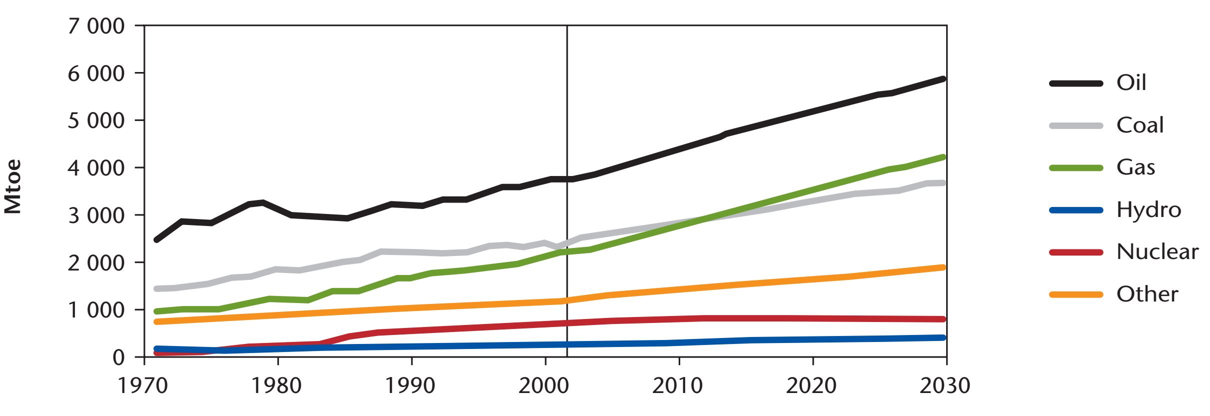

Figure 3: World primary energy demand projection to 2030, according to the IEA reference scenario. Source: International Energy Agency, 2004: 60.

face environmental challenges - fossil fuels because of their contribution to emissions of greenhouse gases, and nuclear power because of the problem of long-term storage of nuclear waste - but these may not be insoluble. Coal may become an environmentally-acceptable fuel, for instance, if we can find ways to use it more efficiently and to remove and store the CO_2 produced when it burns.

Other contributions focus on the long-term vision of energy production systems based on renewable sources, energy-use technologies that are more efficient than those of today, and the use of hydrogen or other synthetic fuels as energy carriers [5].

For the next cycle of the world economy, the primary energy source is often forecasted to be natural gas. We find it more likely that the future will bring more variety in the mix of energy sources: renewable and nuclear energy as well as gas, oil and coal. At least in the longer term. In any case natural gas will play an increasing role in the decades to come.

The issue of primary energy sources is closely related to those of climate change and geopolitics. By 2030, the IEA expects global emissions of CO_2 from fossil fuel combustion to have grown from their current level of around 24 billion tonnes to 38 billion tonnes (in the "reference scenario") or 32 billion tonnes (in the "alternative scenario")[1]. Many industrialised countries have signed the United Nations Framework Convention on Climate Change. Some of these countries have also signed the follow-up Kyoto Protocol which obliges them to reduce greenhouse gas emissions in the period up to 2012. Targets beyond 2012 have not yet been agreed on, but the whole process could have big consequences for future primary energy source mixes and key energy technologies.

Another important point is that inter-regional flows of oil and gas are expected to change considerably over the next decades. The reason is that most of the world's remaining proven conventional reserves of natural gas and oil are far away from the regions of greatest energy consumption: the OECD countries and the rapidly growing economies of Asia and Latin America.

The former Soviet Union and the countries of the Middle East hold more than 70% of the world's gas reserves, while the Middle East is also thought to possess more than half of global oil reserves. In the OECD countries, domestic oil and gas production is generally declining, while demand for oil and gas is growing rapidly.

As a result, by 2030 inter-regional trade in oil is projected to double, and inter-regional trade in gas to triple. In most consuming countries, dependence on imports will rise correspondingly. The EU–25 countries currently import 76% of their oil and 49% of their natural gas. The corresponding figures for 2030 are projected to be 94% and 81% respectively (IEA Reference Scenario).

In Denmark, domestic natural gas and wind power are likely to become more important as energy sources in the coming decades. Wind turbines currently produce around 20% of Danish electricity needs, and this can be expanded to 50% at reasonable cost. The use of modern biomass technologies may increase in the future depending on political decisions in these years. In the longer term photovoltaics might become viable even in Denmark, although this remains highly uncertain.

Today Denmark is a net exporter of oil and gas. North Sea oil and gas resources will remain important in the years to come, but production is expected to peak within a decade or two - although new technologies might extend the production period.

Looking further into the future, rich offshore oil (and gas) resources may be found south-east of the Faeroe Islands and west of Greenland. This has raised the question of sovereignty for these regions, which are autonomous parts of the Kingdom of Denmark. Also significant in this context is Denmark's claim to the area north of Greenland and the geographical North Pole.

Nuclear energy is generally not seen as a realistic option for Denmark in the foreseeable future.

As a small country of low energy intensity, located between the electricity and natural gas system of the Scandinavian Peninsula and continental Europe, Denmark has the opportunity to serve as buffer zone between the energy systems of its neighbours. Thus, energy (electricity and gas) trading is likely to become a key feature of the future Danish energy system.

Energy systems

Over time, complex socio-technical systems have built up around the energy supply structure. The energy system has altered over time as a result of technological innovation and various social, economic and environmental changes.

The term "energy systems" is often associated with electric power. Initially the production of electricity was based mainly on coal, but hydro, oil, natural gas and nuclear energy have subsequently been introduced on a large scale. Following the oil crisis of the 1970s, natural gas increased its market share and energy came to be generally used more efficiently, both in electricity generation and in end-use applications. Expansion of nuclear generating capacity has stopped in many countries, due to a lack of public acceptability that has been reinforced

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[1] The Reference Scenario is based on a set of explicit assumptions about underlying macroeconomic and demographic conditions, energy prices and supply cost, technological developments and government politics. Possible, potential or even likely future policy initiatives are not included.

The Alternative Policy Scenario differs from the Reference Scenario by assuming that OECD countries will adopt a range of new energy and climate related policies and that there will be a faster deployment of new energy technologies.

by several major accidents. Environmental technologies have been developed to clean up the exhaust gases from fossil fuel combustion.

An important question is whether the future electricity system will become more decentralised or continue to be based mainly on large power stations. To a large extend the discussion reflects differences in commentators' opinions on which energy resources and technologies are best in terms of technology, environmental performance, society and the economy.

Some energy analysts envisage a future based on advanced large-scale facilities producing clean energy carriers such as electricity, hydrogen and methanol. The primary energy sources will be coal with CO_2 sequestration, nuclear fission, and - in the longer term - nuclear fusion.

Other energy analysts, including us, see a window of opportunity to begin the creation of much more distributed electricity generation systems. In this picture, vehicles would be based on hybrid fuel cell/battery technology, and many households would use stationary natural gas or even hydrogen fuelled fuel cells to generate combined heat and power. The electricity supply system, which would become fragmented and distributed, would get its power from wind turbines, gas fuelled microturbines, photovoltaics and biomass burners.

These distributed power sources might possibly be connected to a "smart grid" linking a number of self-optimizing micro-grids. Each micro-grid would incorporate real-time information systems to ensure that energy production matches demand at all times.

A few visionaries have even suggested that fuel cell and battery electric vehicles could serve as energy storage devices. By storing off-peak electricity in batteries, or off-peak hydrogen in fuel tanks, these vehicles could then deliver electricity back to the grid during peak load periods. In any case attempts to integrate energy use in the transport sector with other energy demands (electricity and heat) can be expected.

Advanced end-use technologies could also be controlled via the internet. This would allow system operators to smooth out demand curves by switching off non-urgent energy users during periods of peak demand, or when intermittent energy sources are not available.

Furthermore, in the aftermath of 11th of September 2001 and hurricane Katarina's flooding of New Orleans analysts have suggested that distributed energy systems might be less vulnerable to terror actions and natural disasters. On the other hand decentralised energy systems might have different types of vulnerability (i.e. computer virus spread through the internet). This is not yet fully analysed.

Factors encouraging distributed energy systems are:

- the ongoing liberalisation and restructuring of energy markets together with the increased role of private capital/finance will promote power production in smaller units and a more decentralised structure
- new energy technologies such as fuel cells and modern bioenergy are more appropriate for distributed than for centralised energy systems
- information and communication technologies that will help distributed systems to regulate themselves.

For a considerable number of industrialised countries, it is often cheaper to increase the efficiency of energy end-use, and to find ways of matching demand more intelligently to supply, than it is to expand generation, transmission and distribution capacity. Some analysts go even further, suggesting that discussions on the future of energy systems should consider changes not only in technology but also in values, social organisation and lifestyles.

Uncertainties over future energy systems

As mentioned in the introduction of this chapter, the uncertain nature of energy forecasting has been explored in several studies comparing forecasts to actual events. Many forecasts over the last 50 years have underestimated the availability of fossil fuel resources, while over-estimating both the price of oil and the rates at which the cost of renewable energy and other distributed energy sources will fall [6]. In addition, the inertia of the current energy system (especially the infrastructure) has not been accounted for to a sufficient extend. As a result, the forecasts have over-estimated the take-up rate for alternative energy.

Forecasts often rely heavily on expectations that "magic bullet" technologies or changes in lifestyle will solve problems such as greenhouse gas emissions and the depletion of oil reserves; in other words they focus on what is technically feasible instead of what is likely. Forecasts may be influenced by contemporary events and politics, and they are generally biased towards the interests of the person or organisation conducting the study. A key uncertainty is the point in time at which growth in the demand for oil and gas will exceed growth in production capacity; although this date is central to many forecasts, we really have little idea how much oil and gas can be recovered, and at what prices.

The pace at which new technologies are introduced is also a big source of uncertainty. Long-term energy scenarios indicate that radical social and technical changes are needed if we are to reduce our reliance on fossil fuels. An example is the replacement of petroleum road transport fuels with hydrogen fuel cells or battery electric vehicles. Such a shift would require major changes in vehicle technology and in systems for producing and distributing energy, and it is very hard to predict when these changes will happen.

Studies of the links between lifestyle and energy consumption, and of how radical new technologies are developed and adopted, show how social and technical barriers can control the time it takes to bring new technologies to market, or prevent them from being adopted at all.

Energy forecasts should probably not rely on expectations of quick changes in lifestyles or radical socio-technical changes; they should not underestimate the inertia associated with policies designed to influence lifestyles and socio-technical systems.

The example of wind turbines shows that new energy technologies often succeed only with the help of specific policies and incentives set up to establish new markets and promote technical innovation. Experience suggests that new energy technologies require timescales of 20–30 years or even longer between prototyping and widespread adoption. However, it is possible that in liberalised energy markets, changes could happen much faster - at a rate similar to the adoption of, say, mobile phones or digital cameras. Though, adoption of natural gas fired turbines might be an example, we simply do not know at the moment.

Energy R&D

Government-backed energy R&D is essential if radical changes in the energy system are to be achieved. However, government investment in energy R&D in Europe and the US has generally decreased in recent decades; in Japan, government spending on energy R&D has remained stable, or even increased, over the same period. Japan now contributes more than 40% of the total spending on energy R&D across all IEA member countries; the corresponding figure for the US is around 33 %, and 20 % for the EU-15.

Differences in government expenditure on energy R&D often reflect countries' energy policy priorities. The US, for instance, focus on generic energy technologies plus energy conservation. Japan maintains a large nuclear power programme, and also focuses increasingly on energy conservation. European countries carry out significant, though decreasing, amounts of nuclear power R&D, and attach relatively high importance to renewable energy, electricity and energy storage.

On this basis we might expect that Europe would lead the transition to more dispersed energy systems, with higher contributions from renewable sources, and that Japan would take a very different approach to future energy systems.

Conclusion

Even though the future often is hard to foresee, this chapter has tried to distinguish between foreseeable trends and key uncertainties when probing the future of energy systems. Most authorities agree on a small number of foreseeable trends:

- global growth in energy consumption
- restructuring of energy producers, markets and organisations
- environmental concerns as a major driver for energy policy in many industrialised countries
- economic development and access to energy as the main drivers for energy policy in developing countries and the high-growth economies of Asia and South America; and
- energy systems in Europe and other larger regions are expected to become more “dispersed”.

Previous “long waves” in the global economy have been based around single, dominant energy sources: first wood, then coal, then oil. The coming decades will bring an increased role for natural gas but also more variety in energy sources and technologies.

A number of other drivers are just as important as those above, but are less predicable:

- price trends for coal, oil and gas
- geopolitical competition for the oil and gas resources of the Middle East and Russia, between on the one hand the “old” energy-importing countries of Europe, North America and Japan, and on the other hand the “new” energy-importing countries of Asia and Latin America
- the role of climate issues in energy policies; and
- the pace of technological change in restructured and more commercially-oriented energy markets.

4

Denmark in a European market

POUL ERIK MORTHORST, RISØ NATIONAL LABORATORY, DENMARK. AKSEL HAUGE PETERSEN, DONG, DENMARK. FLEMMING NISSEN, ELSAM, DENMARK. AIDAN CRONIN, VESTAS, DENMARK.

Known abroad for being a country with highly efficient coal-fired power plants, Denmark has also for more than a quarter of a century taken an environment-friendly position on energy. Since the beginning of the 1990s climate change has been an important driver for Danish energy policy, and as a result the country has taken a robust approach to improving energy efficiency and developing carbon-efficient technologies such as cogeneration and wind power. Alongside the rest of the EU, Denmark ratified the Kyoto Protocol in 2004 and is committed to reduce its greenhouse gas emissions by 21%, relative to 1990, during the period 2008–2012. The corresponding reduction across the EU as a whole will be 8%. However, owing to the high proportion of coal in the power industry Denmark is also amongst the largest emitters of CO_2 per capita in the EU.

In a European context, Denmark's energy system has three main characteristics:

- We have a very diversified and distributed energy system based on national grids for electricity, district heating and natural gas. The combination of these three grids implies an efficient energy supply system with a high proportion of combined heat and power.
- Renewable energy, especially wind power, supplies a large and increasing fraction of Denmark's energy. At present almost 20% of Danish electricity needs are supplied by wind power and Denmark is the global front-runner in offshore wind farms. In the Danish government's recent Energy Strategy 2025, the baseline scenario forecasts that renewable sources will provide more than one-third of Danish power by 2025 [2].
- Denmark's geographical location between continental Europe and the Nordic nations allows the country to act as a buffer between the energy systems of these two regions. As member of Nord Pool, the Nordic power exchange, Denmark facilitates electricity trading between Germany, other continental European countries and the rest of Scandinavia. The Danish natural gas grid links Sweden with Germany.

The Danish energy sector is currently undergoing big changes as companies expand to face competition at European level. The power companies Elsam and Energy E2 are merging with natural gas supplier DONG to create a single giant energy company. The second-largest player in the Danish energy market will be Swedish power company Vattenfall, which has recently bought several power stations in Denmark.

Yet even when individual companies supply energy from multiple sources, each source brings its own technological challenges. The following sections therefore deal separately with Danish developments in conventional electricity, natural gas and renewables, especially wind power.

Denmark's role in the European power sector

The existing European power system is developed as a result of conditions which differ from those that will apply in the future. Historically, national electricity monopolies were able to make long-term investments without significant financial risk, and so create power systems based as much as possible on national resources. National technological entrepreneurs with long-term vision controlled investments and developed power systems according to national needs. As a result, the hydropower systems of Norway and Sweden are energy-dimensioned, whereas the thermal power systems of central Europe are power-dimensioned. By bridging the energy systems of these two regions, Denmark has been able to take advantage of both.

Market reforms and climate issues have brought drastic changes in the last ten years. Large investments in sustainable energy are needed for the future, but utility companies can no longer make long-term investments without financial risk, and EU member states can no longer close their borders to foreign bidders. The electricity market has proved to be good at optimising the operation of the existing power system, but it needs to show that it can also manage the development of new capacity.

Received wisdom today is that the electricity transmission system should remain a centrally-governed monopoly, while power production should be a matter for private investors and subject to market conditions. Considering how the transmission system can influence investment in generating capacity, however, it is difficult to see how an effective electricity system is possible as long as production and transmission are managed by organisations with opposing interests. Transmission companies base their planning on the lowest possible electricity prices, while production companies want prices to be high.

The biggest challenge facing the European power sector is how to establish a new distribution of responsibilities: a new organisation to ensure optimum long-term investment within a power system that is more sustainable and coherent than the existing one.

Power consumption varies significantly according to the time of day, the day of the week and the season. When

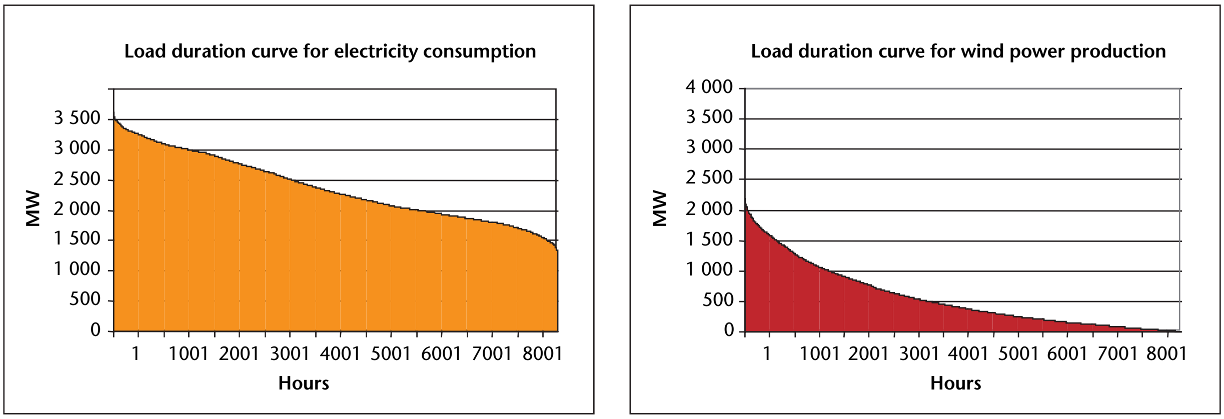

Figure 4: Load duration curves for electricity consumption and wind power production based on hourly data from the Jutland-Funen area in Denmark.

load is plotted against duration, the shape of the curve shows how efficiently the production system is used (see figure 4).

If there are a few hours of peak load each day, but for the rest of the time the base load is much lower, then plant utilisation is said to be low. Any generating capacity added to meet peak loads should have low capital costs (capacity costs), even if the unit cost of electricity from these plants is relatively high. An example of such a plant is a simple-cycle gas turbine. If demand is much more constant throughout the day, with relatively small peaks, then utilisation is said to be high. Any extra capacity will need to have low production costs, even though this is likely to mean higher capital costs (capacity costs). Examples are combined-cycle (gas turbine plus steam turbine) or coal-fired power stations.

One way to increase utilisation is to build transmission lines linking areas with different consumption patterns, or with similar patterns separated by a significant time lag. Another is to introduce price elasticity: increasing prices during periods of high load, and decreasing them when demand is low, can smooth out the demand curve.
If windy sites are available one of the most economical ways to replace fossil fuels in the power sector is to build wind turbines. Wind turbines have high capacity costs but low production costs. They are therefore given priority by the market's despatch rules, under which power plants are started up in sequence until demand is met, starting with the plant with the lowest production cost and finishing with the most expensive.

A power sector with many wind turbines in general has a steep duration curve for the part of the demand that is not covered by wind turbines, since the period of peak demand typically comprises only a few hours each day.

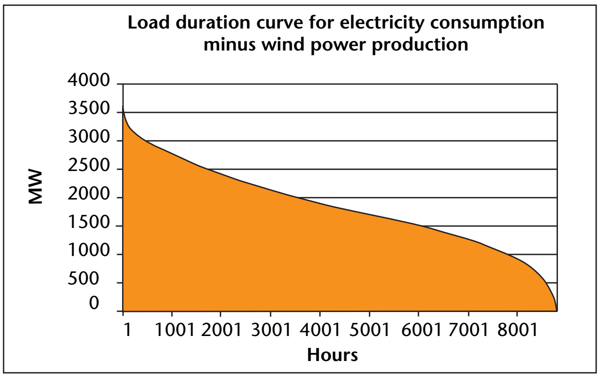

Figure 5: Load duration curves for electricity consumption minus wind power production based on hourly data from the Jutland-Funen area in Denmark.

This is shown by comparing figure 4 and figure 5[2]. In figure 4 the load duration curves for electricity consumption and wind power production are shown. If no wind power existed in the power system the load duration curve as seen by the conventional power system would be equal to the left hand side of figure 4. But introducing wind power with the highest priority in the power system (prioritised dispatch) the load duration curve seen by the conventional part of the power system becomes equal to the one shown in figure 5, where wind power production is deducted from electricity consumption and the data sorted to give the resulting duration curve for electricity consumption minus wind power. As seen from the figure this duration curve becomes significantly steeper than the duration curve without wind power. The conventional power plants needed to meet the peak demand in this situation therefore have low utilisation, and this creates new requirements for the power sector[3].

In Denmark, interconnections to neighbouring power systems have solved this problem till now. For example, Denmark exports wind-generated electricity to Norway

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[2] Observe that the hours in figure 4 and figure 5 are not in the same sequence. Compared to figure 4, the data in figure 5 are sorted after wind power production deducted from electricity consumption.

[3] The actual shape of the duration curve of electricity consumption minus wind power production will depend on the wind resources in the given year. Therefore the duration curve of figure 5 is to be seen as an example only.

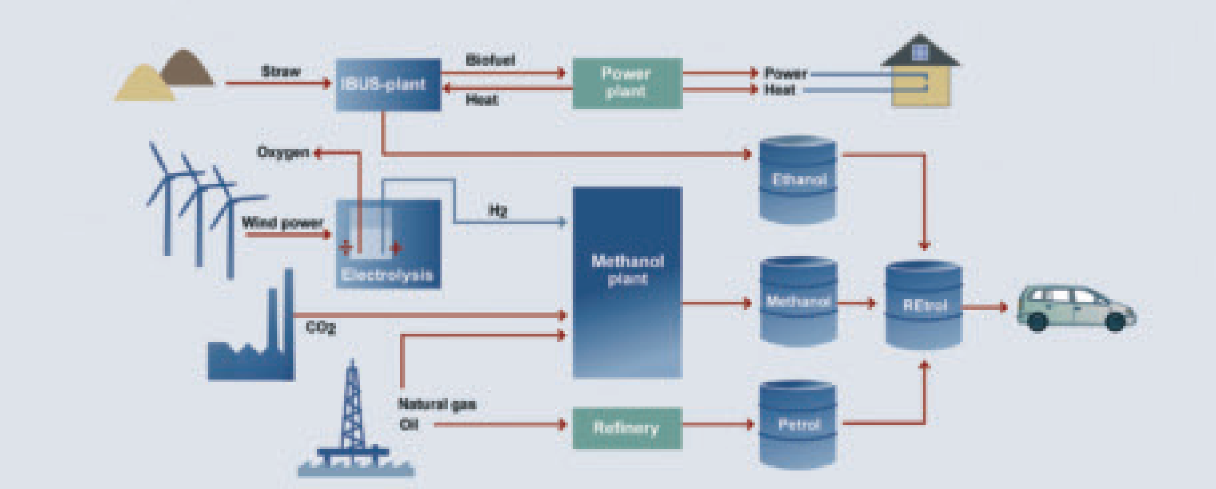

Figure 6: Production of REtrol.

when demand is low, and imports Norwegian hydropower during peak periods - so Norway's hydropower system effectively provides storage for wind power. Other solutions include:

- transmission lines between wind power areas where the wind blows at different times
- higher electricity prices during periods of peak demand
- power storage systems, and
- the substitution of fossil fuels by electricity in sectors such as transport and industry.

Denmark has a tradition of being an "exploratorium" for new and more sustainable energy technologies. It is important to create a new distribution of responsibilities that matches the needs of the new markets, yet which still allows Denmark to continue this tradition - to the benefit of both the environment and Danish businesses.

Denmark could take on an important European role in the development of new energy technologies. Future power systems will probably use several fuels and many different technologies: large central coal-fired plants with SO_2, NO_x and CO_2 removal; large (combined cycle) and small (distributed generation) gas-fired plants; large offshore wind farms; and biomass-fired plants built close to their fuel sources. In the technique known as energy integration, energy "quality" (exergy) will also be matched to end-uses: for example, houses will as far as possible be heated by low-temperature waste heat from other processes, rather than high-quality energy sources such as electricity or direct combustion of natural gas. A strong tradition of multi-fuel systems, energy efficiency and cogeneration has prepared Denmark well for the development of future power systems.

Wind power, energy integration and high energy efficiencies are the hallmarks of the current Danish energy system. Denmark now needs to build on these advantages, for instance by developing energy-efficient electrical devices, promoting price-elastic electricity pricing, and creating links between the transport and power sectors.

The latter can be done by, for instance, using electricity to manufacture petrol, diesel or other liquid fuels. By converting electricity to hydrogen and combining the hydrogen with CO_2 and methane for methanol, cars can be wind power driven. This procedure allows wind energy to be stored, and substitutes wind power for some of the fossil fuels currently used for transport, with few changes to the existing transport fuel infrastructure.

Along these lines the Danish power company Elsam has proposed a conceptual power plant to produce power, heat and transport fuels in the form of ethanol and methanol (Figure 6). The REtrol plant runs on energy from sources including natural gas, coal, biomass, waste material and surplus power from wind turbines, and produces transport fuels through a combination of processes including fermentation and hydrolysis. Elsam already has a demonstration plant producing ethanol from straw, and a demonstration unit to remove CO_2 from the flue gas is on the way.

Denmark and the future of the European natural gas network

Natural gas is the energy carrier that will allow the renewable energy society of the future to evolve from our current dependence on fossil fuels. Demand for natural gas is increasing at the same time as gas markets are undergoing profound structural changes, with implications for organizations all along the supply chain. As a result, gas markets are evolving rapidly, at both national and, increasingly, regional levels.

From the start of natural gas production in Denmark more than 20 years ago, the Danish gas network has been linked to Sweden and to continental Europe through both offshore and onshore pipelines. In 2004 an offshore

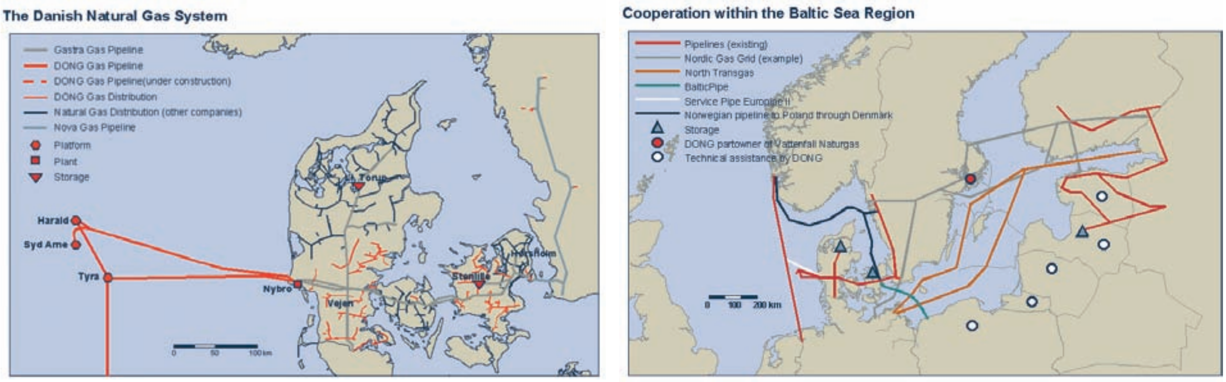

Figure 7: Denmark's existing natural gas connections (left), and future possibilities (right)

connection was also established from the Danish Tyra field to the Dutch gas network. These links allow Denmark to trade gas with other European countries, and more developments are planned (Figure 7). The future may see the transport of Norwegian gas via Denmark, and new routes for gas imported from the huge fields in Siberia. Importing liquefied natural gas (LNG) to Denmark by ship is also a possibility.

How long will natural gas be available? Most forecasts of global fossil fuel reserves predict that oil will last for 20–50 years, gas for 75–100 years and coal for 300–400 years. One country alone, Russia, has gas reserves of more than 55,000 billion m^3, with annual production of just 600 billion m^3 in 2004. As a result, the Danish gas network will be in use for many decades to come.

As a conventional fuel, natural gas can substitute oil or coal in almost all applications. One market segment for gas that has appeared only in the last 10–20 years is as a transport fuel. As the Danish government's recent *Energy Strategy 2025* points out, new fuels such as natural gas, bio-fuels and hydrogen could be important replacements for oil in the transport sector [2]. The EU target, which is for natural gas to meet 10% of transport fuel requirements by 2020, will create new challenges for the gas industry.

Natural gas will also act as a bridge to the "hydrogen society" that could play an important part in future energy supply. In this case, part of the natural gas network might be used to transport hydrogen for vehicles. Another new market for natural gas is in power production as a substitute for coal. This will not have major implications for the Danish distribution system, since many existing central power stations are already connected to the natural gas grid. However, the future market for natural gas will of course depend heavily on the future development of the natural gas price in relation to prices of competing fuels as oil and coal.

The Danish natural gas network faces two important issues for the future: security of supply, and national targets for CO_2 reduction. Taking the last point first, Denmark is committed to reduce its annual CO_2 emissions by 14.6 million tonnes over the period 2008–12, compared to 1990. To achieve this, both natural gas and renewable energy will be required. Moving to gas as a fuel for power production has so far met 10% of the CO_2 target, so there is still a long way to go; converting all Denmark's coal-fired power plants to gas would meet one-third of the target. A big challenge remaining is how to link the natural gas grid to renewable energy sources and renewable power production.

The issue of climate change means that renewable energy is becoming more and more interesting as an option for future energy supply. How can the natural gas system help in the distribution of renewable energy?

For transporting landfill gas, biogas and fuel gas produced from the gasification of biomass, it is straightforward to use the existing natural gas network. Many countries already do this - Sweden is one example. In most cases the gas is purified to natural gas quality before being fed into the transmission system. Another option is a dedicated network for biogas or landfill gas, supplemented if necessary by a mix of natural gas and air.

Transporting hydrogen through the natural gas network is more complicated. Experience has shown that the existing system can handle natural gas containing up to 5% hydrogen without problems, but pure hydrogen can cause cracking of the steel pipes used for long-distance transmission. Danish tests show that hydrogen creates no severe problems for the polyethylene pipes and components used for local gas distribution [3], though more research is recommended.

The introduction of new fuels into the natural gas network will extend the applications of the system and create profitable business opportunities. Producers of alternative gases such as biogas and hydrogen will benefit, because the problem with distribution has so far been a significant obstacle to the wider use of these fuels.

At European level, the use of the natural gas network to transport hydrogen is an important topic. The EU-supported NATURALHY[4] project is examining the implications of supplying end-users with natural gas/hydrogen

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[4] NaturalHy is running from 2004-2007 as part of the 6th Framework Programme

mixtures, including the effect on existing gas-burning appliances. At the point of use, selective membrane separation units fed with natural gas/hydrogen mixtures could supply pure hydrogen. The hydrogen could then be used as a transport fuel during the transition to an all-hydrogen economy, and would encourage the commercialisation of fuel cells and other applications. NATURALHY includes a programme to develop high-efficiency membrane systems at various scales, to separate hydrogen from mixtures with natural gas. Danish research institutes, with their strong background in materials science, could play an important part in developing suitable membranes.

As Denmark continues to install wind power plants, there will be more and more occasions when electricity production exceeds domestic demand. For the time being this power is exported to Germany, Norway and Sweden. However, whenever grid capacity is in short supply, or export prices are low, it might make sense to use the surplus power to generate hydrogen by electrolysing water. The problem is that this route is wasteful: today's electrolysis systems have efficiencies of only 70–80%, and the power needed to compress the hydrogen for pipeline transport means that, at the point of use, the hydrogen contains less than 50% of the original electrical energy used to make it. If the hydrogen is converted back into electricity, rather than used for heating or as a transport fuel, then only 25–30% of the original electrical energy is recovered.

Another option is the compressed air energy storage (CAES) system (Figure 8), in which surplus power is used to compress air stored in underground caverns. When electricity demand rises, the compressed air can be expanded through a turbine in a mix with natural gas. A CAES plant originally established as a backup system for a nuclear power plant in Germany (Huntdorf) is now used mainly as an energy storage system for wind power.

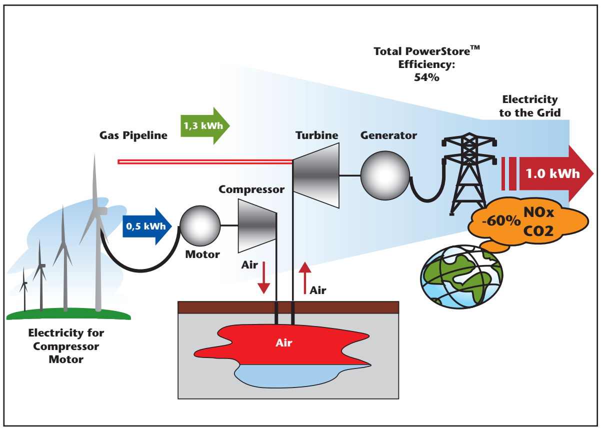

Figure 8: Compressed air energy storage (CAES)

Denmark's role in the development of renewable energy technologies, especially wind power

Renewable energy has been a cornerstone of Danish energy and environmental policy for many years. The government has supported a number of renewable technologies, including wind power, photovoltaics, wave power, and the gasification and combustion of biomass. Of these, wind power is without doubt the most successful in terms of its market readiness and current use. Today more than 48 GW of wind power is installed worldwide and more than 20,000 people are employed directly or indirectly by the wind power industry in Denmark. But what is the future of wind power, especially in a system context where integration and continued technical development are essential?

Integration with conventional power stations and with the grid are big issues for the wind industry. Until a few years ago, most wind turbines were rated at 500 kW–1 MW, and sited individually or in small clusters these relatively low output units could generally be absorbed by the grid without problems. Modern wind turbines are larger: the average size of new turbines is 1.5–2 MW, but machines of 3–5 MW will be common within a year or so, and the number of turbines at each site is rising too. As wind power plants become larger they behave more like conventional power stations, and as such they need tighter integration with existing power systems.

Currently Europe needs to invest some $525 billion in new conventional generating capacity (IEA 2003). If a substantial portion of this new capacity is not capable of providing flexible backup for wind and other renewables, it may become a bottleneck restricting the expansion of renewables. The current rapid development of combined-cycle (CCGT) generating plants could hinder the connection of more wind power unless the gas turbines are supplemented with aero-derivative models, which can cover flexible loads.

Wind power plants of the future will have to interface so well with existing technology that they will be almost invisible in the electrical energy mix. This can be facilitated by:

- making wind turbines more similar to conventional generating plants, e.g. in terms of regulation capabilities
- using wind locally, for direct loads such as glass or cement factories, and timing production to match periods of high wind speed
- using demand management to balance power demand when wind power production falls, and
- converting wind energy to heat for district heating systems.

Achieving this invisibility will require higher-density, high-quality power electronics, and better forecasting of wind speeds so that demand can be managed and backup power sources brought on line at just the right time. Development of short-term (battery) energy storages could also help planners cope with fluctuations in wind speed.

Another integration problem with wind is access to sufficient grid capacity. Many of the best wind resources are in coastal or rural areas, far from the cities and factories where most energy is used. In such areas, the distribution grid was never designed to support local power generation, so increasing amounts of wind power and other renewables will need investment to reinforce the grid.

Grid reinforcement is expensive, and many grid operators are wary of committing large investments to what they consider a marginal, intermittent resource. Compounding this is the fact that some operators have a non-structured approach to planning, and in the current liberalised market they have little incentive to build new lines. On the other hand, the cost of the reinforcement required to handle more wind power is small compared with that needed to enable a liberalised electricity market across Europe, which at the moment is characterised by the national and fragmented nature of its transmission and distribution systems.

Increased security of supply also demands more intelligent self-healing grids, as used for mobile phone networks, with perhaps one or a few dispatch offices serving the whole of Europe.

In physical size - with rotor diameters up to 120 metres - the latest wind turbines are the largest rotating machines ever seen. Generators, gearboxes, blades and towers are constantly being optimised to give the best trade-off between performance and cost. Until recently, technologies and materials were borrowed from the mining, aerospace and defence industries. However, this store of knowledge has now been exhausted and the wind turbine industry is on its own; indeed, the roles have been reversed, so that other industries are learning from the wind turbine manufacturers.

Wind power cannot develop further, however, without new basic research in areas including materials, load modelling, aerodynamics and resource modelling. If Denmark is to retain its global leadership of the wind industry, the nation's research institutions will need to contribute even more than today. There are already problems with the pace of development: ever-larger wind turbines are appearing on the market at an ever-increasing rate, and manufacturers sometimes pay dearly as they scale a very steep learning curve. Perhaps bigger is not necessarily better or more reliable.

Onshore wind power plants in Europe have the potential to produce approximately 600–700 TWh/year [4]. Offshore wind, which is gaining in popularity as objections to more land-based wind turbines grow, has the potential to produce approximately 3,000 TWh/year [5], although how difficult it will be to harvest this potential still remains to be demonstrated.

Wind is intermittent and variable, so the future success of wind power rests on the ability to mitigate these disadvantages. Options include:

- High-level intelligent integration. In the medium term, wind power will flourish best if wind power plants behave like conventional power stations and interface easily with the existing grid.
- "Closed" power systems: relatively small, distributed generating plants operating on a mix of energy sources, including wind and capable of running either connected to the grid, or independently.
- Using wind power to generate hydrogen for use as a transport fuel. Unlike electricity (at least with today's technology), hydrogen can be stored to cover periods when the wind does not blow.
- Electrical storage, where power could be stored and released at will, would be the ultimate solution for wind energy. Workable storage systems would have to offer high energy density and high efficiency, and be able to operate at high voltages.
- Inexpensive superconducting materials would allow wind power to be exported from wind-rich regions to the rest of Europe, instantly and without the transmission losses that reduce the efficiency of today's transmission grids.
- As clean water becomes scarcer, water purification and desalination plants running on wind power will become economic. If the water purification system has sufficient capacity, it will be possible to run the end use intermittently to match the electrical output of the wind generator.

Machine size is an important issue across the wind industry. Small machines - up to 1 MW - will continue to be used in terrain where access is difficult. Elsewhere, however, space is often at a premium and objections to large wind parks are growing, so large machines will be the rule. At the current rate of progress, within ten years we can expect to see a 10 MW turbine with a rotor diameter of 180 metres. Such huge machines will have to have availabilities approaching those of conventional power plants, as the cost of non-operating plants will be unacceptably high. Among the challenges facing the designers of larger machines will be the need to build blades and nacelles in several parts so that they can be transported by road and ship.

Conclusion

In the future Denmark will be more closely integrated into the energy systems of the rest of Europe. The Danish power industry is currently in the process of merging into larger entities, whose size will allow them to compete at European scale. This consolidation will bring together expertise from the power and natural gas industries, with the result that these two forms of energy will become more closely linked. We can also expect new connections to renewable energy and transport fuels, underpinned by the growing importance of sustainability.

The energy system of the future will therefore be much more complex than that of today. The integration of intermittent resources will require new capabilities in the control and regulation of both gas-fired power stations and wind turbines, and new systems for controlling demand.

Today Denmark is a leader in energy fields including system integration and renewables, with wind power as the most prominent technology. But retaining this leadership and extending it into new areas will require new initiatives:

- Denmark could take on the role of the EU “exploratorium” for the development of new and more sustainable energy technologies. This will require the proactive involvement of the Danish government, including a long-term vision for research programmes and the creation of suitable organisations and legal entities.
- Denmark has the world’s highest installed generating capacity based on intermittent resources, notably wind power. This provides a unique chance to develop the definitive integrated power system, with features such as intelligent demand management with high price elasticity, power storage, heat storage and, eventually, a hydrogen network. Again, long-term vision from the government and the Danish Transmission System Operators will be needed to take advantage of this outstanding opportunity.
- The future will bring complexity. Close integration of power production, natural gas, intermittent renewables and transport fuels is the way forward if we are to develop a sustainable energy system. Organisational structures, fuel taxes and fiscal incentives can all act as barriers to development, and we may need to change them if we are to promote the evolution of complex energy systems.

Future business opportunities will be limited only if we fail to adapt and innovate.

5

Distributed generation

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What is distributed generation?

Distributed generation (DG) refers to an emerging evolution of the electric power generation systems, in which all the generating technologies available in a given centralised or decentralised region are integrated in the power supply system according to the availability of their respective resources. These resources are known as distributed energy resources (DERs).

It appears that there is no consensus on precise definitions of DG as the concept encompasses many technologies and applications, [1]. When referred to as small-scale electricity generation it is obviously understood as consisting of small size generation units only, but when referred to as large-scale electricity generation it is usually understood as containing a high proportion of distributed or decentralised generation units regardless of their size. Thus large-scale DERs would in this understanding encompass technologies ranging from e.g. Stirling engines in small, decentralised CHP type generation to large wind farms.

On this background, this chapter emphasises DG as the large-scale integration of renewable energy sources (RESs) and technologies, applied to regions ranging in size from communities to continents. As well as the generating equipment, DG includes the necessary grid support technologies, operational strategies and regulatory regimes.

DG has been recognised by the Commission of the European Union (CEU) as an essential part of the development of the European power system: *"Transforming the current fossil-fuel based energy system into a more sustainable one based on a diverse portfolio of energy sources and carriers combined with enhanced energy efficiency, to address the pressing challenges of security of supply and climate change, whilst increasing the competitiveness of Europe's energy industries." [2]*

The CEU´s focus on distributed generation is new, and research in this field is still rather fragmented. One exception is the EU-DER cluster of research projects, which was presented at the First International Conference on the Integration of RES and DER, held in Brussels in December 2004 [3]. The fact that this conference was the first of its kind indicates the novelty of large-scale DER.

This chapter reviews some of the core issues of DG, especially in terms of their consequences for the future development of energy technologies and systems. We have concentrated on need for knowledge regarding the characteristics of DG as they affect planning and the development of both supply and grid support technologies, and we emphasise the use of modelling in these contexts, including:

- strategic planning and policymaking
- detailed system expansion planning, and
- component and system performance, operation, design and stability.

The review is based on information from the Brussels conference and experience of wind energy in Denmark and elsewhere. Wind energy is presently the fastest growing and largest contributor to distributed generation from renewable sources, and as such it provides the main body of experience about the benefits and challenges of switching to renewables on a large scale.

Distributed versus centralised generation

This brief review of DG versus centralised generation is to a large extent based on the proceedings of the Brussels conference [3], including but not limited to the presentations [4–12]. Additional material is given in Pepermans' *Distributed Generation: Definitions, benefits and issues* [1]. We will adopt the following definitions of distributed vs decentralised generation presented in *Introduction to ENIRDGnet* [10]:

Item	Definition
Distributed generation:	Any plant that is used for generating electricity that is connected to the electricity distribution networks
Distributed power:	Distributed generation and energy storage technologies
Distributed energy resources:	Distributed power plus demand side measures
Decentralised power:	Decentralised energy resources, converted at the point of use, irrespective of size, fuel, technology, off shore wind, CHP

DG implies the modular generation of power from systems that are often relatively small, ranging in size from less than a kilowatt to a few tens of megawatts. These generating systems are installed by utility companies, their customers and other organisations, and are often located at or near consumer sites. Distributed systems may be connected to the grid, or they may operate independently. They are generally not centrally controlled, and with few exceptions at the present time they are not dispatchable - that is, they cannot be switched on and off according to the needs of the grid - unless they incorporate suitable grid support technologies such as energy conversion and storage.

The eventual goal of DG, as we see it, is to "reinvent" the grid. Instead of electricity produced in large central plants and transmitted in one direction, DG gives consumers a number of benefits such as:

- a degree of energy independence
- opportunities for local control to improve security of supply
- financial optimisation
- equal or better power quality, and
- a cleaner environment

This opens the possibility to include millions of small suppliers with a high proportion of renewable energy sources.

With DG, 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 e.g. 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.

DG is often described as "integrated" and "decentralised" to distinguish it from traditional centralised systems, in which power is generated at large, centrally located and centrally controlled plants. Electricity is presently the dominating medium of exchange in DG, although heat from e.g. CHP plants also plays an important role in district heating and other kinds of energy supply. In the long run, energy carriers such as hydrogen and biofuels are expected to contribute very significantly to the energy exchange in DG. Regardless of size, fuel or technology, the central issue in DG is the large-scale integration of decentralised energy resources.

The generating technologies and energy sources behind DG 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 (some technologies such as fuel cells and microturbines are not intermittent)
- 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.

These characteristics, and the inflexibility of most renewable energy technologies, pose important constraints on and requirements to energy systems based on DG. As the proportion of renewables grows, energy systems including the necessary support technologies, will face increasing challenges to their operation and future development, affecting both the supply and demand side. Information and control technology (ICT) will be very important to the successful integration of renewables.

The perceived benefits of distributed power systems include increased reliability of service (not all stakeholders have that perception today), 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, yet many existing grids cannot operate without occasional blackouts. The ability of DG, once the concept is fully developed, to act as a robust standby generating system (rather than strictly a UPS) is therefore very attractive. Finally, the redundancy offered by a DG network with its intertwined multitude of generators, converters and connections will certainly enhance the security of the power system to deal with acts of terrorism.

DG 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. Once the concept is fully developed, DG, 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.

Of the various barriers to a robust implementation of distributed power, key barriers include the need for reliable interconnections between DG systems and the grid, and the quality assurance that includes testing and certification of DG systems and components. Developing standards, procedures and techniques for the design, testing and certification of DG systems is a relatively new undertaking, but one that can draw on experiences developed in the wind industry over the last two decades for both systems and projects. Quality assurance of DG systems and components is dealt with separately below.

Large-scale integration of renewable energy

With an annual energy penetration of more than 20% on a national scale (Denmark) and 50–70% in several regions of Europe, wind power has been the pioneering technology for the large-scale use of renewable energy in the power sector. The knowledge developed for wind power provides valuable blueprints for the large-scale integration of RESs in emerging DG systems.

Wind power in particular can place significant constraints on electric power systems. Fluctuating inputs of wind-generated electric power must be balanced by flexibility in other parts of the system, on either the supply or the demand side. The ability to predict actual wind power production hours or days in advance is important, because it creates time for dispatch decisions and efficiency improvements in the overall system.

Scale is important: a number of wind power plants spread across a large geographical area helps to level out the intermittent nature of the wind. Very large areas provide much greater consistency in wind generation, at the cost of potential grid bottleneck problems in transmitting power over long distances.

The concept of base-load changes when DG, and in particular wind power, is used on a large scale. Traditional base-load plants such as coal-fired and nuclear power stations are characterised by low regulation flexibility and low marginal production costs. These now have to compete with wind power, with its moderate regulation flexibility and practically zero marginal production costs. From the viewpoint of the dispatch system or the deregulated energy market, wind power has similar characteristics to traditional base-load plants, and does not compete with dispatchable generating units in the medium to peak load areas. These dispatchable units include both conventional plants, such as CCGT and simple-cycle gas turbines, and DG plants with suitable control systems.

Large-scale integration of wind power may therefore eventually reduce the demand for conventional base-load plants. In the shorter term it will increase the demand and widen the operating regime for flexible generating units capable of variable load operation at times of medium and peak demand. This will favour generating capacity that is relatively cheap to build, such as gas turbines, despite the high price of natural gas. As gas demand rises, and becomes more variable partly due to the intermittent nature of wind, bottlenecks may emerge in the natural gas distribution system.

Present electricity supply systems are generally based on larger (central) power plants connected to high voltage transmission grids, supplying lower-level transmission and distribution grids before reaching the consumer (at the 400V or 240V voltage level). Integrating DG/DER in the electricity supply system usually implies that RES is supplied to the grid at lower voltage levels. Due to geographically distributed inputs that furthermore can fluctuate, the operation of the grid and the power flow patterns can be fundamentally altered. In parts of the grid, power flows may frequently change direction, as RES supplied to the grid at lower voltage level must be transformed upward and fed into a transmission line at higher voltage level before cascading down in voltage to consumers situated geographically in other areas or regions of the overall grid.

This has implications for the future development of electricity grids. In accordance with increasing DER deployments, old grids may need upgrading to cope with altered power flow patters.

Grid stability and power quality are other very important issues that will require special attention when intermittent renewable sources become substantial contributors to energy supply. This means grid support technologies such as power converters, grid reinforcement and energy storage schemes. Energy carriers such as hydrogen and ethanol may also become important for exchanging and storing energy from renewable sources, as well as providing transport fuels.

Developing and implementing DG systems

Proper analysis of DG components and systems is a prerequisite for successful system development, and we will not see the necessary commitment from stakeholders unless we can accurately predict the technical and socio-economic consequences. The complexity and interconnected nature of DG systems makes this a challenging task.

Modelling in DG technology development

Developing successful generation and grid support technologies for DG systems requires the ability to build mathematical models of:

- interconnection
- power quality
- controls and communication
- load balancing and dispatch
- dynamic and transient behaviour
- component performance, efficiency and lifetime, and
- system performance, efficiency and optimisation.

To a large extent the models being developed for DG systems are based on those used for isolated hybrid systems incorporating a large proportion of renewables. They also draw on experiences with modelling centralised systems that include wind power, where tools such as *DIGSILENT* [16] provide detailed representations of system dynamics over very short time scales [17].

At Risø, a tool for estimating the performance of wind/diesel systems was developed in the early 1990s and used in several feasibility projects [13]. The tool did not include energy storage and had limitations in the modelling of operating strategy, but it could model the technical development of the system throughout its entire life cycle. The resulting predictions were shown to be very accurate, but this modelling concept has limited flexibility for adaptation to other and larger system configurations.

Current state-of-the-art simulation tools being applied in feasibility studies worldwide include *Hybrid2* [14] and *Homer* [15], both developed at the US National Renewable Energy Laboratory (NREL). *Hybrid2* can model a wide range of user-defined configurations as well as a number of predefined operating strategies, and gives quite detailed simulations of system performance. Homer is a screening tool used to optimise and compare the energy costs of a number of different configurations. However, both models have a limited set of predefined system control strategies that cannot be changed by the user.

Despite their different origins, the three models referred to above share several characteristics. Firstly, they can simulate only a limited set of configurations and operating strategies. Secondly, they model only the active power balance, and neglect reactive power. Thirdly, the power system is simulated as a single node; in other words, the electrical grid is not explicitly modelled.

On this background, a key factor in a realistic assessment of DG systems is the ability to accurately model the power system. This includes accurate modelling of the actual real life control of the system, voltages and frequency, as well as losses.

A new simulation tool developed at Risø, *IPSYS*, [18], can accurately model the control of DG systems under real life conditions, including voltages, frequency and losses. *IPSYS* currently includes components such as wind turbines, diesel generators and lead-acid batteries, with more to come. The core of the model is a multi-bus-bar load flow calculation for explicit modelling of voltage, frequency and other services such as water production and supply. This is combined with very flexible controller modelling, which makes it possible to include detailed, realistic behaviour for, say, a storage system such as a battery. *IPSYS* can simulate systems ranging in scale from small stand-alone generators to parts of large interconnected systems.

Experience has shown that there is a need for an intermediate level of modelling, between the simple screening models used in early phases of a feasibility study and the complex dynamic models used for analysis and design of dynamic controllers. *IPSYS* fills that need, with an emphasis on system-wide controllers (supervisory controllers) and operating strategies. The main features of IPSYS are:

- explicit modelling of the electrical network, i.e. load flow
- explicit modelling of load sharing between generating units, for active and reactive power
- flexible modelling of system configuration
- flexible modelling of supervisory controllers
- short time steps for accurate modelling of supervisory controllers
- the ability to explicitly include other circuits and balances interacting with the electrical system and the control system, which in turn allows other products and services to be modelled, and
- integration with the WAsP wind resource estimation tool [19].

Power system implementers commonly agree that storage batteries are a weak link in the long-term operation of renewable-based DG systems. Batteries may be necessary when energy sources are intermittent, but not only do they reduce the overall energy efficiency of the system, they are also expensive and can greatly affect the system's overall economics.

Poor predictions of battery performance and lifetime can therefore lead to significant uncertainty when assessing the long-term technical and economical viability of DG systems. Many modelling tools, both technical and economic, for hybrid power systems include battery models, but their accuracy varies [20]. Two new models for predicting the life of lead-acid batteries in hybrid and DG renewable energy systems were developed as part of a benchmarking project (ENK6-CT-2001-80576) [21]. The organisations funding the work included the EU and the US and Australian governments. The two models are used respectively in *Hybrid2* [14] and *IPSYS* [18].

Newer methods of storing energy are being developed. They include redox flow systems and hydrogen storage technologies as well as ultracapacitors and compressed air energy storage. Together with more widespread use of the well known pumped water storage scheme these techniques may eventually out-perform the lead-acid batteries in future DG systems. However, each of these energy storage methods will bring its own modelling challenges.

Modelling in DG energy planning

Simulating DG as part of the overall system translates itself into modelling of typically many individual generating units, often of low capacity and based on several different types of technology. Decentralised combined heat and power plants (CHP) that interact between a heat market and the electricity system are often categorized as DG, even though these flexible plants may have substantial capacities.

Conventional models often treat DG production as an inflexible production, following forecast production profiles, much in the same way as an inflexible demand side may be modelled. This is acceptable as long as the DG capacity in the system is only marginal, even though parts of the DG capacity may possess valuable flexibility. As DG deployment increases, and the DG capacity no longer is marginal, it becomes important to include or mobilise regulation flexibility. DG technologies can actually contribute to such regulation flexibility. Therefore it becomes increasingly important also to include DG technologies in the modelling of power systems. Small individual units can be costly to integrate in the overall system dispatch and may increase system complexity. However, developments e.g. in power electronics and communication systems now allow for many very small units to contribute to the overall system regulation, much in line with large conventional units.

In conventional centrally-planned power systems, system operation at the hour is optimised, based on the characteristics of every available production unit, the state of the grid, and current and predicted future demand. The models used determine the order in which units are dispatched so as to minimise the total generating costs. The generating capacities needed to maintain system stability, power quality, and reserves to cover faults and fuel interruptions have already been allocated days, weeks or months ahead, using optimised planning models.

The introduction of DG adds complexity to the processes of planning and scheduling production, and of communicating scheduling information to individual DG units or groups of units. It also brings new challenges in the long-term strategic modelling needed to plan new investments and meet political goals.

Deregulation of electricity markets also adds to the complexity of the modelling process. The system operation and the unit dispatch are now governed via markets. Supply and demand determine price, volume and unit commitment at the hour in the overall system. When system requirements are to be mainly allocated via markets, it is an important analytical and modelling challenge to ensure that the set up market structures are capable of providing the necessary requirements for the proper technical functioning of the overall system. Likewise, there are important analytical and modelling challenges concerning the analysis of effects of interacting markets aiming to provide the long-term system development goals desired with respect to e.g. costs, security of supply, and environmental and social aspects.

The European power system is moving towards a fully liberalised market (Directives 2003/54 and 2003/55). In Scandinavia, the Nord Pool power exchange controls trans-regional as well as national power trading. Transmission system operators (TSOs) are responsible for the physical networks that make power trading possible, and for maintaining system and grid stability.

The Nord Pool market covers non-bilateral electricity trading in the Nordic/NordEl regions. At present, Nord Pool markets for physical trade include **Elspot**, a day-ahead market in which bidding closes at noon for deliveries from midnight and 24 hours ahead; **Elbas**, in which bidding closes one hour before delivery; and the **Regulating Power Market** (RPM), which operates with a timescale of less than one hour. In modelling terms, the main differences between these markets are the timescales from the closing of bidding to the time of delivery.

The main job of the RPM is to provide power regulation to counteract imbalances relative to the planned operation according to the Elspot trade. The RPM is therefore in particular important for DG technologies such as wind power, where the prediction of the production hours ahead is uncertain. The RPM is also important because it values flexibility in generating systems. By encouraging and mobilising flexibility, the RPM can improve the regulation capabilities of the entire power system.

As well as these three markets, other less-formal markets exist for both physical deliverances and power system support services. One type, known as **Auxiliary Service Markets** or **Ancillary Delivery Agreements**, serves to allocate the various levels of reserve capacity, including frequency and voltage control, needed to ensure proper operation of the system. Another is the **Cross Border Transmission Capacity Auction Market**, which in the Nordic system is administered by Nord Pool. The Nordic TSOs have handed over the administration of grid bottlenecks within the Nordel system to Nord Pool, a system that helps maximise the utilisation of grid capacity.

Other markets of importance for DG modelling include the **EUA** (European Allowances Market) for greenhouse gas emission quotas, following EU directive 2003/87 and the start of emissions trading in 2005, and the **TGC** (Tradable Green Certificates) market used in Sweden since October 2004. Austria, Belgium and Italy have similar markets to the TGC; Denmark awaits a common EU standard on this issue.

New markets might also emerge to cover generating capacity and services that are currently handled by informal trading systems. These could include, for instance, a **Reserve Capacity Market** and **markets for specified ancillary services to the grid**, such as frequency and voltage control reserves, and emergency power needed to resume generation after a wide-area power outage (“black start”).

As the fraction of DG within a power system increases, the decentralised nature of DG changes the way in which the grid operates, and spatial resolution becomes increasingly important in system modelling. DG has important implications for load flows in distribution and transmission grids, and for the interactions between voltage levels. Large-scale use of DG brings both benefits and constraints to the architecture and operation of the grid.

Developments in power components and grid design have brought new ways of configuring and operating grids so as to improve stability, reliability and safety. An example is the partitioning of large integrated grids into smaller interconnected sections, each of which can function independently for at least part of the time. Such a development, which can increase overall system reliability, may emerge from the spread of DG.

Comprehensive planning tools are important in identifying and analysing the costs and benefits of increased DG capacity. Models capable of handling most of the complexities discussed above include **Wilmar** (Risø), **Balmorel** (Ramløse), **MARS** (Eltra) and **RAMSES** (Danish Energy Authority). Other models are also used for narrower aspects of DG system design [26, 27].

Quality assurance of DG systems and components

A core problem associated with the widespread adoption of DG is the urgent need for a quality assurance system to serve generating companies, investors, insurance companies and regulators. To justify a switch to DG, stakeholders - investors and society as a whole - need to be confident that the DG system will deliver the expected levels of economy, performance and reliability. To maximise the credibility of DG, we need tools and facilities for testing the safety, quality and performance of DG components and systems, including:

- equipment characterisation, tests and documentation
- design review
- performance verification
- best practices in project preparation and implementation
- quality assurance
- standards and certification.

The experience already gained with wind power in several national power generation systems can be helpful here.

Standards and certification

An international system of standards and certification for wind energy has been developed under the supervision of the International Electrotechnical Commission (IEC), based on national systems developed in the USA, Denmark, Germany and elsewhere. The relevant standards are IEC WT01, which deals with international certification requirements and the underlying IEC 61400 series of technical standards.

Risø has held the chair of IEC Technical Committee 88, *Safety of Wind Turbine Generator Systems*, since it was established in 1987. From 1980 to 1999 Risø developed and implemented the Danish wind turbine certification process under contract to the Danish Energy Authority (DEA). Today Risø manages the Danish approval scheme for the DEA.

The system developed for wind energy over two decades covers all the issues described as mandatory for quality assurance of DG systems and technology [10]:

- utility requirements relating to engineering compatibility with the grid
- protective equipment and safety measures to protect utility property, personnel and power quality, and
- engineering reviews, design criteria, engineering studies, operating limits and technical inspections.

Similar systems for quality assurance have been established for other renewable energy technologies, so a large body of experience in quality assurance exists in the laboratories and other institutions that have worked on standards, certification and testing for renewable energy technologies.

We can draw on this experience to create standards for DG technology that will support safe, reliable and efficient power supplies of sufficient power quality [7]. The standards should guarantee the compatibility of the components and control techniques used, so that conventional electricity grids can be transformed effectively into networks with high proportions of DG including renewable energies.

In Europe, standardisation in DG has so far been mainly on the basis of energy source - such as wind, photovoltaics or CHP - but new interdisciplinary committees are now looking at entire systems and trying to harmonise connection issues. These committees are:

- IEC TC8: System aspects for electrical energy supply
- IEC 61850: Communication networks and systems in substations
- IEC 62257: Joint Coordination Group (JCG) for Decentralised Renewable Energy Systems; and
- IEEE1547: Standard for interconnecting distributed resources with electric power systems.

Several national and European R&D projects concerned with standardisation activities support these committees, including the EU Network of Excellence DERLab described in some detail below.

A key barrier today is the interconnection of DG with the grid. The US Institute of Electrical and Electronics Engineers (IEEE) led the development of a consensus standard for interconnection: IEEE 1547 *Standard for Interconnecting Distributed Resources with Electric Power Systems* [11]. This was adopted in June 2003 and is intended to ensure that DG systems operate safely, reliably and in a uniform way across the US power system. Compliance with this standard will streamline the installation and operation of distributed systems. Other standards in the P1547 series are under development.

Laboratory networking and collaboration

European laboratories concerned with DER are participating in a cluster of research projects supported by the European Commission. Between them, the seven projects have over 100 partners and a total budget of €34 million [7, 10]. Regular cluster meetings ensure the free flow of information between the projects.

From 2004 onwards the existing cluster projects have been supported by the “concerted action” project IRED, which includes further projects funded by the Commission under the 6th Framework Programme. The most important elements of IRED are:

- systematic exchange of information by improving links to relevant research, regulatory bodies, and policies and schemes at European, national, regional and international levels
- setting up strategic actions such as trans-national R&D co-operation and common initiatives on standards, test procedures and education
- identifying the most important research topics in the field of integration, and taking action to address these.

As the first step in a planned international exchange programme, the European cluster projects have begun an information exchange with three US laboratories: EPRI-PEAC, NREL and DUA.

There is also a plan to establish a network of European laboratories, known as DERLab, for DG research [8]. The main objective of the network is to support the sustainable integration of RES and DG in the electricity supply by developing common requirements, quality criteria, tests and certification procedures. Planned activities include:

- developing requirements for the connection, safety, operation and communications of DG components
- developing requirements for the effective and economic operation of sustainable power systems
- developing quality criteria for DG components
- developing common certification and qualification procedures
- supporting manufacturers, grid operators and DG operators through workshops
- supporting the development of common European and international standards, and integrating national developments, and
- joint research activities.

The DERLab network will participate in the international exchange programme mentioned above.

Future developments and visions

Four independent trends are laying the groundwork for the possible widespread adoption of DG [9]:

- utility industry restructuring
- the political will to increase the use of renewables
- technology advances, and
- environmental improvements.

One vision for the future technical development of DG systems is referred to as "microgrids" [12]. The microgrid concept includes outline proposals for system operation and control, including the management of voltage and frequency, but further standards-based work is needed on the necessary technical and commercial protocols, hardware, safety systems and simulation. Most of these issues are dealt with in this and other chapters of the *Energy Report*.

Apart from the technical issues, policy is an important key to the way forward for DG [10]. New regulatory policies are needed to create new solutions, including a market-based approach to ensure reliability. Regulators and stakeholders need to confront barriers including electricity prices, interconnection issues, siting and permissions. It is important to recognise how market-oriented programmes can send appropriate price signals about the conditions under which DG can be cost-effective. Finally, methods for allocating costs and benefits should be developed and approved, so as to be able to create appropriate market price signals. Once DG gets a fair evaluation by the market, it can expect high levels of penetration.

6

Efficiency improvements

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Introduction

Energy efficiency can be improved at many levels, from energy production to final energy use. As Figure 9 shows, the energy chain - from primary energy to what might be called “energy welfare”, satisfying our human demands can be divided into three main levels: lifestyle, end-use and supply [1]. At each level we can define and measure energy efficiency, and so envisage efficiency improvements.

At the highest level, our choice of work, leisure activities, size of household, diet and many other lifestyle factors influence our demand for energy services. “Lifestyle” in this context also includes the economic system that forms the background to daily life.

In principle, at least in developed countries, there is great potential for saving energy by improving our “lifestyle efficiency”. Efficiency improvements need not reduce our general level of well-being: for instance, we can simply develop the habit of switching off lights and other electrical equipment when we leave a room. For short-distance travel we can walk or bike rather than take the car - and even improve our health in the process [3]. In general, more sharing of goods and services, less fashion-driven replacement of goods, and more repair, reuse and recycling are examples of lifestyle changes bringing significant energy savings.

However, improving lifestyle energy efficiency by changing human behaviour is not easy. A recent study by the Danish Electricity Savings Foundation [4] lists a number of obstacles, real or imagined, to well-intentioned ideas on how both people and organisations can save energy this way.

The next level of the energy chain covers end-use technologies that provide the energy services required to maintain our lifestyles. This is a very extensive area: it includes the buildings we live and work in, our electrical appliances, means of transport, industrial technologies, infrastructure and more. The potential for improving energy efficiency in end-use technologies is large, and forms the main subject of this chapter.

At the lowest level of the energy chain are the supply systems that provide our end-use technologies with the energy they require. This energy is almost always “secondary energy”, meaning that it is in a different form from the “primary energy” at the very bottom of the chain. Examples of secondary energy are electricity, gasoline and district heating; examples of primary energy are coal, uranium, biomass and wind. Primary energy is converted to secondary energy by supply technologies such as refineries and power plants and transported via pipelines and transmission lines. Potential efficiency improvements at the supply level are described in other chapters of this report.

Energy losses and environmental emissions occur all

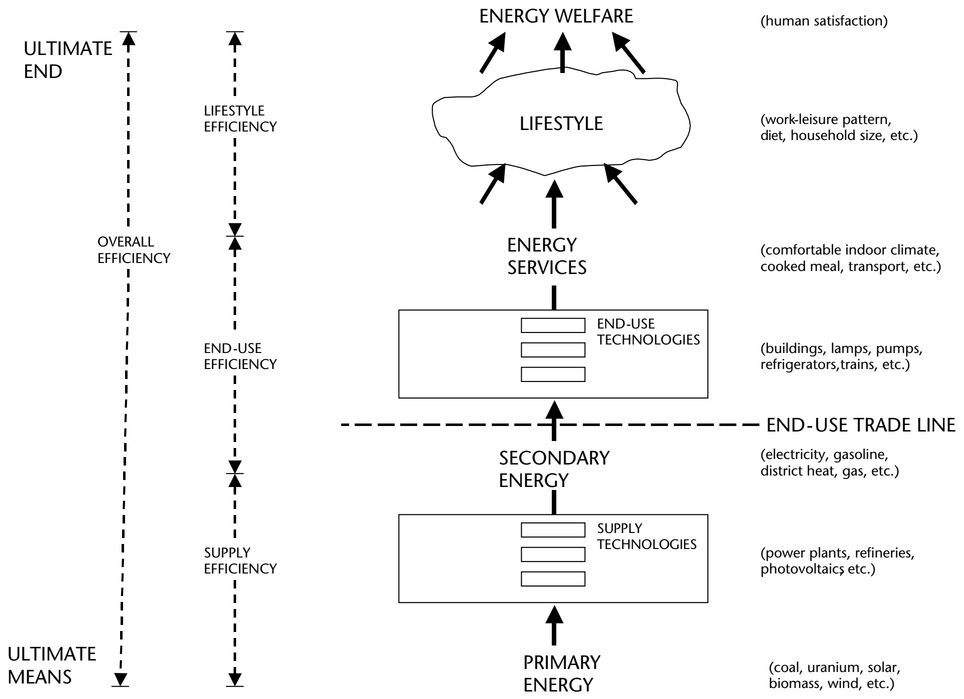

Figure 9: The energy chain with the three levels of potential efficiency improvements.

along the energy chain, from an electric cooker in a European house, via the coal-fired power station where the electricity is generated, to South Africa where the coal is mined. The further up the chain that efficiency is improved, the greater the impact on primary energy consumption and emissions.

As an example based on data from 2002 averaged over the EU, 1 kWh of electricity delivered to the point of use in the EU requires 2.2 kWh of energy from primary fuel to be converted in a power plant, with the emission of about 314 g of CO_2 [5, 6]. Including energy used upstream of the power plant - to extract, process and transport the primary fuel - multiplies the primary energy consumption and CO_2 emissions by a further factor of 1.08 [5], so every kWh saved at the point of use means a saving of around 2.4 kWh in primary energy and 340 g of CO_2. Saving secondary energy also reduces the demand for new power stations and refineries; in the case of electricity, it reduces both base-load and peak demand.

This chapter concentrates on potential efficiency improvements in end-use technologies. In 2004, the World Energy Council carried out a comprehensive study of energy end-use technologies for the 21st century [7]. The study was divided into four parts, covering respectively industry, buildings, transport and “crosscutting technologies” (energy applications used in multiple sectors). This chapter deals with the first three topics - industry, buildings and transport - but ignores crosscutting technologies, since these are described in other chapters of this Energy Report. After presenting examples from the three end-use sectors, we describe some political tools for implementing energy efficiency improvements. We end the chapter with a discussion of potential energy efficiency improvements in Denmark, and some concluding remarks.

Industry

Currently, industry consumes 30% of the world’s primary energy, or approximately 120 EJ/year [7]. Within this sector, the main consumers are heavy process industries producing materials such as aluminium, steel, pulp and paper, chemicals and cement.

Industrial energy efficiency can be increased by improving existing technologies and processes, shifting to known alternatives, or inventing new ones. Industry covers a vast spectrum of technologies; many are specific to individual industries, while others, for example pumping, ventilation and lighting, are used across many industries.

Steel production is based on a range of processes with big variations in energy intensity. Blast furnaces use 4.3 MWh of fuel per tonne of steel produced, while electric furnaces uses 0.8 MWh of electricity, equivalent to 3 MWh of fuel, per tonne of steel [7]. Despite their higher energy efficiency, however, electric furnaces cost more to operate than blast furnaces, and are thus mostly used for high-quality steel. The US Department of Energy is presently supporting the invention of a new steel production process, with the aim of cutting energy consumption in the US steel industry by 25% per tonne of steel.

The aluminium, paper, chemical and cement industries have the potential to save approximately 20% of their energy consumption, according to the WEC [7].

The main obstacles to improving energy efficiency in heavy industry are the high costs and long payback times associated with investing in new technology.

Buildings

Buildings currently consume slightly more than 30% of the world’s energy, or approximately 120 EJ/year [7]. Residential and commercial buildings typically last for 50–100 years or even longer, at least in the developed world. Parts of buildings, such as thermal insulation, windows and doors, may be replaced more often, say every 10–20 years. The fastest rate of change, however, is reserved for the appliances we put into our homes, so this is the area in which we can expect the quickest penetration of new technologies.

The following sections discuss potential efficiency improvements in buildings under three headings: heating and cooling, lighting, and intelligent systems. We have chosen two examples of technologies that may lead to breakthroughs in energy efficiency for buildings in the near future: passive houses and light emitting diodes.

Heating and cooling

Space heating, space cooling and ventilation are the main elements of indoor climate control, with hot water as an additional service that is often closely linked to space heating.

Reducing hot water consumption is mostly a behavioural matter, limited by the need for a reasonable level of hygiene. The need for active space heating and cooling is dominated by heat transfer to and from buildings through their envelopes. With careful design it is possible to eliminate traditional space heating and

Figure 10: The new common ground school of Klaus, Weiler and Fraxern in Vorarlberg, Austria exemplifies the fruitful union of architecture and sustainability. Photo: Søren Pedersen.

cooling systems altogether (the “passive house”). This can work well for new buildings, but these comprise only a very small fraction of the total building stock.

In older buildings, architecture and economics generally make it impractical to do without conventional heating and cooling systems. It is still possible to save energy in older buildings, however, and this is very important given the fact that older buildings make up the great majority of the stock. One study, for instance, showed that retrofitting better insulation to all residential buildings in Denmark over the period up to 2050 could reduce heat loss by 80% [8]. Renovation projects in Zürich already demonstrates this.

Passive houses: reducing heat consumption by 80%

In 1986, German researchers started developing what later became known as the “passive house” *(Passivhaus)*. They drew on previous know-how from experimental low-energy buildings in Denmark and Sweden.

Since 1991, the principles of the passive house have been used to create thousands of homes, offices, schools, kindergartens and other buildings, all with a heating demand of only 5 kWh/y per square metre of net area. This is at least 80% lower than the corresponding figure from the current Danish and German building codes, so the passive house improves energy efficiency by a factor of five. Most existing passive house projects are in Germany and Austria, but the trend is spreading to Switzerland, Sweden, the Netherlands, Ireland, Belgium, the USA and Denmark.

Reducing heat demand by 80% does not mean that heat loss have to be reduced by the same amount. In any house, heat is provided by electrical appliances, artificial lighting and people, and these contributions become proportionally more important as heat loss decreases. As a result, a cut in heat losses of 50% is typically enough to meet the passive house standard. Total heat consumption in a passive house is typically 15 kWh/y·m^2 net area.

On the technical side, passive houses are generally characterised by:

- walls and roofs with heat transfer coefficients (U[5]) of 0.07–0.15 W/m^{2}K - about half of the values found in standard buildings
- windows with low heat losses (U values of 0.75–0.85 W/m^{2}K for the whole window area) and high solar energy transmittance (g-values[6] of 50–60% for the glass)
- controlled ventilation with heat recovery and low electricity consumption. The temperature efficiency is typically 75–90% and electricity consumption for air transport is below 0.4 kWh/m^3
- construction joints with thermal bridges which are zero or negative when using outside dimensions as a reference
- minimal air leakage, so that the amount of air bypassing the heat recovery system is less than 4% of the building’s volume per hour. At a differential pressure of 50 Pa this corresponds to fewer than 0.6 air changes per hour.

The Cepheus project measured heat consumption and other energy use in 258 passive houses at locations from Rennes in France to Gothenburg in Sweden [9]. Over the first two heating seasons, the average annual heat demand was 16.6 kWh/y·m^2 net area.

Figure 11 shows the heat consumption measured in three passive house projects (one of these, Hannover Kronsberg, formed part of the Cepheus project) compared to conventional low-energy housing. The results show that absolute variations in the heat consumption are much reduced by the low heat consumption of passive houses.

House buyers looking at the “big picture” often ignore energy costs, but it should be equally possible to ignore the small extra cost needed to build a house meeting the passive house heat consumption standard of 15 kWh/y·m^2. Cost increases of up to +20% (for the first demonstration project) have been reported, but the typical differences are closer to 5–10%. In many European countries, savings of 80% in heating bills over the term of a mortgage will finance extra construction costs of 5–10%, depending on the type of mortgage, so passive houses are clearly economically justifiable.

Passive houses are comfortable to live in. Highly-effective insulation and elimination of hot spots hold the inside temperature steady as the outside temperature fluctuates. Because all the ventilation air passes through a heat exchanger, it can easily be filtered to remove pollen and spores. In the summer, thermal decoupling between the house and its environment keeps the inside cool.

It is interesting to consider what makes the passive house concept successful. Some of the reasons are:

- simple concept: a building is passive if it has an annual heat consumption of 15 kWh/y·m^2
- impressive figures: an 80% reduction in heating bills is something to boast about
- architectural appeal, thanks to some excellent examples
- credibility, because results have been confirmed by measurement and documentation
- presentations focus on comfort and economy rather than technical details.

Continuous growth in the market share taken up by

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[5] U=Q/(A(T2-T1)), Q, heat flow through material (J/s); A, Area of building material (m^2); T2, indoor temperature (K); T1, outdoor temperature (K).

[6] The g-value is the percentage of the energy contained in the sunlight that passes through the glass in the windows.

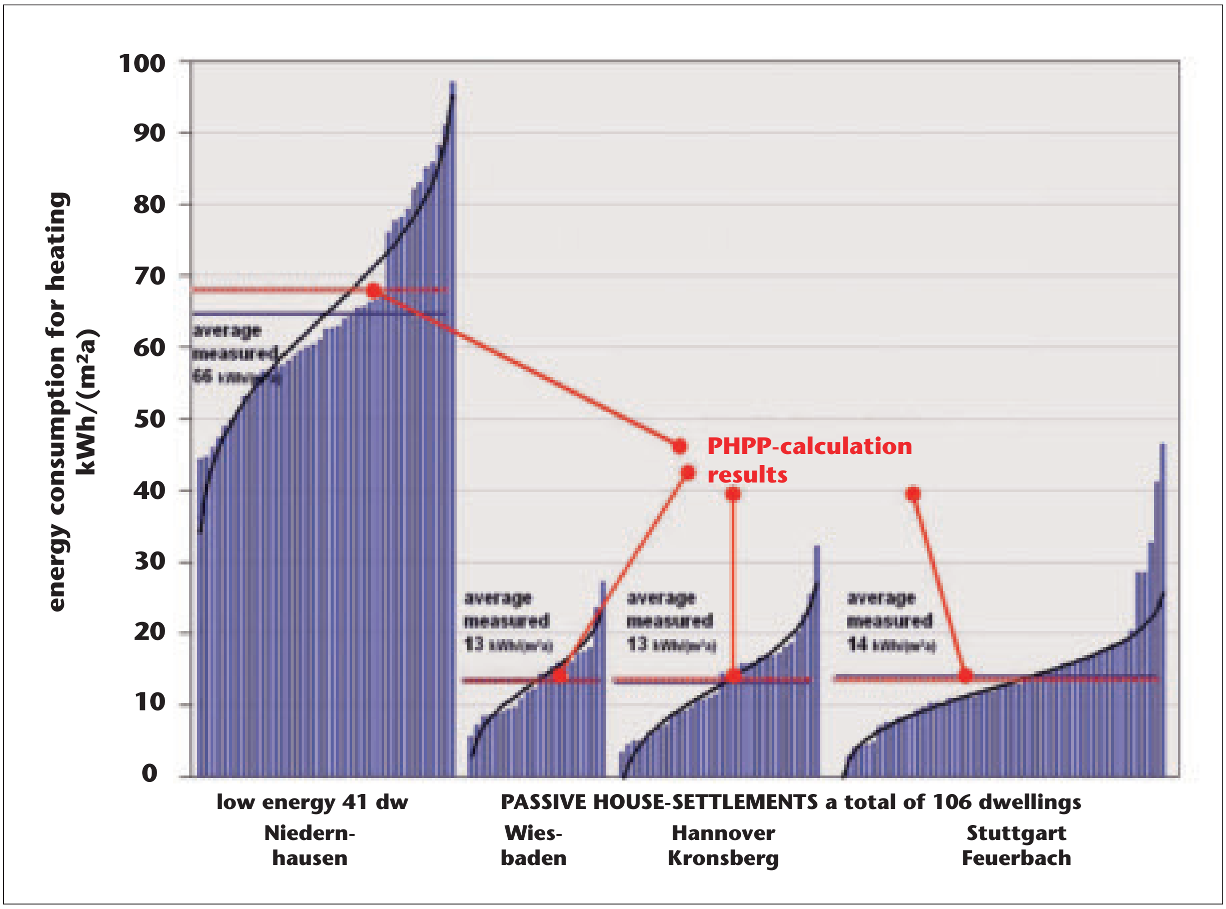

Figure 11: Heat consumption in passive houses compared to conventional low-energy houses. The graphs are presented as “backwards load duration curves”. Copyright Passivhaus Institut, Darmstadt.

passive houses in Germany and Austria over the last 5–10 years seems to indicate that passive houses are here to stay. Two new definitions of low-energy buildings in the Danish building code will encourage Denmark to repeat the experience of Germany and Austria.

The development of passive houses has already given rise to new inventions, new technologies and improved efficiency in existing technologies. In the future, new designs for windows, ventilation systems, vacuum insulation panels, miniature fuel cells and many other building components will reduce energy consumption in buildings still further.

Lighting

Electric lighting consumes around 10–15% of the world’s electricity and about the same percentage of primary energy consumption (approximately 40–60 EJ/year). There is significant potential for energy efficiency improvement in lighting, often with low investment costs and short payback times compared with other areas such as industrial processes and transport. Figure 12 compares the energy efficiency of different lighting technologies, calculated as luminous flux (light intensity) per watt of electricity input.

Figure 12 shows that a 13 W compact fluorescent lamp delivers the same amount of light as a 60 W incandescent lamp. Incandescent lamps are still preferred in some applications because of the warm colour of their light, but fluorescent lamp technology is improving in this area. A massive penetration of compact fluorescent lamps may lead to harmonics in the electricity lines [23].

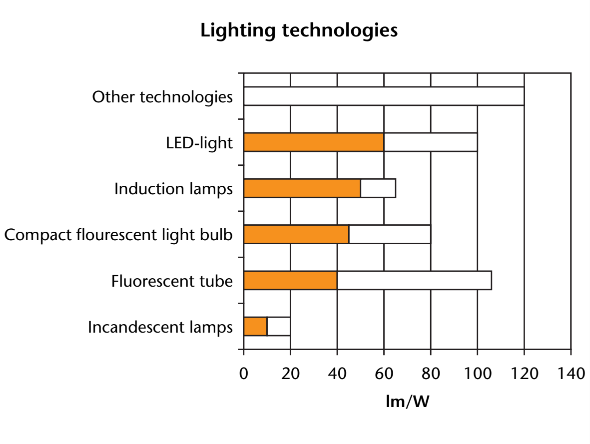

Figure 12: End-use efficiency in the form of lumen per Watt for different lighting technologies. The white part of the bar illustrates variations within the technology. (Danish Energy Agency, 1996 321 /id)

This problem can be solved technically, but leads to higher costs.

One energy-efficient way to get light of a better colour than is possible with fluorescent lamps is to use optical fibres to distribute daylight around a building ("hybrid light") [10]. Another is to use light emitting diodes, which can create any colour of light by mixing the primary colours red, green and blue (see below).

Light emitting diodes

Lighting based on light emitting diodes (LEDs), also called diode lighting, has developed tremendously in recent years and is regarded as the light source of the future. LEDs are becoming more efficient year by year, and in the near future they are expected to surpass the most efficient conventional lighting available today. The best coloured LEDs today produce more than 60 lumen/W; incandescent lamps produce only 10–15 lumen/W, and much less when coloured light is required.

In addition to their energy savings, LEDs have a number of other advantages. A lifetime of up to 100,000 hours cuts the cost of replacing lamps that have failed. Their solid-state nature makes LEDs almost immune to shocks and vibration. Due to their high efficiency they generate little heat, and they produce no infrared or ultraviolet radiation.

LED lighting therefore has the ability to become the ideal energy-efficient replacement for attractive, but inefficient, incandescent and halogen lighting. A number of technical problems remain to be solved, however, before LED lighting goes mainstream.

Recent estimates from the US Department of Energy (DOE) suggest that LED lighting could displace incandescent and fluorescent lamps by 2025. If the amount of lighting in use does not change, this would cut energy consumption for lighting by 29%, or 3.5 EJ/y [11]. In Europe as a whole, about 10% of all electric power is used for lighting; in Denmark the figure is 12%.

Nanotechnology plays a big part in the development of new LEDs with higher energy efficiency and also higher total luminous flux. The total luminous flux from individual LEDs today is so low that only low-wattage incandescent lamps are readily replaced by LEDs, but this is expected to change. Novel growth technologies using nanoscale patterning are being used to create improved substrates and precise layering of semiconductor materials. Quantum-dot heterostructure LEDs with structure sizes of around 10 nm can act as high-efficiency light sources. Nanocomposite LED die/chip encapsulants with high refractive indices are being developed to increase the amount of light extracted from the LED chip. Quantum-dot structures in the encapsulant material can emit visible light when excited by an ultraviolet LED, allowing them to be used as nanophosphors. This may provide an alternative to yellow phosphors for generating white light, and new ways to tune the spectrum of the light.

Figure 13: Early demonstration from the Danish LED project: A microstructured optical plate mixes light from coloured LEDs to form "white" light of high quality with low electrical power consumption.

The development of LED technology has mainly been driven by large organisations in the USA, Japan and Germany, including research institutes such as Sandia National Laboratories. An ongoing project in Denmark is developing a high-quality LED lamp to replace low-wattage incandescent lamps. It will create light of the desired colour by blending red, green and blue light; novel micro- and nanostructured optical elements are being developed for efficient colour mixing and light control (Figure 13). The project being carried out by a consortium including Risø National Laboratory and Danish industrial partners NESA, RGB-Lamps and Nordlux. A new project that started early in 2005 takes this work further, including the development of new lamps for the new generation of light sources, with the help of two Danish companies: Asger BC Lys and Louis Poulsen Lighting.

Information and communication technology

More and more household electronic appliances, such as computers, multimedia devices and communication equipment, are being left permanently on standby whenever they are not in use. In 2003, the Danish Energy Agency estimated that approximately 10% of the electrical energy consumed in private homes is “wasted” on standby equipment [12].

Similarly, in many commercial buildings a large number of electronic devices run for longer than the working day. In some cases, open-plan offices are lit 24 hours a day. The Danish Energy Agency has estimated that about 40% of the electricity used in commercial buildings in Denmark is outside normal working hours, mostly by electronic equipment on standby [12].

There is obviously great potential for saving energy by shutting down electrical equipment that is switched on for more hours than necessary, whether in normal or standby mode. Smart buildings can do this with the help of information and communication technology (ICT) systems, dedicated energy monitoring systems and advanced sensors. The use of such systems to capture detailed information on energy consumption allows wastage to be quickly identified and tackled, and helps in identifying costs of individual appliances to individual users. ICT systems involving mobile phones, personal digital assistants (PDAs) and satellite navigation (GPS) could be used to keep equipment on standby while the user is within a few kilometres’ range, and switch it off completely at other times.

ICT systems can also create substantial energy savings by influencing the way we work [13]. Teleworking, for instance, reduces the need to travel between home and office. E-business can improve the management of supply chains, leading to lower inventories and associated energy costs, and substitute electronic for physical activities (a process sometimes called dematerialisation). Even when physical transport of people and goods is necessary, ICT systems can use GPS and radio links to track and control the movement of cars and trucks in real time, helping them to avoid traffic congestion and thus save fuel.

It can be argued that ICT equipment itself consumes considerable amounts of energy. However, a comprehensive study of all aspects of ICT conducted by the Institute of Energy Economics in Japan concluded that better use of ICT could cut Japanese energy consumption by 1.9% by 2010 [14].

Transport

An increasing fraction of world energy consumption relates to transport, which currently accounts for about 20% of global primary energy, or approximately 80 EJ/year. The demand for transport services is growing rapidly, and transport - at least for the present and the immediate future - is totally dependent on oil products. Alternative technologies and fuels are being developed, but there is a long road from prototype to commercial technology and from there to full implementation.

A Danish study, *Long-Term Technological Options in Transport - Visions for Denmark* [15], explores some of the possibilities for improving energy efficiency. The study distinguishes several levels of technology [15–18]:

- The Best Sold Technology Level (BST) represents improvements that are available at present without further technical or commercial development, and simply need incentives to overcome purchasers’ resistance.
- The Moderate Technology Level (MOD) defines technologies that are close to commercialisation, with no outstanding engineering constraints, but which carry manufacturing risks, due to limited experience with large-scale production, and commercial uncertainties. Technologies on this level typically require three to five years before they reach the market.
- The Efficient Technology Level (EFF) comprises technologies that are relatively advanced but which need some technical development before production and commercialisation can be considered, although such development is limited to incremental improvements based on known designs. These technologies typically need a further 10–15 years to reach the market.
- The Maximum Development Technology Level (MAX) refers to breakthrough technologies which fall outside current development trends. Such technologies are at very early stages of development, so they carry high risks in engineering, production and commercialisation. They do not represent the maximum *theoretical* improvement potentials, but the maximum *practical* potentials given the assumptions of the project. The timescale for marketing is typically 10–25 years.

Figure 14 shows the expected effect of the application of various technology levels in transport by 2030, assuming that the demand for each mode of transport continues at its 2002 level. The maximum potential energy saving is just over 60%, with a greater effect on passenger transport than on freight. When comparing technology levels, the most significant difference is between MOD (no technical development needed) and EFF (some tech-

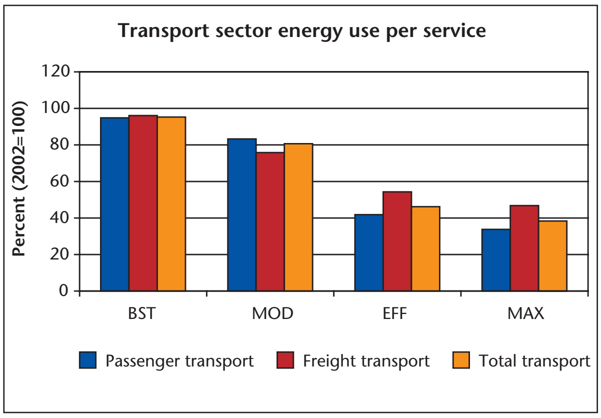

Figure 14: Impacts of Technology Levels on transport sector’s energy intensity, that is, the energy consumption, if the 2002 level of energy service, like passenger*km or tonne*km, is maintained (index 2002=100).[15]

nical development needed). EFF transport technologies include fuel cell vehicles and advanced combustion engine technologies.

The time needed for new technologies to reach their full energy-saving potential depends partly on the incentives used. The shortest realistic implementation time would be the sum of the technology's lead time to market, the time needed for sales to take off, and the time needed to replace the current stock of vehicles - though there is usually some overlap between these phases. The shortest full-scale implementation time would therefore be 15–20 years for BST, 20–25 years for MOD, 30–35 years for EFF and 30–45 years for MAX. A transition to renewable fuels would introduce further complications, but would not necessarily delay full-scale penetration of new technologies as long as we start the process soon. Renewable fuels generally require EFF or MAX technologies [15].

Efficiency improvements in liberalised markets

To create a demand shift towards energy-efficient technologies it may be a good idea to back up economic incentives with appropriate regulatory measures. Economic theory says that higher energy prices will encourage users to invest in energy efficiency improvements as they attempt to recoup some of the extra cost; conversely, lower energy prices encourage energy consumption.

We would therefore expect that raising energy prices, say by increasing taxes, would improve energy efficiency. Unfortunately, energy taxes increase the cost of industrial production, and so reduce economic growth. Uncompensated energy taxes introduce a wedge between the energy prices perceived by consumers and those perceived by energy producers, making a socially fair distribution of costs impossible. What we need is an instrument with the specific purpose of stimulating energy efficiency improvements at minimum cost to society.

A traditional energy policy solution would be to impose a tax on energy consumption and use the revenue to support energy efficiency improvement projects. This is clearly more effective than an energy tax alone, but the problem of energy price distortions remains. More effective policy instruments could use market information to create less distortion.

A promising alternative to energy taxes is the concept of Tradable White Certificates (TWCs), which attempts to internalise energy efficiency improvements within the electricity markets. TWCs are issued to electricity consumers who have documented investments in energy efficiency improvement.

Many countries are developing TWC certification processes following a proposal from the European Commission for a directive on energy end-use and energy services [19]. The proposal has not yet been ratified, and was amended in March 2005. Its target is an annual energy saving of at least 1%, and a large number of policy measures have been short-listed with this in mind.

TWCs are already implemented in Italy. They follow the paradigm set by Italian green certificates, where electricity producers carry the obligation to buy. In France, a proposed law says that electricity producers should either obtain white certificates to meet the savings target or pay a penalty for non-compliance. In the UK, the programme called the Energy Efficiency Commitment puts a legal obligation on both gas and electricity suppliers to reach an energy savings target. The TWCs themselves have many names, including Energy Efficiency (EE) Commitments, EE Obligations, EE Titles and EE Certificates.

Because TWCs are issued for investments in energy-saving equipment, they do not address those energy efficiency improvements that are achieved through changed behaviour.

It is likely that to be awarded a TWC the technology introduced will have to meet a pre-defined efficiency threshold. This will ensure that TWCs promote "tomorrow's technology" instead of just "yesterday's technology".

The case of Denmark

Several surveys in Denmark have looked at potential end-use energy efficiency improvements. In spring 2005 the Danish Energy Agency presented a study of socio-economic and private economic saving potential [20]. Figure 15 shows the estimated efficiency improvement potentials for different end-use technologies in the Danish energy system. Keeping the same level of energy services as today then e.g. electricity consumption for lighting can be reduced to 75% by introducing the socio-economic investments. Taking private economic investments into account it can be reduced to 40% and by

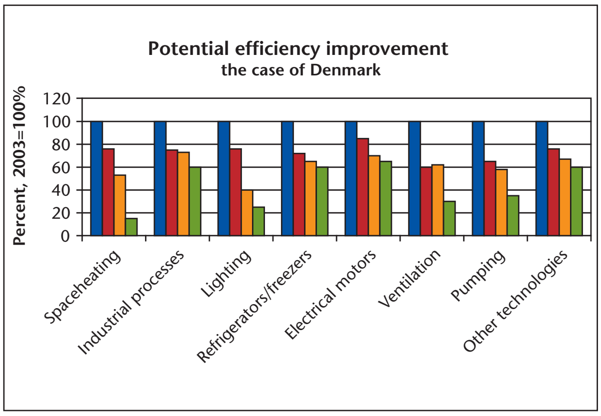

Figure 15: The potential for improving end-use energy efficiency in Denmark. Column 1 (100%) shows consumption today; Column 2 shows socio-economic investments that are profitable up to 2015. Column 3 shows private investments that are profitable, assuming the present pattern of energy tax, up to 2015. Column 4 is a conservative estimate of technically-possible efficiency improvements (not theoretical limits). [20]

including technical-possible improvements electricity consumption for lighting can go down to 25% of today.

Excluding energy used for transport, space heating accounts for more than half of Danish end-use energy consumption. Next come industrial processes and "other" technologies, each consuming around 16% of all end-use energy. These three fields have the largest potential for saving energy by improving efficiency.

Short-term savings in energy used for space heating will be made mainly by replacing existing windows with new energy-efficient ones. Long-term improvements include better standards of insulation for the rest of the building envelope, and ventilation systems with heat recovery.

Energy losses from industrial processes can mainly be reduced by increasing the efficiency of thermally-intensive processes and recovering surplus heat for use elsewhere in the process, or for district heating.

"Other technologies" includes all kinds of electric appliances in households and industry. Energy reductions here are achieved by increasing the market share of the most energy-efficient appliances.

Implementing energy-saving measures that are socio-economically profitable would reduce Danish end-use energy consumption by 25% by 2015, if the present level of energy services were maintained. Energy taxes in Denmark mean that private investments in energy saving could produce a considerably bigger energy saving - 40% - in the same period. Taking the estimated technical potential into account, the reduction could be 65%.

Concluding remarks

End-use improvements in energy efficiency reduce the consumption of primary energy such as fossil fuels and decrease the resulting environmental pollution as primary energy is converted into power, heat and traction. Energy savings can postpone the need to build new power stations and heating systems, create more comfortable living and working environments, and cut utility bills.

Adding up the possible efficiency improvements shows that we could reduce end-use energy consumption by 20–50% over a twenty-year period, or 1.0–3.5% annually. This is barely enough to balance expected global economic growth over the same period - 100% in 25 years, or around 3% per year, according to the IEA [21] - but it is still significant. In 2005, the EU Commission presented a Green Paper on energy efficiency [24] discussing how EU could achieve a reduction of the energy consumption of the EU countries by 20% compared to the projections for 2020 on a cost-effective basis. Improving "lifestyle" energy efficiency by changing human behaviour could yield even larger reductions, but these may be difficult to achieve and have not been further considered here.

Despite the obvious benefits of efficiency improvements, ordinary market forces will not be sufficient to drive all of them to their fullest extents. Some improvements may require regulatory sticks, and others may need economic carrots introduced through policy changes; an example is the introduction of Tradable White Certificates. We have mentioned a study which showed that retrofitting all residential buildings in Denmark in the period up to 2050 could reduce heat loss by 80% [8]. However, it is doubtful if this target could be reached without new laws or economic incentives.

Much of the potential for efficiency improvement lies in technological developments that have not yet reached the market. We have mentioned a number of areas where R&D investments can yield a high payback by reducing energy costs. For Denmark, promising research areas include energy-efficient lighting and ICT-based systems for monitoring and controlling energy consumption. Success in these research areas could create innovative Danish companies with good market opportunities. It is also important for Danish industry to continue to develop established markets for insulation products, windows and heat recovery systems.

7

Flexibility, stability and security of energy supply

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Decentralised power generation based on renewable energy sources can – and is expected to – provide a significant contribution to a sustainable future energy supply. Depending on penetration levels and system characteristics, such an increased use of renewable and decentralised generation creates new requirements for both generating units and the power system as a whole, so as to optimise operation and maintain power quality and power system stability.

State of the art decentralised power plants are typically characterised by:

- lower installed capacities of individual units than the centralised power plants in the system;
- grid connection to the distribution system grid rather than to the transmission system;
- dependency on the availability of a stable power system; and
- lack of responsibility for the reliability and control of the power system.

In general, renewable energy sources such as wind, solar and hydro are also characterised by their intermittent production due to variations in wind speed, solar radiation and water inflow, though the timescales involved are different for each energy source.

Typical problems that appear as decentralised or renewable power generation increases are:

Phase 1: Local power quality problems

Maintenance of local power quality is a typical problem that occurs at low levels of decentralised power generation. In this context, the main power quality variable is the voltage in the distribution system. Voltage quality problems include the slow and steady variations in voltage amplitudes which must be limited e.g. to protect equipment against thermal overload, more rapid voltage fluctuations contributing to flicker in the light from bulb lamps, short voltage spikes and dips which may damage or interrupt equipment, and harmonic emission from power converters which has to be limited due to distortion of communication equipment and for other reasons.

Phase 2: Global system control and stability problems

At a certain penetration level of decentralised power plants the influence on power system control and stability has to be taken into account. Presently, most decentralised power plants only produce power, and they do not contribute to the ancillary services required to control the power system and ensure stable operation. The main stability related service is the so-called “fault-ride-through” capability, which ensures that the power plants will stay connected during and after faults in the power system. Other important services from power plants are contribution to voltage amplitude and frequency control.

Power system characteristics

The penetration level at which a particular power system experiences these various problems depends on its characteristics. In the following sections, three very different power systems – in Denmark, Ireland and India – illustrate problems that can occur as the share of decentralised generation and renewable energy increases.

West Denmark

The West Danish power system is synchronously connected to UCTE, the central European power transmission system. UCTE is one of the largest synchronously-interconnected power systems in the world, supplying more than 150 million consumers, from Denmark in the north to Italy in the south and from Portugal in the west to Romania in the east (Figure 16). The UCTE connection, together with DC connections to the Nordic power system, gives strong power-balancing support to the West Danish system. Wind power development in North Germany, however, limits the amount of electricity that the West Danish system can export during periods of high wind.

In 1988 the total capacity of decentralised combined heat and power (CHP) plants in the West Danish power system was 150 MW, and the total wind power capacity

Figure 16: Member countries of the UCTE (Union for the Co-ordination of Transmission of Electricity). (Source: www.ucte.org)

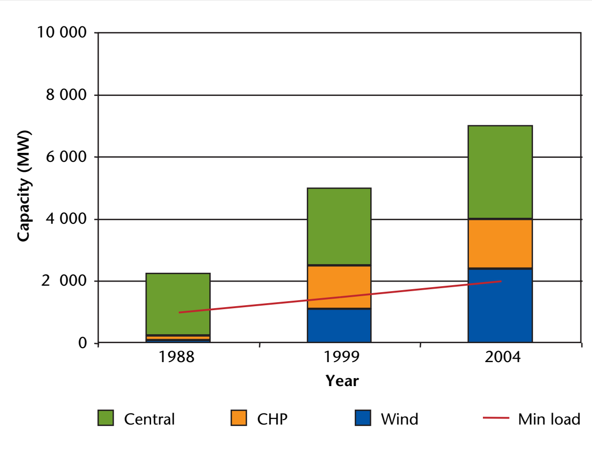

Figure 17: The rise in decentralised CHP and wind power in the West Danish power system, 1988–2004.

was 100 MW. This low level of penetration, in a system whose minimum load is more than 1000 MW, had little effect on the power balance.

As the wind turbines were concentrated in rural areas with low load densities and relatively weak power distribution systems, however, local power quality became an issue. As a result, in 1988 DEFU[7] issued recommendation KR-77 for the grid connection of wind turbines [1]. The power quality requirements in KR-77 are summarised in Box 1 below.

Grid connection of wind turbines to LV (400 V) or MV (10 kV) grids.

Wind turbine requirements:
- inrush current limitation equipment
- limited number of inrushes
- reactive power compensation (capacitor banks)
- grid fault protection

Grid requirements:
- voltage quality influence
- LV grid voltage
- LV / MV transformers

Box 1: Requirements for the grid connection of wind turbines in West Denmark in 1988 (KR 77 recommendation issued by DEFU).

By 1999 distributed CHP had increased to 1400 MW and wind capacity to 1100 MW. At the same time the Danish government in its Energy 21 plan set a target of 50% wind power penetration by 2030, requiring an additional 4000 MW of offshore wind power, developed as large offshore wind farms.

The two main concerns at the time were the effects of wind power on system reliability and power balance. The issue with reliability was that a grid fault on the transmission system could cause disconnection of many large wind farms simultaneously, which would cause the sudden loss of a significant generation. The power balance concern was that on cold and windy winter nights, demand for heat from CHP plants would be high, but demand for power from the same plants would be low because the wind farms would be generating at full capacity.

With this background, Danish transmission system operators (TSOs) were the first to develop a grid code specifically for large wind farms connected to the transmission system [2]. The code specifies how wind farms should behave in the event of grid faults, and how they should participate to the control of the system voltage and frequency.

By 2004 decentralised CHP capacity had reached 1600 MW and the installed wind capacity was 2400 MW. In this year 30% of Denmark's electricity was supplied by decentralised CHP plants and 23% by wind turbines, so decentralised generation accounted for more than 50%.

Meanwhile, the grid connection requirements have been upgraded to cover both individual wind turbines connected to the distribution system and large wind power plants connected to the transmission system [3], [4].

In Germany the pattern has been quite similar: the guidelines first covered local power quality, and then, as wind power penetration grew, they expanded to include requirements affecting reliability. The German rules for the behaviour of wind power:

Definition of power quality characteristics for wind turbines:
- maximum power
- reactive power
- flicker and voltage drops
- harmonic currents

Measurement procedures for power quality characteristics.
Assessment of influence of multiple wind turbines on grid power quality.
Requirements to the power quality characteristics in KR-111 and other national specifications are based on IEC 61400-21 characteristics.

A new revision of IEC 61400-21 will also include characteristics for:
- fault ride through
- power control - inclusive contribution to grid control of voltage and frequency.

Box 2: The main points of the IEC 61400-21 standard for characterising wind turbine power quality.

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[7] DEFU: The Danish Utilities Research Institute (www.defu.dk).

Frequency regulation (primary) reserve consists of both up- and down-regulation reserves that are activated momentarily when the frequency changes, such that the total amount of reserve is activated at ± 0.1 Hz deviation from 50 Hz. The required amount is decided by Nordel.

Momentary disturbance (primary) reserve consists of an up-regulation reserve that is activated automatically when the frequency drops to between 49.9 and 49.5 Hz. The required amount is decided by Nordel using the so-called N-1 criterion for the whole of the Nordic system, i.e. the system should be able to handle loss of the largest generating unit in the Nordic system. Planned, automatic shedding of consumption such as electric heating can be part of the momentary disturbance reserve.

Fast (secondary) reserve is up-regulation that is activated manually and has to be available within 15 minutes. It can be delivered by both production and consumption. The required amounts are decided by the different system operators using a N-1 criterion for each country considered separately.

Slow (tertiary) reserve is up-regulation reserve activated manually, with a warning time varying from one to several hours.

Box 3: Nordel classification of the types of reserve capacity needed to maintain the power balance. (Source: Nordel, www.nordel.org)

plants during grid faults are part of the general requirements covering all high-voltage and extra-high-voltage grid connections [5].

To provide an international reference for national power quality requirements, standard IEC 61400-21 for power quality from wind turbines was issued in 2001 (Box 2) [6]. Although the IEC standard specifies how power quality from wind turbines should be measured and assessed, it forms a basis for national standards such as the Danish KR-111 [7], rather than replacing them.

IEC 61400-21 is currently under revision; the plan is to include specifications for behaviour during grid faults and responsibilities for voltage and frequency control. This reflects the fact that in several power systems, rapid growth in installed wind power capacity has altered the focus of concern from local power quality to issues of system reliability and power balance.

Ireland

Ireland has good wind potential, but its power system has limited interconnection capacity: a single 500 MW DC link to Scotland. This makes the issues of wind power integration, power balance and frequency control much more challenging than in West Denmark.

India

The Indian power system combines weak grids with a substantial amount of installed wind power capacity. It is therefore a good place to study the influence of weak grids on the economics of wind energy [8], as well as issues of power quality and the ability of the grid to integrate wind power [9]. The system frequency is essentially controlled by load shedding in the daytime, and the frequency variations are very high compared to those in developed countries. Large motor loads for pumping water also challenge the grid's voltage stability, and this makes the issue of power quality from wind turbines even more important. However, "power quality" has a different meaning in systems where grid outages are daily events.

Power system issues

Decentralised power generation and the use of renewable energy may affect power system issues including power quality, power balance and system stability. These issues are now dealt with for new wind power installations.

Power quality in the distribution grid

The need to keep the steady-state voltage seen by consumers within acceptable limits is normally the main design criterion when connecting decentralised generation units to the distribution grid. In many connection points in the distribution grids, the short circuit level is critically low, which will cause large voltage variations. On the other hand, it is important to limit the costs of the grid reinforcement, which is typically the solution to increase the short circuit level and thereby limit voltage variations.

Flicker, a measure of rapid voltage fluctuation, is a dominant issue in the German guidelines and in IEC 61400-21. The fluctuating power output of wind turbines contributes to voltage fluctuations in the grid, and standards have been developed to quantify this. However, flicker does not normally prevent wind turbines from being connected to the grid.

Electronic frequency converters and other power electronic devices emit harmonic distortion onto the grid. Harmonics can damage capacitors and other components on the grid, and can distort the electromagnetic environment.

Power balance and frequency control

In any power system, the instantaneous power production must be maintained in perfect balance with power consumption at all times. The TSOs use different types of reserves to maintain this power balance, as the Nordel[8]

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[8] Nordel is a body for co-operation between the transmission system operators (TSOs) in the Nordic countries (Denmark, Finland, Iceland, Norway and Sweden) (www.nordel.org).

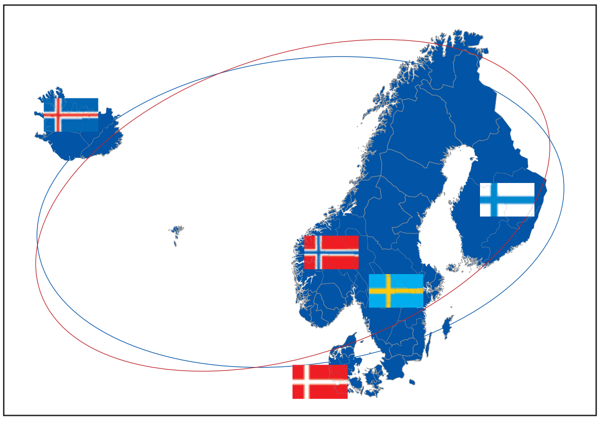

Figure 18: The Nordel area. (Source: www.nordel.org)

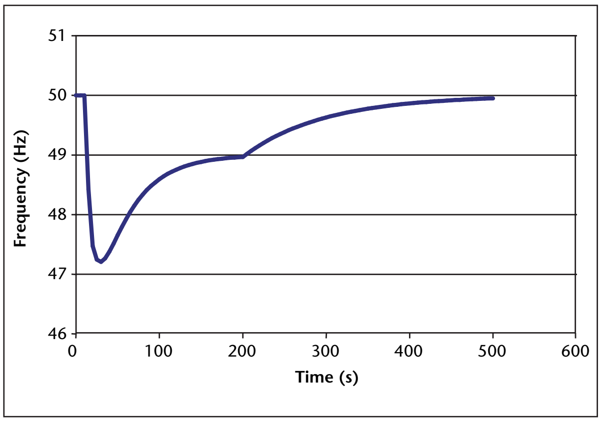

Figure 19: Frequency regulation using primary and secondary reserves after the failure of a central power plant.

classification of reserve capacity shows (Box 3) [10]. The Nordel market area comprises the AC-connected synchronous Nordic system (Norway, Sweden, Finland and East Denmark) and West Denmark, which is connected to the synchronous Nordic system via HVDC links. Besides, Iceland is a member of the Nordel organisation. The member states are shown in Figure 18.

The reserves are activated whenever planned production and expected consumption deviate from actual production and consumption. The system operates as a cascade. As soon as there is a power imbalance, the frequency changes and the primary reserve reacts very rapidly to counteract this. Next, the secondary reserve is activated manually (or automatically using Automatic Generation Control, AGC) by the TSOs. Activation of the secondary reserves relieves the primary reserves, which enables it to handle new deviations (Figure 19).

Deviations between power production and consumption have three main causes: errors in forecasting consumption, fluctuating production, and outages of power plants or transmission lines. In the Nordic system, Nord Pool[9], producers and consumers sell and buy electricity on a day-ahead market: obligations to produce or consume power are undertaken 12–36 hours before the power is actually delivered or consumed. Wind power producers base their day-ahead sales on wind forecasts for the corresponding period, and these are less reliable than the forecasts of electricity consumption relied on by buyers. Therefore as the amount of wind power in the system increases, power balance predictions become dominated by the error in predicting wind power production.

As Box 3 shows, the necessary sizes of both primary and secondary reserves have traditionally been determined by the N-1 criterion - the amount of reserve needed to cover the loss of the largest generating unit in the whole Nordel system (for primary reserves) or the region covered by each TSO (for secondary reserves). As the amount of wind power increases, the wind power forecast error starts to increase the required size of reserves, especially secondary reserves.

Decentralised production can add control capacity to the system. Currently, production by decentralised CHP units in Denmark is driven by the demand for heat, so power production may vary unexpectedly. To improve the situation, tariffs have been introduced that encourage CHPs to give more importance to power production, but the control capability of decentralised CHP is still underused. Using surplus power to generate heat that can be stored by the CHP unit could support the system power balance.

Power control of wind turbines is a less obvious solution to imbalance between supply and demand, because, unlike with a conventional generating plant, down-regulated wind power is lost forever. However, the Danish grid codes require large wind farms and new large wind turbines to have active power control. The two largest wind farms in Denmark, Horns Rev (160 MW) and Nysted (165 MW), both have controllers which support active power control. The wind farm controllers are used by the TSOs to maintain stability in critical situations, while power producers owning both wind farms and conventional power plants take advantage of the rapid controllability of wind farms to balance the much more sluggish response of conventional power plants.

Reactive power and voltage control

Modern wind power plants are equipped with components that make it possible to participate in the control of reactive power and voltage. Wind turbines with electronic power converters can control their reactive power

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[9] Nord Pool ASA - The Nordic Power Exchange - the world's first multinational exchange for trading electric power, established in 1993 (www.nordpool.com).

continuously, while turbines with shunt capacitor banks can control reactive power in discrete steps. When the grid voltage decreases, power electronics provide better reserves of reactive power than shunt capacitors. This is important because reactive power is mostly needed during voltage dips.

Today, distributed generation typically operates with a fixed power factor (reactive power). With appropriate co-ordination, however, it is possible to use reactive power control of distributed generators to control the grid voltage. This system has already been tried in several wind turbine and wind farm controllers, but voltage control does not appear to be used as the normal mode of operation in any existing installations. The ability to support frequency and voltage control is a requirement for new wind turbine installations in Denmark, not only in large offshore wind farms but also for individual turbines connected to the distribution system.

Grid fault behaviour and reliability

As mentioned above, the fault behaviour or “fault-ride-through” capability of wind power is a key issue in the large-scale use of wind power in power systems. The purpose of fault-ride-through is to ensure that wind turbines are able to stay connected to the grid during a grid fault. They should not trip out when a short circuit on the grid causes undervoltages, overcurrents, overspeeds, nor under any other condition that goes outside the limits imposed by the systems which protect the turbines from damage under fault conditions.

If wind turbines are not able to ride through the fault, they will trip. The consequence is a sudden loss of generation which must be replaced by fast reserves from other generators to prevent loss of load. Fault-ride-through is not unique to wind turbines; similar capabilities are required of conventional generators to ensure that the system will continue to operate if one generating unit fails (the N-1 criterion again). The Nordic system is operated in such a way as to be able to withstand the sudden loss of the largest generating unit, which is 1000 MW. In Ireland, the corresponding figure is only 400 MW [11]. In both cases, it has to be taken into account if wind turbines without sufficient fault-ride-through capabilities could trip simultaneously with the largest generating unit, due to the same grid fault.

Fault-ride-through is very challenging for the wind turbine industry, and significantly increases the costs of wind power. Jauch *et al* [12] have compared the fault-ride-through requirements of different TSOs, and Bolik [13] has studied the ability of a wind turbine manufacturer to meet these requirements.

Another system reliability issue arises when part of the grid becomes isolated from the main synchronous system. If the isolated area is able to control its own frequency and voltage, then a blackout can be avoided. Dynamic control of decentralised generation can enable the isolated grid to stay in operation.

Long-term security of energy supply

Wind energy contributes to the long-term security of energy supply. The EU Green Paper on security of supply predicts that if existing trends continue, by 2020 more than 70% of the EU’s energy will have to come from imported fuels [14]. Limited resources and political uncertainties cause fuel prices to be unstable, and in the long term to rise. Wind energy, which now supplies Denmark with 20% of its electricity, is important in making the economy less sensitive to fuel price changes.

Conclusions and recommendations

In this chapter we have used wind power and decentralised CHP to demonstrate some of the characteristics, problems and options affecting the integration of decentralised generation and renewable energy into the power system.

Large wind farms cannot necessarily be treated as decentralised generators; instead they behave more like conventional (if less controllable) power plants. On the other hand, the introduction of micro-CHP for individual households may mean that CHP generation becomes even more distributed in the future. With its ability to generate electricity as required, while storing the resulting heat until it is needed, CHP has huge potential for adding flexibility to power systems.

Fuel cell technology is promising for CHP. For instance, micro-CHP units based on reversible fuel cells operating on natural gas could add flexibility to energy systems by operating outside their normal role of producing electricity from natural gas. At times when electricity is cheap and gas prices are high, micro-CHP plants could use electricity to generate hydrogen. This could then be fed back into the gas distribution system, which can carry at least 10% hydrogen without any technical problems.

In the longer term, other renewable technologies such as photovoltaics (PV) may become significant. One of the advantages of photovoltaic technology is its ability to be integrated into buildings, and so to produce power where it is needed. PV generation is therefore likely to be highly distributed, like micro-CHP. The fact that PV generation cannot be controlled sets new requirements on system flexibility.

In a power system based largely on distributed small-scale generators, these small units need to play their part in providing system-level services including system stability, security of supply and power quality. This imposes new requirements on control, regulation and communication for both the generators and the system. The generators must be able to provide the services required by the system; the system must be able to keep track of its own requirements; the communication system must be able to collect status information from all parts of the system and provide control information to the generators; and the overall control system must be able to maintain stability, security of supply and power quality. There is no experience of doing this in large systems, and the design of suitable control systems is very challenging.

Our main conclusion is that because different power systems have very different characteristics, the issues raised by distributed generation are also very different. For small-scale use of wind power, power quality in the distribution system is the main issue. For large-scale integration of wind power, global system issues such as reliability and control of frequency and voltage become more important. Large wind power plants require fault-ride-through to an extent that depends on the grid structure, including the protection scheme used. Therefore, to reduce the costs, distributed generation will always have to live with different requirements in different grids.

8

Interaction between supply and end-use

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Introduction

In a future power system with a high proportion of distributed and intermittent generation, it will be difficult and costly to ensure short-term security of supply if demand is unable to react to fluctuations on the supply side. At present, most power consumers in the EU, with the exception of the largest consumers such as energy-intensive industries, buy their power on fixed tariffs. Fixed tariffs provide no incentives for consumers to alter their patterns of power consumption.

This calls for more interaction between the supply and demand sides, which in turn would allow better matching of demand to intermittent supply. The development of cheap and reliable electronic communication technologies has made this a realistic option, so we are left with the general question of how the demand side can become more active in the future power market.

Liberalisation of the wholesale power markets has introduced market-based pricing for the marginal electricity supply. Prices are set hourly, or even more frequently, by reference to the balance between the expected demand and supply at the time. If the expected demand exceeds supply, prices increase until demand falls or more generation comes on line. If supply exceeds demand, prices fall. In this way, market prices are used to determine the balance level between generation and consumption.

In liquid markets, the power price is a reliable indicator of the state of the electricity system. Price fluctuations reveal the cost of marginal production capacity; very high prices indicate that capacity is limited compared with demand.

At present, it is mostly the generation side that adjust their supply in order to create balance between supply and expected demand. If demand, as well as supply, could respond to price signals from the market, the flexibility of the energy system would increase. This would make it easier to increase the proportion of intermittent renewable energy sources in the system.

Demand response (DR) is the term used to describe the short-term response in demand to different prices. As examples, electricity consumers can achieve DR by reducing consumption during periods of peak load (and peak prices), shifting consumption to periods when prices are lower, or replacing electricity with other energy resources.

By shifting demand according to price signals from the market, DR can reduce the peak-load levels and the necessary reserve generating capacity, and thereby reduce the cost of securing short-term security of supply. When there is a generating shortfall, prices will rise. The rise in the prices may act as a signal to the demand side to respond by decreasing the demand.

Creating an effective DR mechanism requires us to know when, and for how long, the electricity will be used or not used, and how much notification time is needed to allow demand to react to price changes. All these factors may vary, so we need to find a pricing mechanism that is broadly applicable.

The issue of short-term supply security can be divided into several sub-problems with different timescales. In real time, the power balance is a physical issue: shortage of capacity manifests itself within seconds as a drop in frequency on the grid. At timescales of hours or days, maintaining the balance between expected generation and consumption is a market issue, in the sense that the market balance is set some time before the physical balance take place.

DR and the security of supply problem thus take different forms depending on the timescale we look at. We must therefore expect that the corresponding markets, actors, price signals and regulation mechanisms will also differ according to the timescale.

This chapter shows that existing liberalised power markets are well set up to handle the new mechanisms for DR that could encourage the introduction of more distributed generation and intermittent renewables. Using the Nordic power market as a case study we show how DR can be categorised and priced, and examine future technical options for increasing flexibility on the demand side.

Demand response on the Nordic Power Market

Nord Pool, the Nordic power exchange covering Denmark, Norway, Sweden and Finland, consists of several markets addressing different notification times - the time between market clearing (the determination of price and quantity) and delivery. The Nord Pool Spot Market is a “day-ahead” market, with 12–36 hours of response time between market clearing and delivery. The balance market, Elbas (Electricity Balance Adjustment Service), is open until two hours before delivery. In addition to these two markets, the Nordic transmission system operators (TSOs) run a Regulating Power Market,

Figure 20: Markets and response timescales related to Nord Pool.

which has a notification time of 15 minutes. In connection to these markets at Nord Pool, each country also runs its own reserves market, with notification times measured in seconds.

Using Figure 20 as a guide, we can describe the issues relating to security of supply and DR at different timescales. Security of supply on a timescale of days is handled by the Spot Market. Shortage of capacity will show up in situations such as outage of a large power plant combined with a limited wind power production forecast and expected high demand for electricity. The latter is typically due to low temperatures throughout the area, since heating accounts for a large part of household electricity demand in the Nordic countries.

At this timescale, DR is generally a matter of shifting consumption from peak load periods to normal or baseload periods. This will only happen if consumers are able to respond to spot market prices, e.g., if the consumers announce a lower demand at higher spot prices (real-time pricing). Another way to create incentives is to use time-of-use pricing, for instance, if tariffs for electricity consumed during the night are cheaper than those for the daytime.

Security of supply problems within hours can be handled at Elbas. Of all the wind power traded on the day-ahead spot market, only 70%, on average, is actually delivered. The remaining 30%, delivered at unplanned times [5], can be traded on the two-hour Elbas market, where it fetches better prices than on the 15-minute Regulating Power Market.

Power balancing on a response timescale of minutes can be done either through rapid-response reserve generating capacity or through regulating power that can react within 15 minutes. At present it is the individual Nordic TSO’s that run these markets. The consumer side can offer up-regulating power by cutting down their planned demand, or offering down-regulation power by increasing their demand. Consumers with backup generation (BUG) or combined heat and power (micro-CHP) may do this without affecting their actual electricity consumption, because any reduction in power taken from the grid can be replaced by generating their own power.

The amount of DR available from a particular type of consumer at a particular time depends on the pattern of demand for that type of consumer. Water treatment plants, for example, may be set up to use most of their electricity during the night, when prices are lower. These plants can therefore offer larger reductions in consumption during the night than during the day.

Power systems also need “instantaneous” reserves, with notification times measured in seconds, to cope with sudden failures of power plants and transmission lines. Such reserves must meet the imbalance for up to 15 minutes, until extra capacity can be brought on line, though in practice they are often needed for only 1–5 minutes.

One way to obtain this kind of DR is to establish agreements with private consumers regarding controlled power-cuts during periods of peak consumption. A Danish questionnaire analysis [3] has shown that controlled power-cuts in the households can be obtained at a cost of approximately 0.7 €cent per kWh.

So far, DR has not been used for instantaneous reserves in Denmark. In New Zealand, however, household water heaters are used to provide instantaneous reserves; in the event of a fault, signals transmitted over the power lines by ripple control technology switch off water heaters within six seconds to reduce demand [1].

The New Zealand system uses a monthly auction to set the price of this reserve capacity (DR), with the grid company acting as an intermediary between individual households and the TSO. The typical amount of DR available using this system is 1 kW per household, and in 2002 each household earned an average of €15.5 per year in return for the possibility of interruptions to its hot water.

The main symptom of an immediate shortage of generating capacity is a drop in frequency on the synchronous grid. Suitably-designed consumer electrical equipment can detect this frequency drop and adjust its demand automatically, rather than having to wait for an external signal as in the case of the New Zealand water heaters. Danish TSOs have decided to make an initial experiment with frequency-controlled equipment in households and businesses [6]. Important questions include how much of this DR capacity to install, and how to manage the evolution of the system as the installed base of equipment changes over time.

Categorising demand response

From the discussion above it is clear that the various trading mechanisms in the Nordic power market, with their corresponding response timescales, could support greater degrees of DR. We can categorise this DR into timescales of days, hours, minutes and seconds (Figure 20).

The first three rows of Figure 21 show the characteristics of the various security of supply issues and their markets, while the fourth row shows possible DR solutions.

Using markets for DR obviously requires individual power consumers to participate in these markets, through mechanisms such as demand-side bidding or online pricing. If consumers cannot react before the market price is finalised, they will not be able to affect either the price or the supply-demand balance during that market period. In this case, however, they can still bid in markets with shorter response times; if spot market prices are high, for instance, consumers could take action on the balance market.

If the announced supply cannot meet demand in a particular market, the conventional solution is for supply prices to rise until it becomes economic to bring more generating capacity on line. DR takes a different

	Days	Hours	15 minutes	Seconds
Problems:	Allocation of demand and production	Adjustments of planned production	Maintain the frequency and system conditions	Fast decrease in frequency
Causes:	Where to produce? Shortage of capacity Imbalances in the spot market	Prognosis errors Excess capacity	Prognosis errors Failures	Failures in plants or transmission lines
Markets:	Nord Pool Spot Time of use tariffs	Elbas / balance power Two-hours ahead Real-time pricing Dynamic pricing Contracts	Fast reserves Regulating power Contracts	Contracts Ancillary service Instantaneous system disturbance reserves
DR actions:	Load management Consumers active at the spot market	Adjust central production Own production Contracts between TSO and consumers Consumers active at the balance market	Consumers active at the regulating power market Contracts between TSO and consumers	Automatic activation of reserves Disconnection of consumption

Figure 21: Demand response (DR) categories and timescales for the Nord Pool market.

approach: as prices rise, demand falls until the system is balanced. This means that both the final prices and the amount of electricity traded are decreased and critical supply-demand situations that can cause problems in the present markets may be avoided.

Very large consumers can do their own trading in the markets, but most consumers would need to delegate trading to their supply companies. Under this system, consumers would sign contracts with the supply companies saying how flexible they are prepared to be within each timescale, and what payments they would receive for this flexibility. The supply companies would then make price-flexible bids on the markets, and activate this flexibility as necessary once market prices has been fixed. An example of this is the abovementioned case from New Zealand, where the demand for water heaters in some households are offered as demand response within seconds.

Future technical options

As mentioned above, there are also DR solutions that do not require market trading. The simplest of these is equipment programmed to favour fixed time periods when demand and prices are low, such as at night (time-of-use tariffs). A more sophisticated solution is to use frequency-sensitive devices that cut out when the frequency falls below a certain limit. Neither of these solutions requires communication with other equipment or central control systems. However, they do require detailed metering.

The next level of load control is to use one-way communication from a control system to disconnect the required number of consumer devices, as in the case of the New Zealand water heaters. All three of these solutions are relatively cheap and easy to implement, but they are limited in their applications.

In a more advanced system, individual loads such as households, businesses and factories would play the markets in real time, bidding on load increases or decreases at several timescales. This will require much more intelligent communication between the loads and the grid, and between the market participants, as well as a schema to ensure the integrity of trading. The development of such a system will be driven by improvements in information and communication technologies, and the increased use of flexible micro-CHP units and advanced intelligent power systems on the demand side. Chapter 9 discusses communication in more detail.

The link between electricity and heat provided by household micro-CHP systems can contribute to short-term flexibility in the electricity system by making use of the capability to store energy in the form of heat from one hour to another. When supply of power is in short while heat demand is low, micro-CHP systems can generate at full capacity and store the surplus heat, for instance as hot water. When supply of power is not needed while extra heat is needed the household can draw on the stored hot water. This option requires the micro-CHP units to have a surplus capacity above the average heat demand, and a system for short-term heat storage - both of which will normally be the case anyway.

As new technologies develop, the potential for more flexible household appliances increases. Micro-CHP systems based on reversible fuel cell technology fuelled by natural gas, for instance, have the additional advantage that when excess power is available they can run in reverse, using electricity to generate hydrogen which can then be fed back into the natural gas grid. The gas distribution network can carry up to 17% of hydrogen without problems.

Case 1: Technical options for micro-CHP in Denmark

Denmark has 2.5 million households, of which 1 million have their own heating units. Of these, half (500 000) are fuelled by natural gas (2003). The average consumption of a single household is 60 GJ/y (or 2 kW in average) of heat and 15 GJ/y (4 MWh/y or 0.5 kW in average) of electricity.

If half (250 000) of these household boilers were replaced by 50%/50% micro-CHP units rated at twice the average heat demand (in average 4 kW electricity + 4 kW heat, necessary to meet peak heating requirements) over the day, producing the heat required by the households, this would create 1 GW of flexible electricity generating capacity producing 4 TWh electricity annually in order to meet the annual heat demand. The households themselves would use 1 TWh of electricity annually, so 3 TWh of surplus electricity could be exported to the grid. This represents 10% of total Danish annual electricity consumption (2003) [7].

Case 2: Technical options for electric vehicles in Denmark

The Danish transport sector used 175 PJ of energy in 2004, and by 2030 this is expected to increase to around 200 PJ/y. If 1 million vehicles (about 40% of the fleet) were to be battery-powered by 2030, their electricity consumption would be around 2 TWh/y. This would require a 6% increase in Denmark's electricity production, according to the national energy plan Energi21 [4].

Therefore, the transport sector too might come to play an important role in the power markets. Large-scale use of battery-powered or hydrogen fuel cell vehicles would/could require large amounts of electricity to charge batteries or generate hydrogen by electrolysis. Since charging is flexible and could be done in low load periods of the day, it could provide effective DR. Power stored in vehicle batteries also forms a reserve that could be fed back to the grid if necessary.

When the vehicles are connected to the power network, electric communication between the household and the system operator of the power network makes the fleet of electric vehicles a potentially very flexible consumption group. The demand for recharging the batteries can be coordinated according to the need for demand response and the actual need for using the vehicles.

Long-term perspectives and technological challenges

New DR programmes need to be developed. The power exchanges have to be designed in order to on the one hand, to handle the future increase in intermittent generation, and on the other hand, to allow demand to respond to the supply.

Communication systems will continue to develop in the future. This will open new opportunities within the power system, with the demand side playing an active part in both local intelligent supply-demand systems and regional systems. Further research in systems analysis is needed so that we can create a system that is optimal for society, consumers and power suppliers.

There are technological challenges as well. Fuel cells, for instance, could become key components of decentralised energy technologies such as micro-CHP, energy storage and energy conversion. In these roles they would provide the basis for interaction between supply and demand, and so add the flexibility needed to support large-scale use of intermittent renewable energy.

Besides being able to run in reverse, fuel cells may reduce pollution from NO_x and other undesirable by-products compared to conventional energy conversion technologies. Fuel cells have no moving parts, they are quiet in operation, they are extremely scaleable in capacity, and their physical form can be adapted to suit the application. One important challenge is to develop fuel cells that can operate efficiently at dynamic load, for maximum flexibility.

Fuel cells used in reverse, as electrolysers, can convert electricity to hydrogen and other chemical energy carriers. Hydrogen can be used to power vehicles and other end-use appliances, however, hydrogen is difficult to handle, distribute and store. To use hydrogen effectively we need to develop not only the fuel cell electrolysers but also technologies for storing and using hydrogen cheaply, safely and reliably.

If electricity is going to be used in the transport sector it is important that this increase in consumption is made as flexible as possible. The technological challenges lies in the development of batteries and their availability to charge and to be discharged according to the need for DR. The cost of storing electricity and converting it also has to be decreased in order to be competitive to other DR resources.

Final remarks

An active demand side helps to create a more flexible power market and thus facilitates a larger share of intermittent renewable energy and distributed generation. To create a flexible demand side:

- consumers' energy requirements and equipment must be flexible enough to make load shifting possible
- consumers must have incentives, such as lower costs, to vary their patterns of power consumption and DR agreements should be made
- the need to increase or reduce consumption must be transmitted from the grid control system to consumers (directly or indirectly) through market prices, or to their equipment via automatic communication links and other technical solutions, and
- the communication system must be in place.

This chapter has shown that suitable driving mechanisms for DR already exist in the power markets. Taking the Nordic power market as a case study, we described how DR can be categorised and priced. In other words, the power markets are ready to handle more DR as an supplement to an increased share of intermittent and distributed generation.

DR is a valuable addition to electricity markets at all timescales, not just the spot market, though different timescales do require different approaches to DR.

Both existing and new technologies are important to the development of DR. Examples of the latter are micro-CHP and electric vehicles.

Active DR requires communication between generating units, consumers and the market. The continuing development of cheap and reliable electronic communication technologies means that there is great potential for this type of DR in the next 10–20 years, and it is likely that in the future most consumers will have intelligent two-way communication systems to manage demand. This will facilitate online pricing from suppliers and rapid responses from consumers.

DR brings environmental advantages because it reduces the need to run peak-load plants. It also improves the reliability, security of supply and flexibility of the power system. In doing so, DR facilitates the greater use and better integration of decentralised generation and renewable energy technologies such as wind and photovoltaics, and helps the power markets to run smoothly.

By avoiding the generation and consumption of power that does not reflect the marginal demand and supply situation, DG saves money for society as a whole as well as for individuals. It is therefore important to carry out further systems analysis research to find out how to optimise the interaction between demand and supply.

9

System control and communication

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System control issues and the importance of communication

Rapid and ongoing development in the energy sector has consequences for system control at all levels. In relation to system control and communication the control system is challenged in five important ways:

- Expectations for security of supply, robustness and vulnerability are becoming more stringent, and the control system plays a big part in meeting these expectations.
- Services are becoming increasingly based on markets that involve the transmission system operators (TSOs), generators and distribution companies. Timely, accurate and secure communication is essential to the smooth running of the markets.
- Adding large amounts of renewable energy (RE) to the mix is a challenge for control systems because of the intermittent availability of many RE sources.
- Increasing the number of active components in the system, such as small CHP plants, micro-CHP and intelligent loads, means that the system control will be much more complex.
- In the future it is likely that power, heat, gas, transport and communication systems will be tighter coupled and interact much more.

The following sections discuss these points in turn.

Increased requirements for security of supply

The development of society has made everything and everyone more dependent on the availability of infrastructures, including the power network. Loss of power has a significant economic impact [1]. Consumers are also becoming increasingly aware of their rights in a market-based system, and are therefore beginning to demand compensation when power is interrupted [2]. All these factors provide an economic incentive to increase the security of supply.

Recent large blackouts in North America (August 2003), Denmark/Sweden (September 2003) and Italy (September 2003) have revealed the vulnerability of power systems and how fast the consequences of local events can spread to large areas. These large blackouts have different causes, but several of them could have been avoided or significantly mitigated if the situation just before the collapse had been interpreted correctly and the appropriate action taken by the operators [3].

Studies of the chain of events leading to the North American blackout show that two major control system problems contributed significantly to its severity [4]. The initial problem affected a system called a state estimator, which belonged to the TSO MidWest Independent System Operator (MISO). The real-time input data to the state estimator failed, so its output was inaccurate, but the operators did not recognise this.

Two hours later, just before the collapse, the energy management system (EMS) operated by transmission company First Energy (FE) lost its alarm function, again without the operators being aware of it. These two failures of the monitoring and control system were the major contributors to the collapse. Not only did the operators not have a complete and correct picture of the system, but they were not even aware of this fact. As a result, they could not perform the actions needed to stop faults from cascading.

There are two important lessons here. First, it is crucial to have correct and timely information about the state of the system. Second, the blackout was made more severe by the use of centralised control - in which all information is transmitted to a central control room for processing and control decisions, after which instructions are passed back to generators, substations or other central control rooms. Robustness in communication and information systems is very important and decentralised control, in which control decisions are taken by controllers embedded in e.g. generators and substations, could add a useful degree of robustness to the system.

Energy systems are increasingly market-based

Energy systems increasingly depend on markets for their operation. There are markets for every type of service needed to operate the grid - generation, power regulation, spinning reserve and so on - though their organisation varies between power systems.

The Nordel system covering Sweden, Norway, Finland and Denmark has at least three markets: long-term bilateral energy contracts, a day-ahead market (12–36 hours), and a balance market. The market participants are power producers, traders and retailers. Large amounts of wind power could bring the need for a new market operating at a timescale between that of the existing spot and balance markets.

To operate successfully, all these markets require a good communication infrastructure. As market time horizons become shorter and the number of trade participants increase, the need for timely and accurate communication will, of course, rise. One very likely development is loads controlled by real-time pricing, and this will further increase the requirements on communication systems.

Another very significant effect of the change to a market-based power sector is that the utilisation factor of transmission systems has increased. This is because liberalisation has reduced the rate of investment in the power sector generally, yet consumption has risen. The markets have also increased the amount of long-distance transmission contributing to the increased utilisation of the transmission system.

The higher grid utilisation factor during normal operation means there is less margin to cover faults. Systems are operating closer to their stability limits, and the limited capacity available to handle abnormal situations means there is an increased risk of cascading when faults do occur. To mitigate these problems the system operators are installing new equipment and more comprehensive monitoring and control systems. All this increases the requirement for reliable operating data, communication systems and security assessment models.

Increasing amounts of renewables

As explained in earlier chapters, wind energy is already beginning to have significant effects on the operation of the German, Spanish and Danish grids, for several reasons. At high penetration levels of renewable energy it is necessary to take the stochastic nature of renewable energy into consideration in order to ensure economic and safe operation of the grid. A lot of wind capacity is being installed in rural areas where the grid cannot easily absorb all the power generated. Since local demand in these areas is generally low, the power will also have to be transmitted over long distances across power system control area boundaries.

A key point in integrating wind power into the rest of the power system is the interaction between wind and other types of generation. Reliable forecasts based on meteorological data and real-time measurements of wind power production are the starting point. This information then has to be fed into the power producers' energy management systems (EMSs), taking into account transmission capacities and other constraints. This requires the exchange of information between system operators and power producers, and internally between each producer's production sites.

The value of wind energy depends heavily on the market structure; a move towards shorter lead times will increase the value of wind energy because generating predictions will be more accurate. Any shortening of timescales will further increase the amounts of data to be exchanged, however, and as the market approaches real time it will become essential to have efficient secure trading mechanisms.

More active components

Several new types of components are appearing on the market or are close to commercialisation. These include mini- and micro-CHP plants, energy storage units, advanced UPSs and controllable loads. It is characteristic for these new types of components that they can have sophisticated grid interfaces as well as intelligent control functions. To harness their potential for advanced control, however, the rest of the system must be capable of taking advantage of this new functionality.

This will require two-way communication between the grid and a large number of small units distributed throughout the system; in large interconnected systems the number of connected devices could easily run to billions. The resulting communication will be complex, and will require a shift in system control philosophy. International standards on communication in power systems are under development. The international series of standards, IEC61850, dedicated to substations are the core standard with respect to communication in power systems. IEC61850 defines a scalable, flexible and standardised communication system based on object models, and it is presently being extended to other power system technologies, e.g. wind turbines and CHP plants.

More interconnection between infrastructures

The efficiency of energy systems can be increased significantly by getting them to work together, so that one system can utilise losses in another system or take advantage of extra capacity or operating flexibility in another. Other ways of interconnecting energy networks to increase overall efficiency include the use of renewable energy to produce transport fuels. An example is Danish power company Elsam's vision of integrating wind energy, biomass and coal into a single process yielding power, heat, fuel and other outputs [6]. This vision is further described in chapter 4.

Increased interaction between different systems also brings an increased risk that faults will propagate from one system to another. Interconnection between systems includes the communication infrastructures, and as power systems come to depend increasingly on communications links it will be crucial that problems with the communication network do not have effects on the power system, and vice versa.

Of all the energy systems, the power system is the most sensitive and probably also the one undergoing the biggest changes. The sensitivity comes from the very tight coupling between components of the system, which means that even small imbalances in active or reactive power can quickly have dramatic effects on the system. The key issue for future system control is to achieve high reliability by exploiting the intelligence embedded in the system components for real-time control interaction.

The stability of the power system depends on both local and global issues. Maintaining the power balance of the system is paramount, but it is also important to avoid low-frequency oscillations between different parts of the grid. These oscillations can be very large and can result in loss of synchronism. These stability issues are system-wide.

As well as maintaining stability, it is necessary to ensure that grid events do not trigger a collapse of the system.

This is typically achieved by isolating the fault, control actions at power plants, HVDC-lines or load shedding. In such cases it is critical to identify the events quickly and correctly and take optimal action.

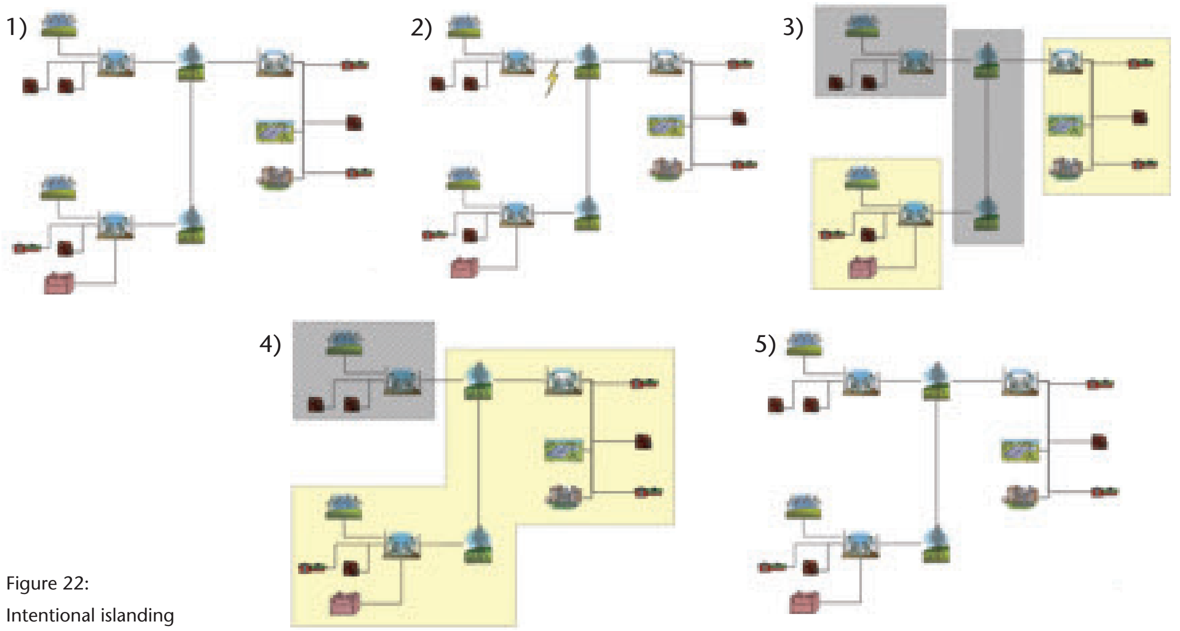

Figure 22:
Intentional islanding
Five states of the system:
1) Normal operation;
2) Fault on the transmission system;
3) System splits into autonomous cells, one of which is not sustainable;
4) Sustainable cells synchronise as the transmission system returns to normal;
5) The last part of the system is reconnected.

The system's voltage stability is a more local issue, since it depends on maintaining a balance of reactive power locally as well as globally. If insufficient reactive power is available locally, the voltage can collapse as a consequence of the impedance of the grid. The stability of the grid thus requires information on both local and global scales to be conveyed to the various active components of the system.

A new technology capable of anticipating voltage collaps and other severe system conditions is wide-area measurement and control systems, WAMS. These types of systems, which are under development, are made up of several phasor measurement units, PMUs, embedded in the transmission system. The PMUs utilise GPS-satellite signals to extreme accurate phasor measurements, which can be compared across the power system with the object of anticipating voltage collapse etc. The technology is dependend on a reliable and fast communication system.

As markets increase in geographical size, it will become more important to trade and transmit power over long distances and to involve many participants. The effective operation of power markets requires accurate and timely information to be available to market participants and system operators.

Solutions

Robustness can be increased by decentralising power systems in terms of both generation and control. Such a distributed system will consist of a larger number of smaller units than the power systems of today. The smaller size of generating units means that distributed systems are less sensitive to single events since the loss of production capacity is smaller and the impact on the grid will also be smaller. The risk of cascading can therefore be expected to be reduced.

Combining distributed generation with intelligent loads will increase robustness still further. Such a system will be able to operate if necessary as a collection of autonomous segments or cells, a process known as intentional islanding (Figure 22). This minimises the chance of cascading in the event of a fault, allowing most of the system to keep running while the segment with the fault is isolated. Once the fault is cleared, the segments can re-synchronise and reconnect.

Increasing system robustness requires changes to control and communication systems as well as the power part of the system. Both generators and loads will have to be intelligent and able to participate in the system's frequency and voltage control. Information about each component's state will need to be communicated to the other components of the cell and to the other cells. The communication and control part of the system will also have to be robust under fault conditions. To provide the robustness needed to achieve the security of supply demanded by modern societies, the complete system will have to have a web-like structure.

Many of the distributed generators in future power systems will be based on intermittent renewable energy sources. It will be easier to add large amounts of renewable energy if loads that can be controlled by the availability of renewable energy as well as the overall power demand are used. Such loads include heaters and coolers

- space heating, cold stores, freezers and refrigerators - because they incorporate a degree of energy storage, and can therefore provide flexibility in the demand that can be used to match the renewable energy production. Other loads of this type are hydrogen generators and desalination plants for drinking water.

To improve the operation of power markets and increase the utilisation of the transmission and distribution systems, real-time power trading and real-time constraints of the transmission and distribution systems are very desirable. A real-time market requires fast and accurate communication between traders. Real-time constraints add the need for accurate real-time system data in order to determine the state of the system, the security level and suitable margins for transmission capacity and active and reactive power reserves.

With billions of units set to participate in power markets and system control, some kind of organisation will be required. Currently, several projects are concerned with grouping small generators into so-called virtual power plants [8]. The idea is that a group of generators that are geographically distributed should act as a single large power plant by providing services such as regulating power to the system. A power system composed of virtual power plants will resemble a traditional centralised system in many ways, so it will be easier for system operators to maintain an overview.

A similar idea can be applied to the control room in terms of virtual control rooms. A virtual control room is an interface to the control of the system that is established by using the communication system to transfer relevant data for the operators but the control is distributed in the system. It can therefore be established where there is enough communication bandwidth. The central control room is one of the most vulnerable points of a distributed system, and distributing control as well as generation makes the system more robust. Operators, however, still need an overview of the control system. Virtual control rooms could provide the best of both worlds: the robustness of distributed control and the logical simplicity of centralised control.

A further development would be to make systems self-organising, and self-healing in the face of faults [9]. Self-organisation can be used to form cells dynamically, when stability is threatened, and also to create ad-hoc virtual power plants that can trade on the power markets. A self-healing system would automatically determine the cause of the fault, decide how to cope with it so as to minimise the effect on customers, and take the appropriate action.

To achieve this functionality, new control methods will have to be applied. One promising technology is software agents [9], [10]. A software agent is an autonomous software module that performs a certain action and has the ability to execute itself in the current context to satisfy internal goals. It bases its actions on inputs which can be measurements or information received from other agents.

Software agents in power systems come in several flavours. The main types are simple agents, which control a particular component and have a fixed behaviour; and complex agents, which can adapt to the current context and can co-ordinate, compete and collaborate with other agents to achieve certain goals for the system. Complex agents can handle security assessments, state estimation, auctions, allocation of regulating reserves and other advanced functions. At the moment agents are being used in power systems mainly to provide decision support.

Self-organisation and self-healing are still topics of much research, and are in their infancy in the power sector. Other important research areas include state estimation in systems containing renewable energy, real-time security assessment of distributed systems, wide-area measurement and control, and applications of agent technology in power systems with stability issues and short timescales.

Tools for system design

Advanced methods based on information and communication technology (ICT) are being applied in the power sector. One of the major efforts is the Intelligrid Architecture being developed under the control of the Electricity Innovation Institute, an affiliate of EPRI [11]. This is a comprehensive framework for all communications within the power system. It includes outline specifications for communication between TSOs, real-time trading, supervisory control (SCADA), substations and other activities. The Intelligrid Architecture has yet to be used in a real system, but field tests are under way.

The development of simulation tools for distributed systems is very important. These models will have to address the special issues of distributed systems, including system control and the multitude of different types of interconnected components. This will involve modelling at several timescales.

The modelling of agent-based control is also a key issue. A suitable simulator, IPSYS, is now being developed at Risø [12]. The open architecture of IPSYS allows the simulator to be used to test advanced controllers, including agent-based ones.

Conclusion

The rapid development of energy systems towards distributed generation, greater use of renewable energy and an increasing reliance on markets, plus tightening requirements for security of supply, calls for new methods of control. The answer is to utilise developments in ITC to create control systems that are distributed and with a higher level of intelligence. To develop these new technologies successfully we need to involve experts in ICT, power systems and renewable energy. We also need to ensure that new control and communication technologies are deployed as part of the ongoing development of energy systems.

10

Supply technologies in the future energy system

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A key theme of this chapter is that the energy systems should be (and already are) becoming more complex. The different parts of future energy systems will be more and more integrated; an example is the production of transport fuel using surplus wind power, biomass from forestry and agriculture (biorefineries), waste heat and carbon dioxide removed from power station flue gases. Integration is necessary if we are to include a large proportion of intermittent renewable resources in the energy system.

Figure 23 characterises the various technologies in the interlinked future energy system, which has a mix of local and central production and close coupling between supply and end-use.

Wind

Global wind energy capacity is already more than 48,000 MW and is expanding 20-25 % every year [16]. The cost per kWh appears to fall by about 15 % with every doubling of installed capacity [18]. On this basis, 90,000 MW of installed capacity would make wind power directly competitive with electricity from coal- or gas-fired power plants, and this point could be reached in 2008 [14].

Denmark now has about 3100 MW of installed wind capacity, about 400 MW of which is offshore, providing more than 20% of the country's electricity [8]. During long windy periods, however, Denmark produces more electricity than it can use, and exports the surplus at low prices. Better uses of this surplus electricity would be to produce renewable transport fuel (REtrol, Chapter 4) or heat, whether from direct electric heating, or heat pumps. Other uses for surplus power could be found through the development of intelligent system solutions that optimise the interaction between wind turbines, other energy sources and consumers in the electricity system.

Biomass

Biomass covers wood, agricultural residues, energy crops, household waste and agro-industrial waste.

At present only about one-fifth of the global technical, and economic potential of biomass is used to produce energy [3]. New sustainable biomass technologies such as biorefineries are being developed, especially to produce biofuels for transport. In Denmark, biomass contributed 91 PJ to primary energy production (waste accounted for 36 PJ of this) in 2003 [8].

Straw, wood, energy crops and household waste for electricity and heat

Denmark is one of the few countries where the use of both straw and wood in power plants is expected to increase. This is due to a plan known as the Revised Danish Biomass Agreement, under which electricity companies were obliged to use 1.4 million t/y of wood and agricultural residues, including at least 930,000 t of straw, in 2004 [4].

Danish farmers currently produce 5.7 million t/y of straw, which is combusted for heat and power (24%),

Technology	First commercial unit sold	Renewable ressource Yes/No	Small/ Medium/ Large units	Modularity Yes/No	Varying over time Yes/No	Local/ Central production	Area demand High/Low
On shore Wind	Exist	Y	S	Y	Y	L	H
Off shore Wind	Exist	Y	L	Y	Y	C	L
Solid Biomass	Exist	Y	S/L	N	N	L/C	H
Biofuels	2010	Y	L	N	N	C	H
Solar PVs	2015	Y	S	Y	Y	L	H
Solar heaters	Exist	Y	S	Y	Y	L	H
Geothermal	Exist	Y	M	N	N	C	L
Wave energy	2015	Y	M	N	Y	C	L
Fuel cells	2010		S	Y	N	L/C	L
Natural gas technology	Exist	N	L	N	N	C	L
Coal/oil power with carbon capture and storage	2020	N	L	N	N	C	L
Nuclear fission	Exist	N	L	N	N	C	L
Nuclear fusion	2050	N	L	N	N	C	L

Figure 23: Energy supply technologies

used for animal bedding (24%), animal feed (17%) or incorporated into the soil (35%). Straw is difficult to burn in boilers, where its high salt content causes corrosion and other problems. As a result, there is interest in pre-treating straw and other waste material, either to make it easier to burn directly or to use it as a source of bioethanol and other biofuels, after which the final residue can be burned. An example is the EU-funded IBUS project, which is a collaboration between Elsam, Risø and others.

Increasing the amount of straw used for energy production would require strategic planning of crop rotation and carbon recycling to prevent loss of soil fertility, since straw is a major source of organic matter in the soil.

The land area devoted to energy crops such as willow will probably increase. So will production of more conventional crops with high biomass yields, including rye, maize, and perennial growth from managed and semi-natural ecosystems. These crops will be used in biorefineries, after which the final residues will be recycled to the soil or burned in CHP plants.

Wood chips and pellets are currently the dominant wood-based energy resources in Europe. An international market is developing for wood chips and especially the pellets market is developing, Denmark has even imported pellets from Canada. Household waste may in the future be used to produce upgraded fuels such as biogas.

A current discussion topic is whether the fibre fraction of animal manure, before or after anaerobic fermentation to produce methane, could be burned to produce heat and electricity. For this to be sustainable, we will need to recover phosphate from the ash, or simply recycle the ash, so that phosphate is not lost from the soil.

Biogas

India and China have large numbers of small biogas plants, and a few countries have built larger plants. Around 20 large biogas plants in Denmark, for instance, are producing electricity and district heating [15]. After a temporary break, new biogas plants are now being planned, and this trend seems set for the next decade.

The use of both animal waste and organic industrial waste creates a synergy that increases gas production. Other biogas systems based on energy crops such as grass-clover mixtures are being developed, and the future of biogas may lie in a mixture of energy crops and manure.

Biofuels: ethanol, diesel and hydrogen

Bioethanol and biodiesel can readily be used in the transport sector as substitutes for gasoline and diesel. Some countries already use biofuels, either straight or as mixtures (5–10% or 85–100% of bioethanol in gasoline mixtures, and 85–100% of biodiesel in mixtures with conventional diesel). Denmark does not yet use biofuels for transport.

Bioethanol can be produced commercially from sugars (such as sugar cane and sugar beet) or starch (such as maize) using well-known processes. The energy balance of bioethanol production needs to be improved, however, since these processes rely heavily on fossil fuels for fertilisers, pesticides and conversion technologies.

It is therefore essential to develop bioethanol processes that can use lignocellulose materials such as straw, grass cuttings, wood and energy crops. With maize, for example, new processes such as IBUS will produce bioethanol from the straw and other waste materials, as well as from the grain. Collecting the straw requires only a small amount of extra energy, so it significantly improves the energy balance of biofuel production [5].

A second important aspect of the IBUS concept is its use of waste heat to drive the process. An IBUS biorefinery would be built next to a CHP plant; the CHP plant would burn the waste from the IBUS plant, and the IBUS plant would use surplus heat and power from the CHP plant.

Energy efficiency in the production of biodiesel also needs to be improved. This can be done by developing low-input cultivation methods and dedicated biorefineries for oilseed crops. The biorefineries would extract the oil for biodiesel, while the straw would be used to produce bioethanol or burned in CHP plants.

Another fuel, hydrogen, can be produced from both thermal gasification and fermentation of biomass, but these technologies are still in their infancy [6].

We conclude that Denmark could go a long way towards the EU goal of using biofuels to supply 20% of the energy used in transport by 2020 (Directive 2003/30EF).

Solar energy

The total amount of solar radiation reaching the earth's surface is more than 10,000 times our global energy consumption. Average annual insolation varies from 1000 kWh/m^2 in northern Europe to 2500 kWh/m^2 in desert areas.

Solar thermal electricity

Concentrated solar power (CSP) plants work best in areas with a lot of direct sunlight. They are categorised according to the ways in which they concentrate sunlight:

- parabolic trough-shaped reflectors;
- parabolic disc-shaped reflectors; or
- central tower receivers using numerous heliostats.

Trough-shaped reflectors, the most mature CSP technology, have demonstrated a maximum peak efficiency of 21% for converting direct solar radiation into electricity. Tower technology has also been successfully demonstrated.

Solar thermal heating

Solar thermal technologies can supply heat for domestic hot water (DHW) and space heating in residential, commercial and institutional buildings, swimming pool heating, solar-assisted district heating and industrial processes.

The main technologies are:

- unglazed solar collectors;
- glazed flat-plate solar collectors; and
- evacuated solar collectors
- passive thermal walls and floors.

More than 100 million square metres of solar thermal collector area were estimated to be used globally at the end of 2001, and this figure is increasing at more than 10 million m^2/y. Unglazed solar collectors are used mainly to heat swimming pools, and account for 28 million m^2, mostly in the USA. Glazed solar collectors cover 49 million m^2. Evacuated solar collectors account for 22 million m^2, mostly in China (IEA, 2004).

The total energy production from solar thermal collectors is difficult to estimate, because it depends on the technology used and the amount of sunshine available.

Solar photovoltaics (PV)

In the last five years, global production of electricity from solar photovoltaics (PV) has increased by about 35% (Figure 24), and the total installed PV capacity is now about 3100 MW [1].

The cost of PV power continues to fall as R&D improves the performance of solar cells. Most of the installed capacity is based on crystalline silicon cells (monocrystalline 33%, polycrystalline 56% in 2003) with efficiencies of 11–17%. PV modules now cost about US $3.6/Wp [2].

Other PV cell types using thinner or cheaper materials may have better prospects for cost reduction. They include:

- thin-film silicon cells (8.8% of Watt production in 2003);
- thin-film copper indium diselenide cells (CIS, 0.7% of Watt production in 2003);
- photochemical cells; and
- polymer cells.

Commercial thin-film cells have efficiencies of 4–8%, but commercial efficiencies of 10% seem within reach in the next few years [2].

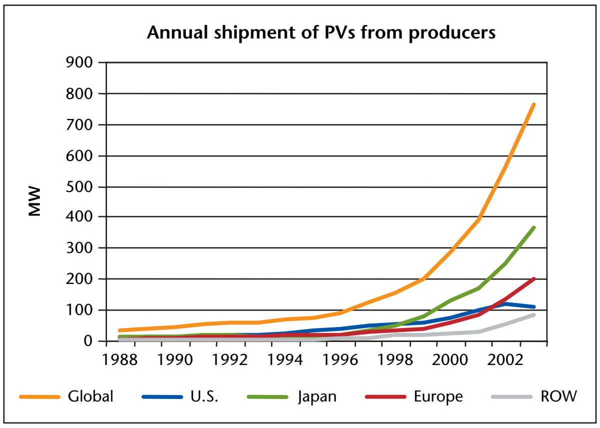

Figure 24: Annual production of PV modules [1]

In new buildings, PV systems are relatively cheap to install because they can form an integral part of roofs, walls and even windows.

Geothermal energy

Worldwide, the present installed capacity of plants generating electricity from geothermal heat is over 800 MW_e. In some countries, including Denmark, geothermal energy is not available at a high enough temperature for electricity production. District heating systems based on heat pumps, however, can make good use of low-temperature geothermal energy. The only plant of this type in Denmark is located in Thisted, where it has supplied 1000 houses with 80 TJ of district heat over 17 years.

Wave energy

More than 1000 patents for wave power machines have been registered. Most are still at the concept stage, and only a few plants have been built and tested. No commercial plants have yet been built, and the wave energy industry is now at a similar stage of development to the wind industry in the 1980s.

Wave energy could take advantage of the infrastructure already developed for offshore wind parks, including foundations, power cables and transport systems. Peaks in wave energy occur about 12 hours after the corresponding peaks in wind energy, so wave power plants could help to balance fluctuations in wind power.

Fuel-cell and battery cars

There are fascinating possibilities in combining the transport and electricity sectors. One study predicts that in Denmark, of the 2.5 million passenger cars and delivery vans on the road in 2030, 1 million will be powered by batteries using 2 TWh/y of electricity, some of it off-peak, and 1 million by fuel cells running on hydrogen [10]. Producing this hydrogen by future electrolysis technology with an efficiency of 85% (today's figure is 70%) will require a further 4.5 TWh/y of electricity. Hydrogen cars clearly use much more energy than battery cars, but they will be needed because they will be able to travel long distances, whereas battery cars will be restricted to an expected range of 200 km.

At present we do not know which technology - batteries or fuel cells - will win in the long term. Whichever technology they use, though, these 2 million vehicles will provide enough electricity storage capacity to allow a large amount of intermittent renewable energy to be used for power generation. If we assume conservatively that each electric vehicle has a power of 50 kW, the total is 100 GW. If 10% of this capacity is connected to the grid at any one time, we have a power source of 10 GW which could be "borrowed" to cover shortfalls in renewable energy and peaks in demand.

We believe that small fuel cells are likely to be important in domestic heat and power. High-temperature fuel cells (SOFCs) may reach this market very soon, since they can run on fossil fuels until renewable fuels become available. Fuel cells are not restricted by the Carnot efficiency of internal combustion engines, so they can produce at least twice as much power per unit of fuel. This would allow us to make big and rapid cuts in the CO_2 production associated with electricity generation. At a later stage, the same fuel cells would facilitate the introduction of hydrogen as an energy carrier. It must be noted here, though, that other energy conversion technologies (an example being Gas Turbine Combined Cycle) may offer the same advantages as fuel cells in terms of efficiency and thus be a notable competitor to fuel cells in several applications.

In the long term we believe that batteries will only be important in transport when they are used in conjunction with other technologies, such as in the hybrid cars already marketed by several manufacturers (notably the Toyota Prius). The reason for this is the relatively short operating radius of vehicles that rely on batteries alone.

On the other hand we believe that special types of batteries will have a role in covering transient power demands, such as instantaneous load balancing on the grid.

Natural gas technology

We expect natural gas to remain a significant part of the energy supply system of 2030. The conversion of natural gas to electricity will, however, be done in high-temperature fuel cells or gas turbines with higher efficiencies than are possible with today's generating technology.

In the short term we also anticipate increased use of natural gas for transport, since it produces less CO_2 than gasoline and diesel per secondary energy unit. Natural gas stored in high-pressure cylinders is already a popular transport fuel in many countries.

Coal- and oil-fired power stations with carbon capture and storage

In a low-carbon future there could still be room for coal and oil fired power plants, if they were coupled to a carbon capture and storage (CCS) system. In such a system the CO_2 would be captured at the power plant and transported to a geological storage site such as oil & gas fields

There are two main approaches to CO_2 capture at a power plant:

- Post-combustion systems, which separate CO_2 from the flue gases produced by the combustion
- Pre-combustion systems, which process the primary fuel in a reactor in the presence of steam or oxygen to produce separate streams of CO and then CO_2 for storage and hydrogen that is used as energy carrier.

No full scale applications of such systems exist. While experiments of CO_2 storage in oil fields and aquifiers are ongoing.

In a CSS system, the cost of CO_2 capture is the largest cost component. This cost is estimated to be within range of 15-75 US\$/tCO_2 . The transport and storage cost is estimated to be an additional 2–16 US\$/tCO_2 (IPCC, 2005).

Nuclear power

Nuclear fusion is not likely to be commercialised in the timescale we are considering here. Nuclear fission will probably obtain increasing importance in some countries in the future in consequence of drastically increasing attention to greenhouse gases and depleting oil resources. We do not believe that nuclear power capacity will be installed in Denmark in the time scale considered here.

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