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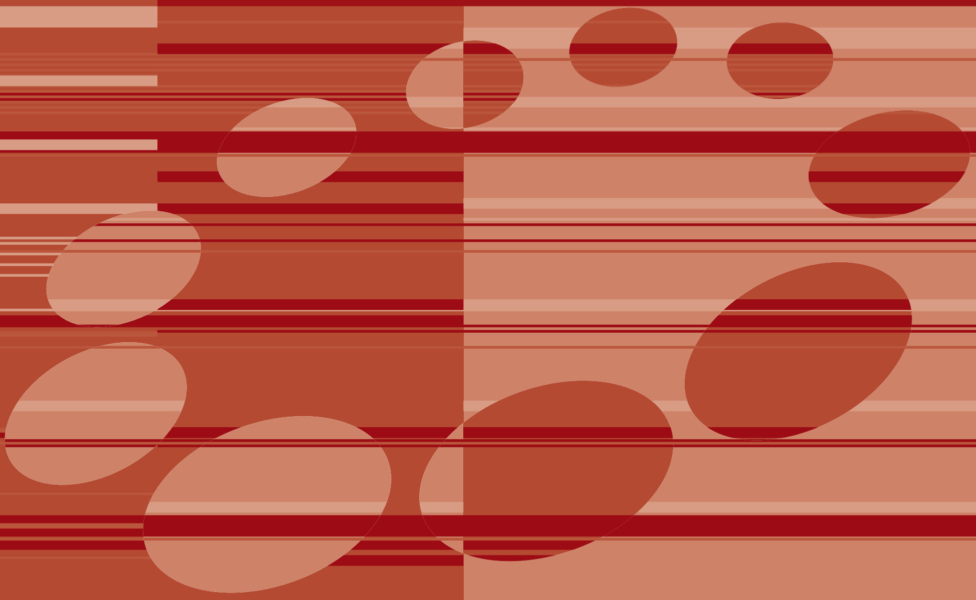
# Risø Energy Report 6

## Future options for energy technologies

Edited by Hans Larsen and Leif Sønderberg Petersen



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# 1 Preface

Fossil fuels provide about 80% of the global energy demand, and this will continue to be the situation for decades to come. In the European Community we are facing two major energy challenges. The first is sustainability, and the second is security of supply, since Europe is becoming more dependent on imported fuels. These challenges are the starting point for the present Risø Energy Report 6. It gives an overview of the energy scene together with trends and emerging energy technologies. The report presents status and trends for energy technologies seen from a Danish and European perspective from three points of view: security of supply, climate change and industrial perspectives. The report addresses energy supply technologies, efficiency improvements and transport. The report is volume 6 in a series of reports covering energy issues at global, regional and national levels. The individual chapters of the report have been written by staff members from the Technical University of Denmark and Risø National Laboratory together with leading Danish and international experts. The report is based on the latest research results from Risø National Laboratory, Technical University of Denmark, together with available internationally recognized scientific material, and is fully referenced and refereed by renowned 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 organizations, the Danish government and international organizations including the European Union, the International Energy Agency and the United Nations.

*Hans Larsen and Leif Sønderberg Petersen,*
*Risø National Laboratory, Technical University*
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# 2

# Summary, main conclusions and recommendations

HANS LARSEN AND LEIF SØNDERBERG PETERSEN, RISØ DTU

The world depends heavily on fossil fuels, which currently cover about 80% of global energy demand, and will continue to do so for several decades. In the European Community we are facing two major energy challenges. The first is sustainability as EUs $CO_2$ emissions are forecast to rise by approximately 5% by 2030. The second is security of supply as Europe is becoming more dependent on imported fuels. Today these account for 50% of our energy consumption, but the 2030 figure is forecast to be around 65%. The Council of the European Union recently agreed that Europe should develop a sustainable and integrated climate and energy policy.

Building on Denmark's traditionally strong environmental profile, the Danish government earlier this year put forward the document "A Visionary Danish Energy Policy for the period up to 2025". This aims to stabilise energy consumption at its current level, and calls for a considerable increase in the use of renewable energy.

## IPCC states that $CO_2$ must peak soon

In its Fourth Assessment Report the Intergovernmental Panel on Climate Change (IPCC) says that if we want to stabilise $CO_2$ at the low level – around 500 ppm – needed to limit the global average temperature rise to 2.5-3.0°C, $CO_2$ emissions must peak soon and then decline. The IPCC states that we must take action now if we are to stabilise $CO_2$ at a low level.

With the global expansion of intermittent renewable energy technologies comes the pressing need to solve the problem of long-term variability.

## It is feasible to save more energy

Even though energy efficiency has improved considerably in recent decades, it is technically and economically feasible to save even more energy, for instance in buildings. This potential plays a prominent role in the new European Energy Action Plan. Energy demand for transport has been rising for many years. Transport consumes approximately 20% of the world's energy, and the transportation sector is largely based on fossil fuels. Long-term solutions include the development of a hydrogen economy, and economical electrical cars with long operating ranges. Biofuels are also a relevant option.

***Carbon dioxide capture and storage (CCS)*** has moved to centre stage in the last few years as a serious option for large scale $CO_2$ emissions mitigation.

***Wind energy*** has seen an average annual world market growth of 17% over the last five years in terms of installed capacity. European countries are leaders in the deployment of wind energy: half of all the new wind turbines installed in 2006 were in Europe.

***Fuel cells*** are within the next five years at the entrance to their break-through. They will be used in three main applications: stationary power generation, transport, and portable equipment.

***Solar cells*** (PV) represent one of the fastest-growing renewable energy technologies, with a global annual growth of more than 40%. Polymer solar cells are a promising new technology. The falling cost of PV systems will eventually make PV electricity competitive in Denmark.

***Bioethanol*** is promising as a transport fuel. The best alternative is second-generation bioethanol from waste materials such as straw. Other liquid transport fuels are biodiesel, synthetic gasoline and diesel produced from gasified biomass. Biomass can also be used for heating, replacing oil or natural gas that can be used as motor fuel.

***Coal*** has, as the most abundant fossil fuel, gained renewed interest. Most of Denmark's electricity comes from the combustion of pulverised coal, and Danish coal-fired power plants lead in the world in energy efficiency. Nevertheless, coal will only be an option for the future if we can cost-effectively reduce $CO_2$ emissions from coal combustion. This can be done in three ways: increase the energy conversion efficiency; switch to a fuel with a lower fossil carbon content (including biomass); and capture and store $CO_2$ produced during combustion.

***Nuclear fission*** is a major source of carbon-free energy. It provides 15% of the world's electricity and 7% of our total energy. 15 countries are currently building new nuclear power stations, and a further 25 plan to do so. In contrast to previous prognoses, the IEA now assumes that nuclear power will increase by 15% by 2030.

***Nuclear fusion*** has great potential as a carbon-free energy source with abundant fuel reserves. An international partnership that includes the EU is building the ITER fusion power demonstration plant, which will start operating in 2017. The first commercial fusion power plant may be in operation around 2045.

***Geothermal energy*** has been shown to have a huge potential in Denmark. With the present high oil prices, the number of towns embarking on geothermal projects is increasing. It is, however, difficult to predict the share of geothermal energy in the future Danish energy system.

***Wave power*** has gained renewed interest in Denmark. Examples are Wave Dragon and Wave Star. These demonstration projects are very successful as a starting point for the commercial development of this technology.

## Energy science system indicators for assessing energy technologies

A new way to assess the prospects of new and emerging energy technologies is a technique we have called energy science system indicators. The indicators calculated in this report show that the EU is very strong in wind energy, and strong in PV and nuclear. For these three technologies the EU has a significant share of both markets and knowledge production. For both geothermal energy and biomass for heat and electricity, Europe has a fair share of installed technology and knowledge production; in biomass for heat and electricity, especially, Europe is home to several world-leading firms. Brazil and the USA are world leaders in biofuels technology, but Europe is quite well placed in this area too. However, the EU lags behind Japan and the USA in the emerging technologies of hydrogen and fuel cells.

## Recommendations

To reach a sustainable energy system there is a strong need for energy-efficient appliances and energy conservation. *Denmark should maintain its long tradition of developing low-energy solutions*. This requires new policy initiatives and strong coordination of existing programmes.

*There are important niche areas for Danish R&D in cutting the electricity consumption of private households*. Examples are methods of visualising power consumption of equipment in standby and idle modes, energy-efficient lighting technology such as LEDs, and energy-efficient circulation pumps for heating and cooling systems.

With plenty of wind power and a highly-diversified energy system, *Denmark can play a key role in developing future flexible energy systems*. The growing wind energy industry is increasingly able to support its own R&D costs. But generic long-term research, and research of common interest to society and industry, still needs *public support for research projects and prototype development.*

In PV, Denmark can gain an important role in research, development and the production of new types of solar cells for buildings and mobile applications. *Encouraging the use of PV in new public buildings would help to reach this goal.*

Denmark's strong position in R&D on second-generation biofuels is attractive to Danish industry. Comprehensive systems analyses are required to clarify the future role of biofuels in the Danish energy system.

*Fossil fuels will be extensively used for many decades to come, so it is important to minimise their $CO_2$ emissions*. R&D activities to support this include improving the efficiency and decreasing the operating costs of biomass and waste combustion systems; tools to minimise operational problems; and methods for burning biomass and waste in high-efficiency suspension-fired and fluidised-bed boilers. *Denmark's strength in various technologies for very-high-efficiency coal combustion and $CO_2$ capture has excellent market potential, and should therefore be pursued.*

*R&D in carbon capture and storage (CCS) should be strengthened and followed up with demonstration projects.*

*Greater use of geothermal energy in Denmark depends on support for R&D and demonstration projects,* and on trends in energy prices.

To give Danish industry a chance to lead the development of competitive *wave technologies, a public-private partnership is needed.* Danish manufacturers and consulting firms also have ample opportunities to contribute to offshore wave power projects around the world.

To exploit the great potentials, *new and renewable energy technologies should be analysed in a systems context, and a small scale demonstration programme set up for fuel cells.*

*A national centre for testing fuel cell and hydrogen technologies should also be created.*

These steps would help *Denmark to become a key international player in selected areas of research, innovation and product development related to the hydrogen economy.*

The energy system indicators show that Denmark could do better in commercialising its research results. *A research initiative in innovation and innovation policy* could create new and more direct links from R&D to commercially-available energy products.

*Hans Larsen and*
*Leif Sønderberg Petersen*

# 3 Energy challenges

POUL ERIK MORTHORST, RISØ DTU; JØRGEN HENNINGSEN, FORMER PRINCIPAL ADVISER, DG FOR ENERGY AND TRANSPORT, EUROPEAN COMMISSION

> *"Energy is essential for Europe to function. But the days of cheap energy for Europe seem to be over. The challenges of climate change, increasing import dependence and higher energy prices are faced by all EU members."*
>
> – EUROPEAN COMMISSION [1]

## 3.1 Danish and European energy challenges

The European Community faces three major energy challenges [1]:

- *Sustainability.* Current energy and transport policies imply that EU $CO_2$ emissions will rise by approximately 5% by 2030. Global emissions are expected to increase by 55% in the same period if no actions are taken.
- *Security of supply.* Europe is becoming increasingly dependent on imported fuels. Existing trends imply that the present import share of 50% will increase to approximately 65% by 2030. This will make Europe's energy system more vulnerable to external factors that are difficult to control, including terrorism.
- *Competitiveness.* Rising energy prices could jeopardise job creation in the EU. Investing in energy efficiency and renewable energy could promote innovation and industrial development, with corresponding benefits for employment and the economy.

Faced with these challenges, the Council of the European Union recently agreed to pursue actions on energy. A sustainable integrated European climate and energy policy is to be developed, including a target of a 20% cut in greenhouse gas emissions by 2020 compared to 1990. However, the EU is willing to increase its reduction target to 30% by 2020, if other developed countries commit themselves to comparable figures. As approximately 80% of $CO_2$ emissions stem from fossil fuels, new measures to regulate the energy field are called for. To that end the European Council has decided to adopt an energy action plan for the period 2007-2009 [2].

For more than a quarter of a century Denmark has had an energy sector with a strong environmental profile, and since the beginning of the 1990s climate change has been the most important driver for Danish energy policy. Denmark has been one of the countries pushing the EU for strong and binding targets in climate policy. Recently the Danish government put forward a new energy plan for 2025; this would stabilise energy consumption at its current level, and calls for a considerable increase in the use of renewable energy for power and transport [3]. Table 1 compares energy consumption, $CO_2$ emissions and population for Denmark, the EU and the world.

## 3.2 Developments in Europe

### *3.2.1 The new EU targets for $CO_2$*

The last couple of years have seen the combined challenge of energy and climate rise to the top of the EU policy agenda. The 2007 Spring Council took important decisions on greenhouse gas emission reductions, renewable energy technologies, biofuels and improved energy efficiency. However, the important task of deciding how these burdens should be shared between the Member States is still to be completed. And viewed over the longer term – since 1990 – the EU has achieved only moderate results in energy policy. We can summarise the situation as follows:

Along with security of supply climate change has now become a key driver for energy policy. The commitment to reduce greenhouse gas emissions by 20% by 2020 compared to 1990 is in line with previous EU policy decisions, such as the sustainable development policy agreed at the June 2001 Gothenburg Council. Similarly, the EU's worldwide negotiating position of a 30% $CO_2$ cut is comparable to its proposal of a 15% reduction by 2010 for the 1997 Kyoto negotiations, if we take into account the fact that the EU enlargement has brought significant emission reductions in most of the new Member States into the EU greenhouse gas emissions accounting scheme, and that the 2020 target will allow the use of flexible mechanisms. In addition, the new Member

Table 1: Gross energy consumption, $CO_2$ emissions and population for Denmark, the EU and the world, 2004

| | World | EU | Denmark | Denmark/World (0/00) | Denmark/EU (0/00) |
|---|---|---|---|---|---|
| Gross energy consumption, EJ | 490 | 73 | 0.8 | 1.6 | 11.0 |
| $CO_2$-emissions, GT $CO_2$ | 26 | 3.9 | 0.06 | 2.3 | 15.4 |
| Population (million) | 6000 | 462 | 5.4 | 0.9 | 11.7 |

States have brought considerable emission reduction potential to the EU, because most of them use energy much less efficiently than do the EU-15 countries.

The targets agreed at the Spring Council are certainly needed if dangerous anthropogenic interference with the climate system is to be avoided. A number of studies have demonstrated the technical feasibility of these targets, which are thus more of a political than a technical or economic challenge. But it is still necessary to decide how the task is to be shared out: either entirely between Member States, as suggested by the Commission, or partly between industry sectors, through EU-wide policies reflecting the EU's internal energy market.

### 3.2.2 An EU target for renewables of 20% by 2020

The EU has steadily increased its use of renewables. In 2005, renewable sources provided around 15% of the electricity consumed in the EU. This figure is lower than expected, though electricity consumption has also grown faster than expected. As the Commission states: *"…with the exception of Germany and Spain, the countries making good progress unfortunately represent only a relatively small proportion of the total EU market. In a number of Member States the share of renewable electricity is even declining* [5]".

This is illustrated in Figure 1, which compares the production of renewable electricity in 1997 and 2004 with the targets for 2010. Figure 1 clearly shows that several countries will need to accelerate their deployment of renewables significantly if they are to meet their 2010 targets.

Figure 2 shows that the EU Member States are very different in their potential for renewable energy. In most countries, the dominant renewable energy source is large-scale hydro, but onshore wind power and biomass are also significant. The variety of renewables found across the Member States increases the benefits of cross-border coordination. Figure 2 includes large-scale hydro which is not expected to be developed significantly in the coming years leaving even more emphasis on "new" renewables if targets are to be met.

The EU commitment to 20% renewable energy by 2020 is ambitious and challenging. In 2007 only around 7% of gross energy consumption comes from renewable sources, and this figure will probably increase to 8-9% by 2010. A significant increase in the speed of renewables penetration is therefore needed if the EU is to meet its 2020 target.

### 3.2.3 Inconsistent energy accounting

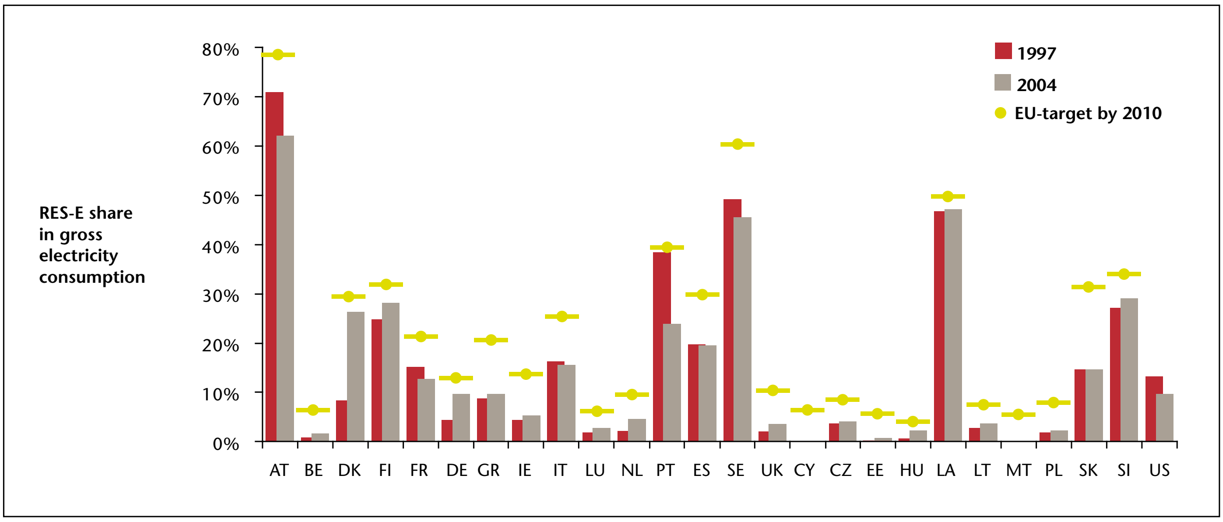
The target of 20% renewables by 2020 implies other challenges beyond simply working out how to share the burden. One of these challenges stems from inconsistencies in the way the EU and other international bodies measure the contributions of different types of renewables.

Wind power, which will make an important contribution to future renewable electricity, is credited in terms of the energy content in the electricity generated. Electricity from biomass, on the other hand, is credited as the energy in the biomass that forms the fuel for the power plant; this primary energy is usually around 2.5 times the amount of electricity generated.

The implication is that the 300 TWh of wind energy that will be generated by 2020, on top of the 100 TWh to be generated in 2007, will contribute only two percentage points to the overall target of 13 percentage points (20% less than the current figure of 7%), leaving 11 percentage points to be delivered by other technologies. If wind power were counted in the same way as electricity from biomass – as displacing an equivalent amount of fossil fuel – it would account for a much larger proportion of the 2020 target.

Even more worrying is the idea that, with no future targets for renewable electricity as such, biomass will be favoured over wind power simply because it is a cheaper way to meet the 20% renewable energy target. At present,

Figure 1: Renewable electricity production in the EU-25 in 1997 and 2004, compared with targets for 2010 [4].



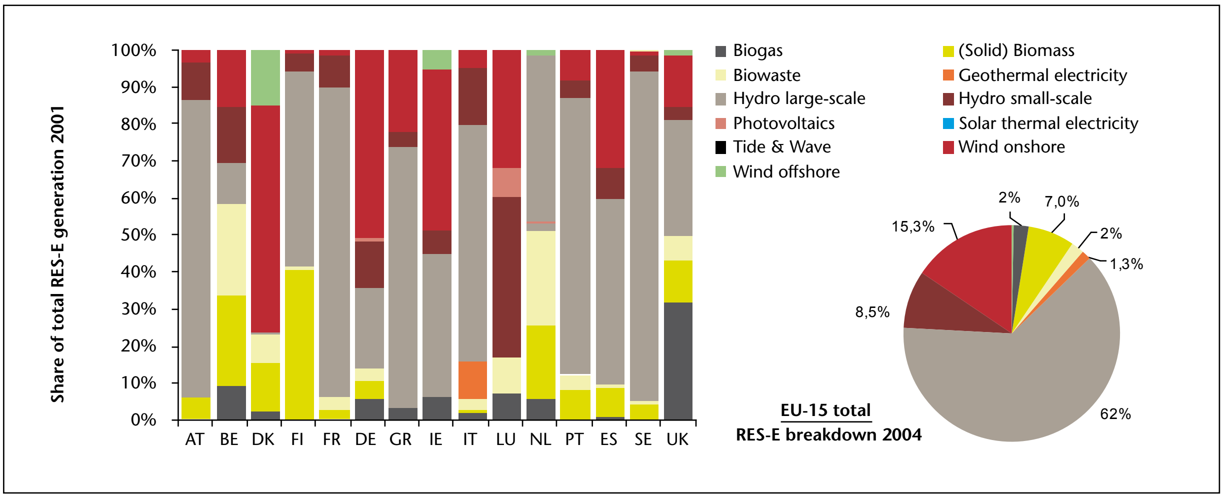


Figure 2: Renewable electricity fuels and technologies vary considerably across the EU-15 [4].

however, wind power seems to be preferred because it is the cheapest of the renewable technologies in terms of meeting $CO_2$ reduction targets.

### 3.2.4 *Are biofuels the way forward?*

The emphasis of renewable energy policies on the input of renewables, rather than the extent to which renewables meet primary policy objectives such as $CO_2$ reduction or oil substitution, is a problem, and not just in electricity generation. The agreement to raise the present EU target for biofuels (5.75% by 2010) to 10% by 2020 by including second-generation biofuels appears to be a good idea at first glance. However, biofuels manufacturing technologies need to become significantly more efficient if they are to be useful in the long term[1]. An alternative way to reduce $CO_2$ emissions and save fossil fuels would be to use biomass to replace oil or natural gas for heating, allowing the oil or gas thus saved to be used as motor fuel[2].

EU energy policy is at a crossroads. The Commission has identified the right direction in which to go, but it is not clear whether the EU as a whole is ready to move ahead with sufficient speed. Much additional routefinding is necessary if we are to avoid dead ends or unnecessarily tortuous trails.

## 3.3 Denmark in a European perspective

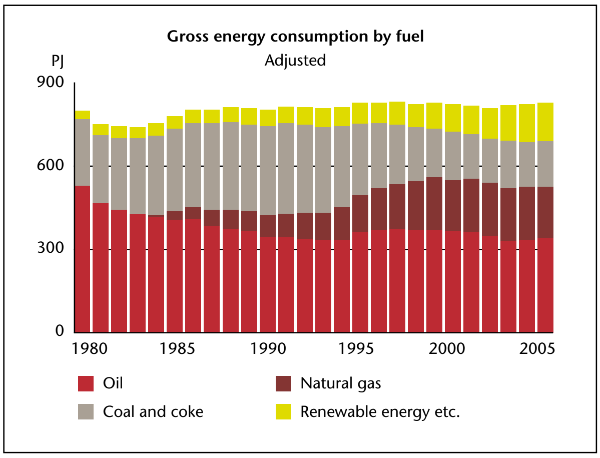
### 3.3.1 *Danish challenges*

Denmark is the only net exporter of energy in the EU. In 2005, production from Danish oil and gas fields in the North Sea exceeded the country's gross energy consumption by 56%. At the same time Denmark has an environmentally-friendly energy profile that includes considerable amounts of renewable energy, especially wind power; strong energy efficiency measures; and widespread use of combined heat and power (CHP). For more than 20 years Denmark has kept its gross energy consumption almost constant, with an increase of just 4% since 1985, despite a 70% increase in gross national product in the same period. In short, Denmark is in a far better energy situation than most countries in the EU (Figure 3).

The country nevertheless faces a number of energy challenges. Some of these are in line with the rest of the EU, while others are specific to Denmark:

- Danish oil and natural gas production will decrease significantly over the next 20 years. Oil production peaked in 2005 and will gradually decrease to approximately 20% of its present figure by 2025. Natural gas production also peaked in 2005, but will decrease more slowly than oil.
- CHP, in combination with an extensive district heating system, is a cornerstone of Denmark's highly efficient energy system. The heating market has exploited small CHP plants to their limits, however, so the potential for further expansion is limited.
- Denmark has the highest share of wind power in the world: wind turbines supply 20% of the country's electricity consumption. Connecting more wind power to the grid will require innovative engineering.

Figure 3: Denmark's gross energy consumption and primary energy sources since 1980 [6].



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[1] Though it should be taken into account that biofuels will increase the diversification of the transport sector and thus improve security of supply.

[2] It might prove useful to utilise life cycle analysis to assess the role of biomass in the future energy system.

- A large proportion of Danish power production is still based on fossil fuels, especially coal. This implies that Denmark has fairly high per-capita $CO_2$ emissions, and a correspondingly high target figure of 21% (1990 basis) for $CO_2$ emission reduction by 2010. Achieving this target will require significant further $CO_2$ reductions over the next three years.

## 3.4 A visionary Danish energy policy

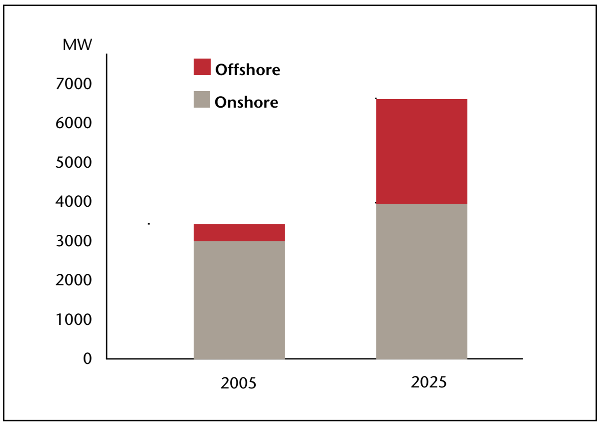
The present Danish government has until recently relied on market forces to guide the development of the energy system. At the start of 2007, however, the government decided that a long-term energy plan was needed to tackle the challenges discussed above. The new plan, *A Visionary Danish Energy Policy,* sets out ways to ensure a robust and environmentally-sound energy supply in Denmark [3].

*A Visionary Danish Energy Policy* has two main targets: cutting the consumption of fossil fuels by 15% (2007 basis) by 2025, and keeping total energy consumption constant until 2025. Achieving this will require a number of new policy initiatives focusing on energy conservation, renewable energy and new high-efficiency energy technologies. The two targets will be monitored every four years, and new policy measures adopted if necessary.

The commitment to keep total energy consumption constant without hindering economic growth will require new *energy conservation* measures equivalent to an annual reduction of 1.25%. Measures to achieve this will include a new energy conservation market trading in “white certificates”, more stringent conservation rules for energy companies, and savings targets for those sectors not covered by the European emissions trading system.

*Renewable energy* currently provides almost 15% of Denmark’s gross energy consumption. To meet the target for fossil fuel reduction, the proportion of energy from renewables needs to increase to 30% by 2025. Wind power (Figure 4), waste and biogas are the technologies to be promoted through a new and more efficient support scheme for renewables[3].

Figure 4: Under the new energy plan, Danish wind generating capacity is set to double by 2025 [3].



Finally, a new development and demonstration programme for *new efficient energy technologies* besides wind power will support second-generation biofuels, hydrogen, fuel cells and low-energy buildings, among others. In transport, there is a target of 10% biofuels by 2020.

### *3.4.1 Integrating wind power into the Danish power system*

Denmark currently holds the world record for the proportion of wind in a national power system. On average, around 20% of Danish electricity consumption comes from wind, and in the western part of Denmark[4] the proportion averages 25%. Occasionally wind even provides more power than is being used in the whole of Western Denmark at the time (Figure 5).

As part of the new energy plan the Danish government illustrates a doubling of wind capacity by 2025, from the present 3100 MW to 6200 MW (Figure 4). Offshore wind farms will provide a large part of this increase. At present, however, the spot market is already stretched to its limits at times when plenty of wind power is available (Figure 5). Increasing wind capacity to meet 50% of Danish demand may therefore require much closer integration of wind power in the energy system, and this will be challenging.

In any given power system, the amount of wind power being generated depends closely on the speed of the wind, which can vary rapidly. The need to keep generation and consumption in balance at all times places constraints on the regulating capacity of the rest of the power system. This happens at two timescales.

In the short term (minutes or hours), wind is relatively unpredictable and frequently delivers either more or less than the forecast amount of power. This means that conventional power plants have to make up the shortfall when wind speeds are lower than expected, and cut production when the reverse is true. Both courses of action lead to increased costs, which should presumably be covered by wind power.

In the medium and long term (days and weeks), the variability of the wind means that there will be many times when little or no wind power is available. In a power system where wind makes up a substantial fraction of the generating capacity, either consumption will have to fall, or other forms of generation capacity will have to fill the gap. Again, this has both systems and cost implications.

## 3.5 System consequences of variability

The short-term and long-term variability of wind pose different challenges to the integration of wind power into the energy system.

Short-term variability means that the market often receives less, or more, wind power than expected. High-capacity interconnectors between Denmark, Norway, Sweden and Germany, plus the regulating capacity of the Nordic market, have so far ensured that this variabil-

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[3] A higher share of renewable technologies might necessitate a more thorough integration to avoid problems of excess supply of power and eventual instability of the system. This will be discussed in the next section.

[4] West and East Denmark is not electrical connected. From 2010 a 600 MW DC-cable will connect the two parts of the country.

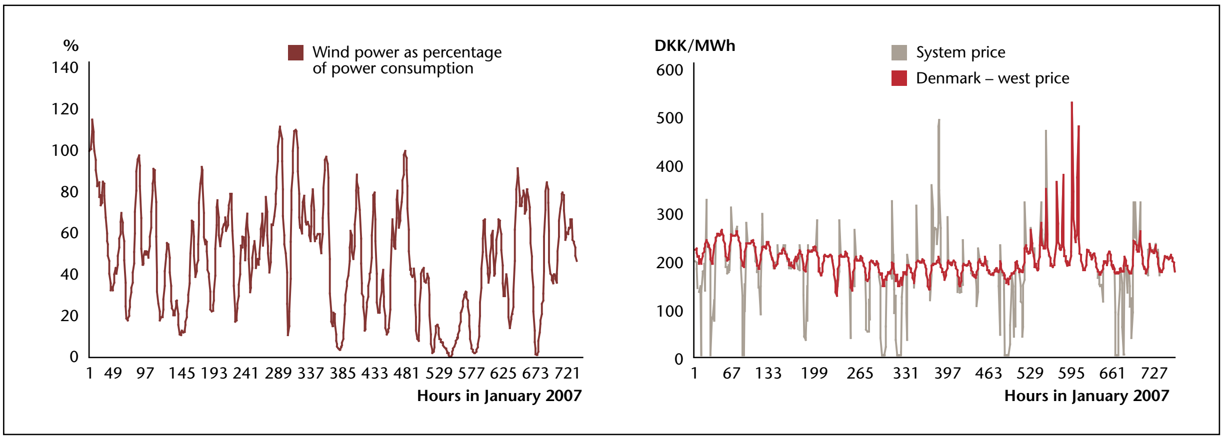


Figure 5: (Left) Wind generation as a percentage of total power consumption in western Denmark; (right) Electricity spot prices for the same area and time period.

ity can be accommodated at reasonable cost. The average balancing cost for wind power is 0.20 c€/kWh, or around 5-7% of the overall cost of wind power. This is considered acceptable, and the cost of short-term variability is not seen as a major barrier to the expansion of wind power. However, it should be taken into account that only Denmark at present has a high share of wind power in the system. If other Nordic countries were to have the same amount of wind power in their power systems as Denmark, this would expectedly increase balancing cost.

Long-term variability is harder to cope with, and could require a complete redesign of the power system. For example, if the wind does not blow for a week in the winter, when power demand is at its peak, the resulting tight capacity balance in the power system will lead to high prices, and perhaps technical problems.

If no spare capacity is left in the system, the only remedies are investment in new capacity or reduced demand for power. New capacity in this context typically means plants based on gas turbines; these have low capital costs but high variable costs, particularly for fuel. Strong interconnectors to neighbouring countries and more integrated power markets might also help solve the problem. Another possibility is energy storage systems such as very large batteries. Although these are commercially available, they are currently expensive.

Eventually, closer interplay between the power system and the district heating system may be a solution to power balancing. Hot water is a cheap way to store energy, so it can be used as a buffer in an optimised heat and power system.

Another possibility is demand side management, which makes it possible to temporarily reduce demand for power when generating capacity is short. Power interruptions of demand lasting several hours or days may be difficult to implement, however, without serious discomfort to power consumers.

Against the costs and disadvantages of the various options for power balancing in systems with a large amount of wind capacity, it is important to remember that investments in new capacity and demand management systems can help the efficient management of the power system, apart from its role in integrating wind power. The problem of long-term variability is closely related to the long-term development of the power system, so the same solutions may benefit both wind power and the operation of the system as a whole.

Danish research institutions are now starting to address the problem of long-term variability. Denmark has a special advantage: not only does it have the world's highest share of wind power, it is also a small country where national-scale demonstrations are relatively easy to carry out. As a result, Denmark has a unique chance to take the lead in overcoming one of the most important barriers to the large-scale deployment of wind power.

## 3.6 Danish opportunities

For more than 20 years Denmark has engaged in developing new and renewable energy technologies. At present we are the world leader in wind power, but we also have a strong position in biogas, biofuels for transport, fuel cells and systems integration. Collaboration between research institutions, private companies and government bodies could further develop these technologies, leading to increased employment and strengthened innovation in the private sector.

The more wind power expands worldwide, the more pressing it is to solve the problem of long-term variability. The need is for a flexible energy system based on technologies including power demand management, smart grids, heat pumps for local and district heating, storage for heat and eventually power, strong grid interconnections, and perhaps links to transport, where a strong growth is envisaged in the coming years. With plenty of wind power and a highly diversified energy system, Denmark has the opportunity to play a key role in resolving the problems of integrating wind power on a large scale, also bringing added business opportunities to Danish companies.

As mentioned above, significant growth is expected in transport, and extra effort is needed to minimise the environmental impact of this sector. Long-term solutions include the widespread use of hydrogen as an energy carrier – which also will benefit the integration of wind power – the development of economical long-range electric cars, and biofuels. The new Danish energy plan sets a target of 10% of transport needs to be met by biofuels by 2020, and extra funds are being provided for biofuel research and demonstration plants. From an industrial viewpoint, the development of biofuel plants in Denmark is very attractive. Finally, Denmark has a strong position in the development of other new energy technologies such as fuel cells and biogas.

### 3.7 Recommendations

Denmark has a unique chance to take the lead in developing flexible energy systems. This complex task should be addressed through intensive projects to develop and demonstrate existing technologies in private public partnerships including collaboration with the transmission system operator, and also through research in new technologies. In both research and demonstration facilities, we should be ready to risk considerable amounts of money.

A new era of electric cars seems to be approaching. We may still have to wait several years for commercially-viable electric cars, and Denmark has limited experience with this technology. From an energy system point of view, however, electric cars are so interesting that Denmark should take the lead in integrating them into the energy system, setting up demonstration projects to do this.

The new energy plan emphasises new energy technologies such as fuel cells, and renewable technologies including biogas. Denmark already has a good grounding in the development of such technologies. Now they should be reviewed in terms of their potential to form part of a future energy system, and a small demonstration programme for fuel cells should be started.

Danish researchers and industrialists also have a strong position in biofuels. There are still uncertainties about the $CO_2$ emissions associated with biofuels, however, and the part biofuels will play in Denmark's future energy system. Resolving the latter point will need comprehensive system analyses.

Achieving a sustainable energy system will also require much work on developing energy-efficient appliances and energy conservation. Denmark has a long tradition of energy saving, and should take care to maintain this through the coordination of existing programmes as well as suitable new policies.

# 4

# Energy efficiency policy

JENS-PETER LYNOV, RISØ DTU; SVEND SVENDSEN, HENRIK M. TOMMERUP, BYG DTU; JØRN BORUP JENSEN, DANISH ENERGY ASSOCIATION

## 4.1 Introduction

Figure 6 shows how energy efficiency improvements have reduced EU energy intensity during the past 35 years [1]. It demonstrates that by 2005, "negajoules" (energy consumption avoided through savings) had become the single most important "energy resource". The upper border curve in this figure shows the imagined growth in energy demand based on GDP development from 1971 to 2005 but with energy intensity kept constant at the 1971 level.

Even though energy efficiency has improved considerably since 1971, it is technically and economically feasible to save even more energy [2]. This potential plays a prominent role in the new European Energy Action Plan adopted in March 2007 by the European Council [3]. As part of this plan, the EU leaders set the objective of saving 20% of the EU's energy consumption compared to current projections for 2020.

Realising this potential, which is equivalent to some 390 Mtoe in the year 2020, will yield large energy and environmental benefits. $CO_2$ emissions should be reduced by 780 million t $CO_2$ for the single year 2020 with respect to the baseline scenario – more than twice the EU reduction required under the Kyoto Protocol for the whole 5-year period 2008-2012. Additional investment in more efficient and innovative technologies will be more than compensated by annual savings exceeding €100 billion by 2020[5].

Opportunities for energy efficiency improvements throughout the energy chain [4, 5] include:

- exploitation and production of primary energy sources such as oil, gas and coal;
- transmission and storage of primary energy;
- generation and transmission of electricity;
- energy distribution and end-use services in homes, offices and factories.

The further down the chain efficiency is improved, the greater the impact on primary energy consumption and emissions. As an example based on data from 2002 averaged across the EU, 1 kWh of electricity at the point of use requires 2.2 kWh of energy from primary fuel to be converted in a power plant. In the case of fossil fuels this is accompanied by the emission of about 314 g of $CO_2$ [6, 7]. Including the 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 [6], so every kWh saved at the point of use means a saving of around 2.4 kWh in primary energy and 340 g of $CO_2$.

Figure 7 shows how the EU uses its primary energy, and it is seen that energy conversion losses account for the largest fraction (33%) of the primary energy consumption.

Table 2 (see next page) shows estimates of energy use and the potential for savings in residential and commercial buildings, transport and manufacturing [1]. All of these sectors have energy saving potentials of 25-30%.

The following sections describe in more detail how energy efficiency can be improved through means ranging from new technologies to new policies.

## 4.2 Energy conversion

As Figure 7 shows, energy conversion – the transforming of energy from one form to another – is the biggest single consumer of energy in the EU, accounting for around one-third of all our primary energy.

This is not surprising given our reliance on electricity and the fact that the average efficiency of electricity gen-

Figure 6: EU energy savings from 1971 to 2005.

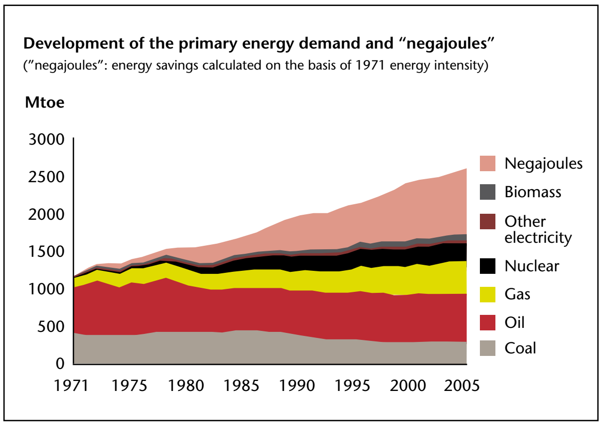
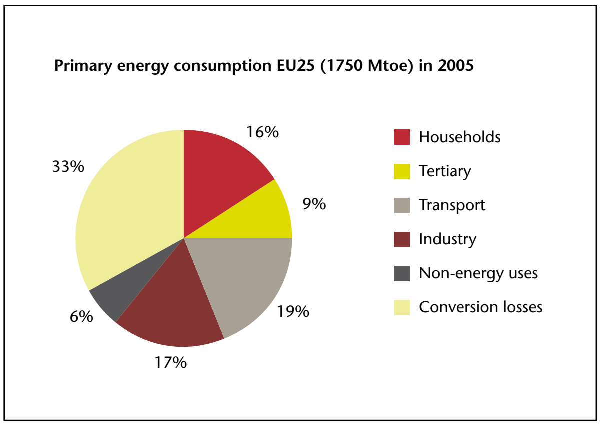


Figure 7: Distribution of EU primary energy consumption in 2005.



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[5] 390 Mtoe at USD 48/barrel net of taxes.

| Sector | Energy consumption (Mtoe) 2005 | Energy consumption (Mtoe) 2020 (Business as usual) | Energy saving potential 2020 (Mtoe) | Full energy saving potential 2020 (%) |
|---|---|---|---|---|
| Households (residential) | 280 | 338 | 91 | 27% |
| Commercial buildings (tertiary) | 157 | 211 | 63 | 30% |
| Transport | 332 | 405 | 105 | 26% |
| Manufacturing industry | 297 | 382 | 95 | 25% |

Table 2: Estimates of energy saving potential in buildings, transport and manufacturing.

eration is around 40%. New generation plants using both gas and steam turbines (combined-cycle gas turbine, or CCGT) can have efficiencies close to 60%, creating a large potential for improving energy efficiency.

The electricity supply chain covers generation, transmission and distribution, with energy losses at every stage. The electricity supply chain in Europe is still largely characterised by generation in large central power plants, connected to consumers by long transmission and distribution cables. Such a system achieves economies of scale, but is also wasteful of energy.

In a centralised electricity system the biggest energy losses occur during generation, when low-temperature heat that cannot economically be converted into electricity is dumped into rivers, the sea or the atmosphere. Long-distance transmission and especially distribution then create further losses.

Europe needs to invest in new electricity generating capacity. This investment could be used to shift electricity generation away from big power stations and towards cleaner generating units sited at or near the point of electricity use, thus reducing transmission and distribution losses [8].

Extra efficiency gains are possible if distributed generation takes the form of combined heat and power (CHP, also known as cogeneration). As well as generating electricity, CHP plants heat buildings and industrial processes using the low-grade heat that is wasted by conventional power stations.

The ability to use “waste” heat gives CHP systems high efficiencies: often over 80% and sometimes over 90% [9]. This efficiency manifests itself in the form of savings in gas, oil or coal that would otherwise have to be burned for heating.

To date, only around 13% of all electricity in the EU is generated using this technology [2]. In Denmark the figure is approximately 50% [10], split equally between centralised and decentralised CHP plants.

## 4.3 Transport

Transport is central to the European economy and as such accounts for almost 20% of total primary energy consumption (Figure 7, see previous page). 98% of the energy consumed in the transportation sector comes from fossil fuels. As transport is also the fastest-growing sector in terms of energy use, it is a major source of greenhouse gases and of import dependency on fossil fuels [1].

In Denmark, transport accounts for 30% of total energy consumption and 60% of oil consumption [12]. Danish energy use in transport has increased by 65% over the last 30 years, and is still growing due to an increased amount of traffic. Almost all the growth is in road transport, which accounts for 94% of the energy, and 95% of the oil, used for transport.

Opportunities to improve energy efficiency and cut $CO_2$ emissions through new technologies in the transport sector are treated separately in Chapter 5 of this Energy Report.

## 4.4 Buildings

Buildings account for about 40% of the total final energy consumption in the EU. Most of the energy used in buildings takes the form of low-temperature heating for rooms and domestic hot water. Electricity, which is a high-grade form of energy, is also used in large quantities for building services such as lighting, air conditioning and ventilation, as well as for the electrical equipment used in homes, shops and offices.

A sustainable energy system that uses no fossil fuels is possible by combining renewable energy with high energy efficiency. This is highly relevant to buildings, where the potential for energy savings is very large, and renewable energy technologies for both heating and electricity are already available.

Energy saving in buildings is the subject of much EU energy policy, especially the Energy Performance of Buildings Directive (EPBD) [13]. This Directive, which will be implemented in all EU Member States by 2009, is revolutionising the energy conservation requirements of national building codes. Its main requirements are:

- all fossil-fuel energy used by new buildings must meet a national energy conservation standard;
- existing buildings must comply with the principles of EPBD whenever they are renovated; and
- national energy conservation standards must be reviewed every five years to take account of progress in energy saving technologies and fossil fuel prices.

The Danish building codes include new energy requirements, which are determined according to the principles of the EPBD. They also introduce two new classes of low-energy buildings, which use respectively 50% and 25% less energy than the new energy requirements. The result

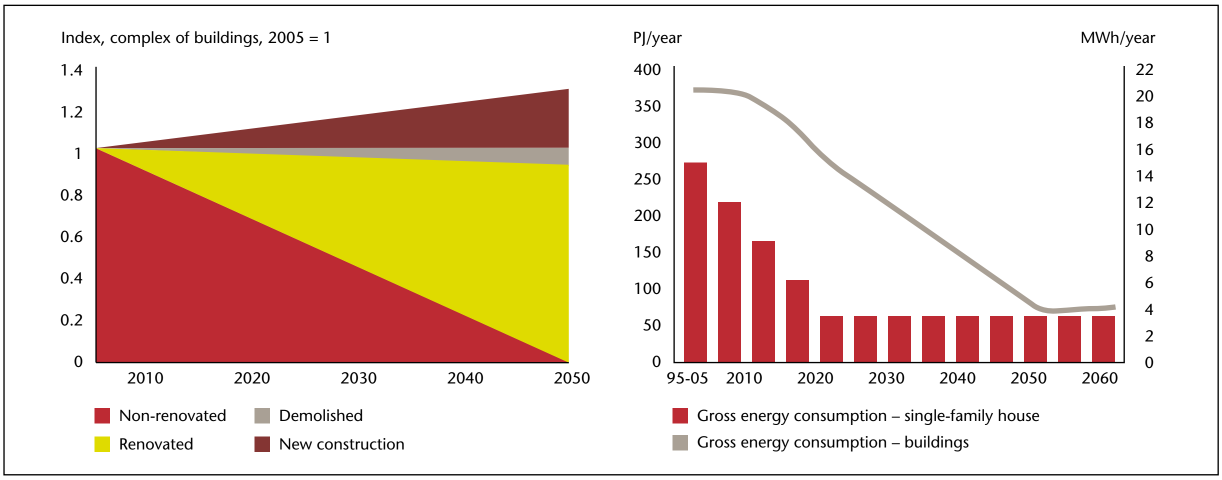

Figure 8: Possible future energy savings in Denmark's housing stock (left), and gross energy consumption in buildings during the same period (right).

will be energy savings in both new and existing buildings in Denmark.

A study of the potential savings in energy used for heating of existing domestic buildings in Denmark [14, 15] has shown that savings of 60-80% in the period up to 2050 are possible if extensive energy conservation measures are put in place whenever the buildings are renovated (Figure 8). The assumption is that during this period the entire building stock is either replaced by new buildings or renovated to the energy standards of new buildings. This would cut Denmark's total final energy consumption by around 30%. A major part of these savings up to 2050 come from renovation.

## 4.5 New low-energy buildings

Large efficiency improvements in new buildings have been demonstrated in many projects. Techniques for creating new low-energy buildings are well-documented, giving rise to names such as passive house, solar house and smart house.

Of these, the passive house concept is probably the best known. This is based on know-how from low-energy housing projects such as Hjortekær, carried out in Denmark in the late 1970s. A more recent Danish low-energy house was built in Kolding in 2005 (Seest) (Figure 9). Its energy consumption for room heating has been measured at 27 kWh /m$^2$/year, which is half that for a house built according to the new energy requirements of the Danish building codes.

The strategy for the future is to further develop existing energy-saving technologies. One current project, for instance, is about developing new low-energy windows based on composite materials, in cooperation with window manufacturers and designers of district heating systems. Another example is the design of commercially-viable single-family houses that consume only half the energy specified by the building codes (Class 1 low-energy buildings, in Danish terminology).

Danish municipal authorities are taking the lead in several projects. One example is in Vejle, where several different project teams are building a group of ten "Comfort Houses". The towns of Køge [16] and Stenløse [17] have both proposed that all new houses in large residential areas should meet low-energy standards.

## 4.6 Retrofitting old buildings

The new energy requirements of the Danish building codes specify that energy savings must be put in place when existing buildings are renovated. This is the first time such requirements have been specified in detail, and in general energy-saving know-how for old buildings lags behind that for new construction. To improve this situation, low-energy retrofitting of large buildings is the focus of a large development and demonstration project to be carried out in 2007-09.

Several Danish projects have shown that it is possible to retrofit energy-saving measures economically. A project in Køge created large and profitable energy savings in a typical single-family house built before 1950. Figure 10 (see next page) shows another project in which a single-family house typical of those from the 1960s and 1970s was renovated in a cost-efficient manner to roughly the energy performance of a new Danish single-family house. As a positive side effect, the renovation also improved living conditions in the house.

A project in Ballerup (Lundebjerg) is a good example of the energy-efficient renovation of a multi-family build-

Figure 9: Highly insulated and airtight low-energy house in Kolding (Seest). The house has a mechanical ventilation system with highly efficient heat recovery.

ing. This multi-storey building was erected in 1961-64, and a combination of thermal bridges, cracked brickwork and blocked ventilation openings had caused problems with condensation and mould. The problems were solved by installing:

- external wall insulation 150 mm thick, protected by a new rain screen made of thin brickwork mounted on a rail system;
- new windows with 1+2 glazing;
- a new mechanical ventilation system (exhaust only); and
- a new heat distribution system to replace the existing radiators and pipework.

From an energy-saving point of view it is unfortunate that a heat recovery ventilation system was not chosen; this was considered too expensive, although cost-benefit analyses typically show that heat recovery ventilation is profitable. The renovated building roughly meets the energy performance of a new building to current standards.

## 4.7 Integrated energy systems

The Energy Performance of Buildings Directive (EPBD) has shifted the focus from individual energy systems and technologies to integrated buildings that make optimal use of daylight, natural ventilation, passive cooling and heating, and renewable energy.

Figure 11 shows an example of an integrated low-energy solution for heating and ventilation. A special rafter design makes it possible to install the ventilation ducts in the warm space above the ceiling instead of in the unheated attic, so heat loss is reduced.

Electricity is a “high-quality” (high-exergy) form of energy [18, 19] that should be reserved for applications such as lighting, electronic equipment and motorised appliances, for which other forms of energy cannot be used. Electricity should not be used for space heating, or any other application that can be met by “low-quality” (low-exergy) energy.

Energy sources suitable for heating buildings include solar thermal systems, heat pumps, waste incinerators and CHP systems. District heating systems, in which heat produced in one place is used elsewhere, can improve energy efficiency through economies of scale and by providing heat storage to smooth out variations in heat supply and demand.

Individual heat pumps and solar heating systems can supply heat to buildings in the countryside and other areas where district heating is not available. Individual solar photovoltaic (PV) systems and wind turbines can also provide electricity, making buildings entirely sustainable and self-sufficient, though using wind power to run heat pumps can be problematic on calm winter days.

The combination of energy saving in buildings and appliances, renewable energy from waste incineration and other sources, CHP and district heating can create complete energy networks that are independent of fossil fuels. New buildings should meet at least the Danish Class 1 standard (50% of the energy use specified by the new energy standards in the latest building codes), and existing buildings should be renovated to approach this standard. The latter point is especially challenging, but work in Germany has shown that it is possible to create ultra-low-energy buildings of passive house standard through renovation.

Based on an economical estimate [15] not more than 20% of current building energy requirements in Denmark can be covered by sustainable energy. In order to become totally independent of fossil fuels, the remaining 80% of current building energy requirements must come from energy savings. This will not be achieved without further pressure from the Danish government. The requirements of the building codes need to be tightened gradually, and the building sector must develop correspondingly effective solutions for both new buildings and retrofits. These include building components, modules and systems; installation methods; and efficient and environment-friendly heating and electrical generating equipment.

A forward-thinking energy efficiency policy that includes stringent standards for buildings can create a Danish

Figure 10: A typical Danish single-family house from the 1960s or 1970s (Næstved). It was retrofitted in 2006 to roughly the energy performance of a new Danish single-family house.

Figure 11: Extending the depth of the rafters in a low-energy house allows ventilation ducts to be installed in a warm ceiling space instead of in the cold attic.

building stock that represents a valuable knowledge resource as well as eliminating dependence on fossil fuels. This is a realistic goal for the construction industry; by putting a little extra effort into energy saving, companies both large and small can expand their business both in Denmark and abroad.

Big improvements in energy efficiency and the use of renewable energy are the subject of policy and projects worldwide, including the United Nations 2007 report on Buildings and Climate Change [20]. To use low-energy buildings effectively, however, requires significant development of suitable integrated energy systems. In Denmark this could be carried out within the state-supported Network on Integrated Low Energy Solutions in Buildings, a network of knowledge institutions and professionals in the building industry [21].

## 4.8 The market for energy-efficient equipment

As mentioned in Chapter 4.1, Europe could cut its energy consumption by 25-30% through initiatives that are profitable at both national and consumer levels. The European Commission estimates that consumers could save up to €100 billion annually by putting into place existing energy-saving technologies. The Danish Energy Association and the Danish Energy Authority agree that Denmark could use known technology to save 25-50% of current energy consumption in several sectors.

So why is this not happening? Chapter 4.4 makes it clear that buildings represent the single largest source of energy savings at the moment. Buildings have long lives, and the long payback times that characterise many energy-saving investments are often not attractive to owners and tenants.

There is a big gap between the large financial savings possible through investment in energy efficiency, and the general reluctance to make this investment. Many studies have tried to explain the reasons for this market failure, and many initiatives have tried to overcome it. To date, however, no-one seems to have been able to create a thriving market in energy-saving retrofits for buildings.

## 4.9 Dynamic standards drive efficiency

One way to cut the energy consumed by electrical and electronic equipment is to copy the building sector by introducing minimum standards for the energy efficiency of new devices.

Since most such equipment is sold in more than one country, national standards are not the answer here. Denmark, for instance, is too small a market to attract most manufacturers on its own, so Danish policy in this area mirrors that of the EU. The Commission's Action Plan for Energy Efficiency [1], and specifically the Ecodesign Directive [22], offer the chance of change that is both rapid and cost-effective.

The Action Plan for Energy Efficiency identifies 14 product groups for which the Commission must adopt minimum energy performance standards by the end of 2008. The use of a Framework Directive means that individual standards do not have to be approved by the Council and the European Parliament; instead they can be set up by technical committees comprising representatives of the Member States. It is important that these standards should be dynamic, so that they become more stringent as technology evolves.

European standards for energy consumption will exclude the least efficient equipment and devices from the market. This will be especially important for electric motors, which are widely used in industrial refrigeration and ventilation equipment, compressed air systems and for pumping liquids.

But the standards will also apply to domestic heating and air conditioning equipment, televisions, computers, refrigerators, washing machines, and the small power supplies used for portable electronic equipment and low-voltage lighting. Much of this equipment has a short working life (3-12 years), so new standards will quickly have an appreciable effect.

From an energy technological point of view, it is important that such standards are made dynamical, i.e. that an automatic revision is built in, so that the minimum requirements of the standards can be increased at the same pace as the technological development. This will also increase the incentive of the manufacturers and the research institutions to develop new and more efficient energy consuming technology, since the increased energy requirements will strengthen the position of these new, and often more expensive, devices on the market.

One application where standards could have a big effect is the power supplies sold with mobile phones, MP3 players, handheld game consoles and laptop computers. More than 95% of these power supplies are made in China in cheap designs that waste a lot of energy: many give off a lot of heat, and over several years they may cost more in wasted electricity than the value of the equipment itself.

Building more efficient power supplies is somewhat more expensive, but not difficult: power electronics developed in Denmark can be used to design a power supply that is 5-10 times more efficient than the average Chinese unit. Since electronic equipment is bought on its performance and initial cost, however, there is little incentive to use this technology at the moment. In spite of this, some global producers on the mobile phone market, e.g. Nokia, are going against this trend and are introducing more efficient chargers.

Dynamic energy efficiency standards could break this impasse by forcing manufacturers to either improve their products or be excluded from the lucrative European market. As long as standards are introduced with plenty of warning, and never go beyond what is possible using current best practice, they should not otherwise restrict trade.

Even though dynamic standards are widely seen as the most cost-effective way to improve energy efficiency, it has turned out to be politically difficult to get the Eco-design Directive implemented at the level of actual devices. Hopefully the rising political importance of energy efficiency will encourage decision-making. In March 2007 the European Council not only gave its support to the Action Plan for Energy Efficiency [1], but also said that lighting is one area where solid progress must be made during 2008 and 2009 [3]. Similar political initiatives have happened in California and in Australia, where in February 2007 Malcolm Turnbull, Minister for the Environment and Water Resources, legislated to phase out incandescent lighting by 2009 or 2010.

## 4.10 Reliable labelling

The "A-G" energy labelling system for household appliances and lighting has had a remarkable influence on the market. Refrigerators, freezers, washing machines and dishwashers with an "A" rating have become best-sellers in Denmark, and this trend is spreading to the rest of Europe. Unfortunately the complexity of decision-making at the European level has not allowed the existing categories to move with the times, so it has been necessary to introduce A+ and A++ labels for new and more energy-efficient equipment.

The value of standards and, in particular, energy labelling depends on whether consumers can trust the label to indicate the energy efficiency of the device. The Danish Energy Association has sponsored several projects to develop generally-accepted procedures for rating specific types of equipment, including pumps, ventilators, cooker hoods, commercial dishwashers, PCs and minibars. These projects normally involve collaboration between technology experts and manufacturers, creating an atmosphere of trust that encourages consensus right from the start.

Manufacturers' participation in projects like this also stimulates technical development, since the process of measuring energy consumption typically reveals opportunities for improvement. In this way, Danish energy labelling projects have helped the competitiveness of Danish manufacturers as more countries adopt energy efficiency standards.

As well as standards and labels, financial support may be appropriate to encourage the development of devices that are much more energy-efficient than their competitors. In the same way, devices with unusually high energy consumption could be specially taxed. Both support measures and taxes are difficult to agree on at European level, however, and in Denmark the current tax freeze would also be a problem.

## 4.11 White certificates

To encourage energy saving, several European countries have introduced white certificates – documents confirming that a certain cut in energy consumption has been achieved [23]. Under such a system, producers, suppliers and distributors of electricity, gas and oil are required to save a defined percentage of the energy they produce or transport. In most applications white certificates are tradable, so that companies that do not wish to carry out the required savings directly can buy the appropriate number of white certificates from another company that has exceeded its target for energy savings.

Italy started a white certificate scheme in January 2005; France a year later. Great Britain has combined its system of energy saving obligations with the ability to trade obligations and savings.

In Denmark, the government wants to establish a market for tradable white certificates (energisparebeviser) from 2010. Under the Danish scheme, households and firms that reduce their energy consumption will receive white certificates that can be sold to energy companies, helping the latter to meet their own energy saving obligations. This will ensure that the subsidy paid to households and firms is controlled by the market, and that energy savings are carried out at the level of the consumer, where they are most cost-effective.

Establishing such a certificate scheme is not easy. The EuroWhiteCert project [23] lists a number of key issues, including:

- How can appropriate targets be set?
- For what period should targets be set?
- Which parties should the targets apply to?
- How do we make sure that all the stakeholders who help to fund the scheme will also receive benefits?

The Danish white certificate plan has already been criticised [24]. One argument against the plan is that it should not be necessary to subsidise energy consumers to make energy saving projects that ought to be economically attractive in their own right. On the other hand, consumers are simply not investing in energy saving, in spite of the economic benefits that they can gain from doing so. Once the scheme is launched, it will be crucial to evaluate its performance regularly to ensure that it does what it was intended to do: increase overall energy efficiency in Denmark.

## 4.12 Behavioural research

Although tools of the types described above are the most attractive from an economic point of view, it may also be necessary to use other tools that have higher costs. These include ways of making consumers more aware of the composition of the energy they use, and showing how they can use this information in practical terms.

Experience shows that it is easy to make people aware of energy-saving campaigns, but that interest soon fades once the campaign is over. One reason for this is that information is not always available when it is most relevant to consumers. As an example, people can benefit from the information contained in their electricity bills, but the bill may not arrive for months or even a year after the power has been used.

In an effort to make this type of information more useful, the Danish Energy Association has launched a user-driven project that uses information technology to improve communications between electricity companies and consumers. The FEED-BACK project uses optical fiber networks, many of which are provided by electricity companies, to collect information on electricity consumption, put this into useful form and make it available to individual consumers. Some of the families in the pilot project are only informed of their total power consumption, while others receive more detailed information about individual electrical devices. They have all been involved in defining the ways in which the information is provided, so each family learns about its consumption in a way that makes most sense for its particular lifestyle.

Learning how best to present information of this kind should open the way to significant energy savings in the future, as well as reducing electricity companies' billing costs. As a supplement to the FEED-BACK project, the Danish Energy Association has also started to develop an improved meter that shows customers the energy consumption of several devices at once.

Another area of interest in behavioural research is the development of energy service companies (ESCOs), whose job is to organise, carry out and finance energy savings at end-users. The initial focus is on standard solutions that can reduce transaction costs for ESCOs, and on measurement and registration methods that can reliably and cost-effectively document the energy savings achieved.

## 4.13 Electricity consumption in Danish households

In 2005, electricity consumption in Danish private households was 9,838 GWh [25]. The main application areas were: refrigeration/freezing (20%), lighting (17%), washing/drying/dishwashers (16%), heating (13%), cooking, including microwave ovens (9%), TV/video (8%), PCs (7%), and other appliances (11%).

A large proportion of household electricity is used by appliances manufactured by multinational companies and sold in countries where electricity is cheaper than in Denmark. The relatively small size of the Danish market makes it difficult to persuade manufacturers to make their devices more energy-efficient.

## 4.14 Recommendations

As shown in figure 7, energy conversion losses account for 33% of the primary energy consumption in the EU. These losses can be cut significantly by introducing combined heat and power (CHP) generation. To date, only around 13% of all electricity in the EU is generated using this technology [2], and it is recommended to increase this fraction to approach the Danish figure of 50% electricity production by CHP [10].

The largest savings potential in end-use energy is in buildings. It is highly recommended that the principles of the European Energy Performance of Buildings Directive (EPBD) [13] are followed everywhere for both new and existing buildings. By doing so in all EU countries, it is estimated [1] that 28% energy savings in this sector can be achieved by the year 2020 corresponding to a reduction of the total EU final energy consumption by 11%.

Although energy savings are profitable at both national and consumer levels, these savings are not happening. In order to overcome the barriers against improving energy efficiency it is recommended that a wide range of political instruments are employed, including: Dynamic standards, reliable labelling, white certificates and behavioural research.

There are important niches for Danish R&D in monitoring and reducing the electricity consumption of private households. Examples are methods of visualising the standby power consumption of equipment, energy-efficient lighting technology such as LEDs, energy-efficient hot water circulation pumps for one-family houses, and integrated heating systems – heat pumps, solar cells and ventilation – for houses and holiday homes.

# 5

# Energy technology for transport

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## 5.1 Background

World energy demand for transport has increased significantly for many years. This trend is projected to continue in the years to come, one reason being that large and rapidly developing economies bring increasing demand for the transport of both goods and people, including rising transport demand due to greater integration of developing countries in the international trade.

Transport not only accounts for approximately 20% of the total world energy consumption, but is almost entirely based on limited and expensive fossil energy resources. As a result, fuel prices have soared, while clear evidence of global climate change is ascribed to the emission of greenhouse gases, notably $CO_2$ from the burning of fossil fuels. This has put huge political emphasis on sustainable alternatives to fossil fuels for transport; the trend in European transport policy is to encourage reduction of fossil fuel use.

The main focus for new traction technologies is road transport. Railways and ships are gaining more attention, whereas almost no activity is found in air transport. This chapter therefore focuses on road transport, though the same technologies may well be useful in rail and marine applications.

## 5.2 Internal combustion engines

### *5.2.1 Existing technology*

Internal combustion engines (ICEs) convert thermal energy to mechanical energy with an efficiency that is unacceptably low compared to other technologies. The overwhelming dominance of ICEs in today's transport, however, will make any phase-out a long-term project.

In addition, at least up to now, governments in Europe, including Denmark, have been reluctant to structure car taxes in ways that significantly encourage the use of vehicles with low $CO_2$ emissions. In fact, emissions from European cars are unlikely to reach the EU target of 120 g $CO_2$/km by 2010 (Figure 12). The car manufacturers claim it is not their fault that the targets have not been met [1]. The European Automobile Manufacturers Association blames "strong customer demand for larger and safer vehicles and disappointing consumer acceptance of extremely fuel-efficient cars".

Certainly the car industry in Europe continues to improve the fuel efficiency of conventional vehicles by reducing weight. In the power train this is done by replacing cast iron with lighter alloys based on magnesium and especially aluminium, while bodywork and structural elements are lightened by using plastics and composites instead of steel. These efforts are strongly supported by the EU, and in principle they will cut $CO_2$ emissions. As described above, however, their benefit is wiped out by consumers' preference for ever-larger vehicles.

### *5.2.2 Compressed Natural Gas*

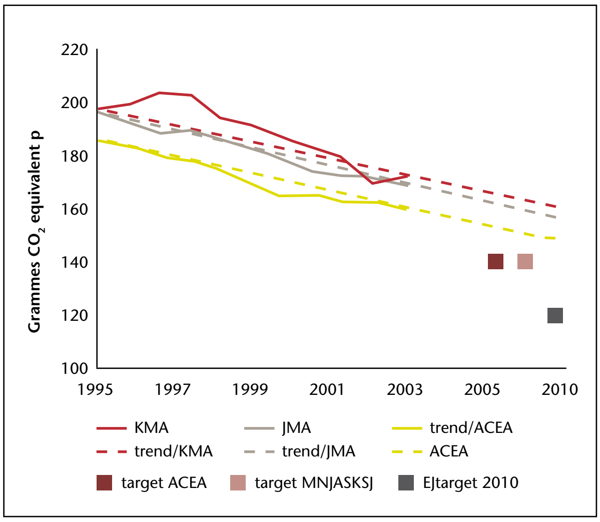
Use of natural gas in ICEs has the potential to decrease $CO_2$ emissions because of the relatively low carbon content of this fuel compared to higher hydrocarbons. In some European countries such as Italy and Spain, natural gas is widely used in passenger cars (in Italy 370.000 vehicles in 2005 [3]), whereas in Denmark the technology is almost non-existent. This is surprising, because natural gas is a straightforward and inexpensive way to cut $CO_2$ emissions.

### *5.2.3 Biofuels*

ICEs may be operated with no net production of $CO_2$ by burning biofuels derived from plant and animal material. Biofuels have become extremely popular in Europe and other parts of the world; they are already significant in transport, and there is little doubt that their importance will increase in the near future.

It is sometimes argued that the production of biofuels raises food prices because rich countries are prepared to pay high prices for crops to be converted into fuel. This affects people in poor economies, who have to spend a greater part of their income on food. This ethical argu-

Figure 12: The average $CO_2$ levels targeted by the three main car manufacturers' associations (European Automobile Manufacturer's Association (ACEA), Japan Automobile Manufacturer's Association (JAMA) and Korean Automobile Manufacturer's Association (KAMA)) have fallen over time, but if current trends continue, the ACEA will miss next year's target of 140 g $CO_2$ / km by 13 g $CO_2$ / km, and in 2009 JAMA/KAMA will miss the same target by 20 g $CO_2$ / km or more [2].



ment against biofuels will weaken, however, with the commercialisation of second-generation biofuel technologies that use agricultural waste rather than whole crops as their raw materials.

Another argument against biofuels is that their production will demand more cultivated land than is currently available. This could lead to the loss of even more of the world's precious forests, subsequently affecting plants, animals and, indirectly, people.

If market forces control the future of biomass as an energy source, combined heat and power (CHP) is likely to be a bigger user than the biofuel industry. It is more energy-efficient to burn biomass in a CHP plant than to convert it to biofuel, so CHP plants will be able to pay higher prices for biomass. In the absence of subsidies, this may prevent the widespread use of biomass for fuel production.

Altogether it is difficult to predict the long-term role of biofuels in transport, there is little doubt that in the short term, biofuels will form a significant source of energy for transport.

### *5.2.4 Synthetic fuels*

Synthetic fuels based on fossil sources have been utilised worldwide for decades, but do not solve the problem of $CO_2$ emissions unless combined with capture and storage. However, several synthetic transport fuels can be $CO_2$-neutral if they are made from non-fossil sources. Hydrogen, the simplest synthetic fuel, is being considered for use in ICEs by car manufacturers like BMW. More complex liquid fuels including ethanol and dimethyl ether (DME) have the advantage that they can be distributed and sold through the infrastructure already used for gasoline and diesel. These fuels can be produced from biomass but also from other sustainable energy sources, so they may well be used alongside biofuels. The technology exists, and only economic reasons prevent the wider use of sustainable synthetic fuels.

In conclusion, sustainable and environment-friendly technologies are indeed available to produce clean liquid fuels for ICEs. These offer substantial advantages compared to switching to new technologies such as hydrogen, which would require a completely new infrastructure for storage, distribution and refuelling. Because of the fundamental drawbacks of ICEs, even $CO_2$-neutral versions are likely be out phased at some point. Based on current policy, investments and price projections for alternative propulsion systems, however, we should expect to see ICEs for at least the next 15–20 years.

## 5.3 Hybrid propulsion

Hybrid cars are powered by a combination of an ICE and an electric motor. The ICE in a hybrid car is small compared to that in an ordinary car, because at times of peak power demand it is backed up by the electric motor. In addition, energy use is controlled more carefully than in a conventional vehicle, and energy released during braking is used to charge the battery so that it can be re-used during acceleration. Taken together, these techniques result in fuel consumption much lower than in today's standard cars (Table 3).

Hybrid cars are already marketed by several car manufacturers. Examples are the Toyota Prius and the Honda Civic Hybrid, both of which use batteries and gasoline engines. Table 3 shows selected details of the Prius [4, 5].

| **Gasoline engine** | |
|---|---|
| Displacement | 1497 cc |
| Power output | 76 hp / 57 kW |
| **Electric motor** | |
| Power output | 67 hp / 50 kW |
| Voltage | 500 V max |
| **Traction battery** | |
| Type | NiMH |
| Power output | 28 hp / 21 kW |
| **Mileage** | |
| EPA estimated – city/highway | 55 mpg / 23.4 km/l |

Table 3: Traction systems of the Toyota Prius.

Hybrid technology has proven viable, and as Table 3 shows, it gives considerable savings in fossil fuel consumption and $CO_2$ emissions.

Hybrid cars are gaining market share in areas such as California, where ownership is encouraged by benefits – apart from the lower fuel costs – such as permission to use special highway lanes during rush hours, and to enter or park in big cities.

In Denmark – again, at least until now – the situation has been just the opposite. Under the Danish tax system, hybrid cars are considerably more expensive than similarly-sized ordinary cars, and there are no official incentives to buy them. This situation is unlikely to change unless there is political will to do so.

Future hybrid cars may replace ICEs with fuel cells; this is discussed in more detail below.

## 5.4 Renewable electricity carriers

For renewable energy fully to meet the long-term needs of transport, electricity must form part of the transport energy mix. This implies the ability either to store electricity or to convert it to another storable form of energy. Besides meeting part of the direct energy needs of the transport sector, storage of renewable electricity will help the power grid to handle an increasing percentage of renewable electricity, which by its nature is subject to fluctuations in availability.

The main challenge in using electricity for transport is to store enough energy, quickly enough, on board an electric vehicle to give an operating range and refuelling time that is comparable to that of a vehicle powered by gasoline or diesel.

At the moment, only two technologies are capable of doing this, and the big question is about which one will win. The first technology is batteries, which in their current form are widely judged to give both insufficient range and slow refuelling. The second is fuel cells powered by hydrogen, which are claimed to be inefficient and costly.

Until now battery cars have had little real market success, due to their high prices, long recharge times and short ranges. However, recent developments in lithium battery technology, including electronic control systems for charging and discharging individual cells in a battery, have significantly improved working life and capacity [6]. Toyota [7] plans to use lithium batteries in its Vitz vehicle, which is designed for automatic and smooth stop and restart of the engine when appropriate. Such applications may well increase market acceptance of battery cars despite their previous bad press.

The nearness of fuel cells to commercial application in electric vehicles can be judged from the cost of the basic fuel cell assembly, or stack. One leading manufacturer, Ballard Power Systems, says that today's price for a mass-produced stack is $73/kW, and expects to reach a commercial price of $30/kW in 2010 [8]. Other stack manufacturers worldwide are making similar predictions.

Once the basic stack has become affordable, the next challenge is the price of the complete fuel cell system. At present this is $5,000-10,000/kW – many times the commercial target of $100-200, depending on the application. Technology development and innovation alone cannot create this reduction in price. The key is production volume, which in the absence of a market creates a "chicken and egg" problem. As with any new technology, establishing a market for fuel cells will be costly and risky.

At the moment fuel cells are being targeted at two main early market applications – emergency power backup systems and fork lift trucks – where higher prices and lower technical performance are acceptable. Both total sales and the numbers of high-volume orders in these applications have increased significantly during the last 12 months.

In August 2006 fuel cell manufacturer Hydrogenics signed an agreement with backup power specialist Danish APC to supply up to 500 fuel cell modules, and in March 2007 Dantherm Air Handling ordered 300–400 fuel cell stacks from Ballard Power Systems, also for use in emergency power supplies [9].

This growth in early markets is likely to support new markets such as bulk transport. In May 2007 Plug Power completed the acquisition of two leading fuel cell system companies in the materials handling sector: Cellex Power [10] and General Hydrogen [11]. The deal, worth more than $50 million, shows the potential of this market.

Hydrogen fuel cells for vehicles require the ability to store large amounts of hydrogen on board. The recently-revealed Honda FCX concept car uses a combination of high pressure and solid-state storage to achieve a claimed range of 560 km between refuelling stops [12]. This is promising, even though no hydrogen storage systems yet satisfy the energy density targets set by the US Department of Energy.

Another obstacle to the use of hydrogen for transport is the creation of a suitable infrastructure for manufacturing, storing and selling hydrogen. In 2006 the total number of hydrogen filling stations worldwide was only 140 [13], though there is a trend towards larger filling stations serving larger vehicle fleets. The CEP Berlin project, for instance, includes numerous cars [14], while Hamburg now operates nine hydrogen fuel cell buses [15].

The concept of a "hydrogen highway" is aiding the transformation from isolated filling stations to an integrated network. A hydrogen highway is a chain of hydrogen-equipped filling stations and other infrastructure along a strategic road, allowing hydrogen-powered vehicles to travel long distances. Hydrogen highways are under development in California [16] and Florida [17] in the USA, British Columbia in Canada [18], and Scandinavia [19].

Hydrogen highway activities in Scandinavia are grouped under the Scandinavian Hydrogen Highway Partnership (SHHP), which aims to make hydrogen vehicles usable in a large part of Scandinavia by 2012. This is an important milestone towards the ultimate goal of a large-scale commercial rollout of hydrogen vehicles and infrastructure after 2012. SHHP is made up of the national hydrogen network bodies in Norway (HyNor) [20], Denmark (Hydrogen Link) [21] and Sweden (HyFuture) [22]. Each of these in turn represents a consortium of interested parties including industry, local government, universities and end-users. SHHP plans to align these several hundred interests to create a large EU-supported demonstration project involving several hydrogen filling stations and several hundred hydrogen-fuelled vehicles throughout Scandinavia.

Though batteries and hydrogen are sometimes considered competitors, recent developments suggest that both technologies will be important in the future. Both tech-

Figure 13: TH!NK hydrogen cars have a hybrid traction system based on both Danish-designed hydrogen fuel cells and batteries. They promise fuel efficiency of up to 65%.

nologies have their strengths; used separately or combined in tailor-made hybrid systems, they should be able to match users' requirements closely.

Hydrogen and fuel cells are good for large vehicles that need long ranges or short refuelling times. Batteries are ideal for small city cars, where customers are typically satisfied with short operating ranges and long recharge times. Batteries are also energy-efficient, especially when they are used to store energy recovered when using the electric motor to slow the vehicle down (regenerative braking), and when used in hybrid designs they can increase the lifetime of fuel cells by enabling these to operate at a steady load. The combination of both technologies can therefore give a good balance between range, refuelling time and efficiency, so hybrids could well be the key to the economic and widespread use of electricity for transport.

Hybrids of batteries and fuel cells have recently seen a big increase in activity. In December 2006 Think Technology AS (Norway) and H2 Logic A/S (Denmark) agreed to launch up to seven TH!NK hydrogen city cars on Norwegian roads in 2008, based on a combination of a fuel cell system from H2 Logic with a standard battery [23]. This hybrid configuration gives the vehicle a range of 300 km at an efficiency above 65% (Figure 13, see previous page). In early 2007 Ford Motor Company and General Motors continued this trend with the release of respectively the EDGE [24] and VOLT [25] fuel cell/battery vehicles.

## 5.5 Recommendations

Technology development and economic incentives are key areas in bringing clean energy to the transportation sector.

Technology development must aim to make each link of the energy conversion chain, from the production of sustainable electricity to powering the vehicle wheels, cheaper, cleaner and more efficient. It should be driven by public-private partnerships, with a funding balance that reflects the nearness of each technology to commercial application. Onboard storage, for instance, still needs basic research, whereas fuel cells are already competitive in certain markets.

For consumers, fossil fuels are certain to remain the cheapest option for transport as long as energy prices do not reflect the cost of environmental damage. To reduce $CO_2$ emissions from transport, we therefore recommend governments to set up strong economic or other incentives to encourage customers to opt for low-carbon vehicles or public transport. As well as reducing environmental damage, such measures could generate money to support research and development in clean energy technologies.

# 6

# $CO_2$ capture and storage

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## 6.1 What is $CO_2$ capture and storage?

Carbon dioxide ($CO_2$) capture and storage (CCS) is a process in which $CO_2$ is separated from sources such as boiler and vehicle exhaust gases, and held in long-term storage instead of being released to the atmosphere. Captured $CO_2$ may be stored in geological reservoirs such as oil wells or aquifers, or on the ocean floor; or it may be chemically fixed, by converting it into solid substances known as inorganic carbonates (Figure 14).

$CO_2$ capture can be divided into post-combustion and pre-combustion (Figure 15). In post-combustion capture, carbon-containing fuels are burned as usual; special materials absorb $CO_2$ from the flue gas and then release it for collection and storage. In pre-combustion carbon capture, the fuel is first "de-carbonised", either by gasification or a process known as reforming, to yield a hydrogen-rich stream that can be burned in an engine or fuel cell, and a $CO_2$ stream for storage (see chapters 7.3 and 7.6 for further details).

Not all $CO_2$ arises directly from burning fuels. $CO_2$ is also generated by industrial processes such as the manufacture of steel or ammonia, and carbon capture can be used with these processes too. The choice of capture system depends on the concentration of $CO_2$ in the gas stream, the pressure, and the fuel type (solid or gas).

The higher the concentration of $CO_2$ in the flue gas, the easier the removal process. Ordinary flue gases consist mostly of nitrogen derived from the air used for combustion; substituting pure oxygen for air (oxy-fuel combustion) yields a flue gas that is almost pure $CO_2$, and so is easier to treat.

After $CO_2$ is removed from the gas stream, it can be transported by onshore or offshore pipeline, tanker or truck. Pipeline or tanker transport is preferred for large $CO_2$ producers such as power plants. Commercial $CO_2$ pipelines already exist, mainly in the USA, based on the technology used for natural gas pipelines [1].

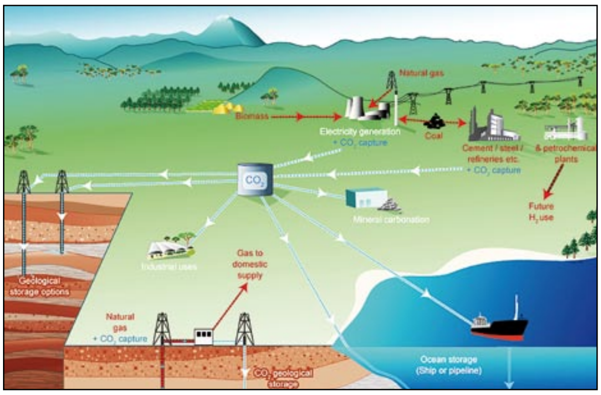
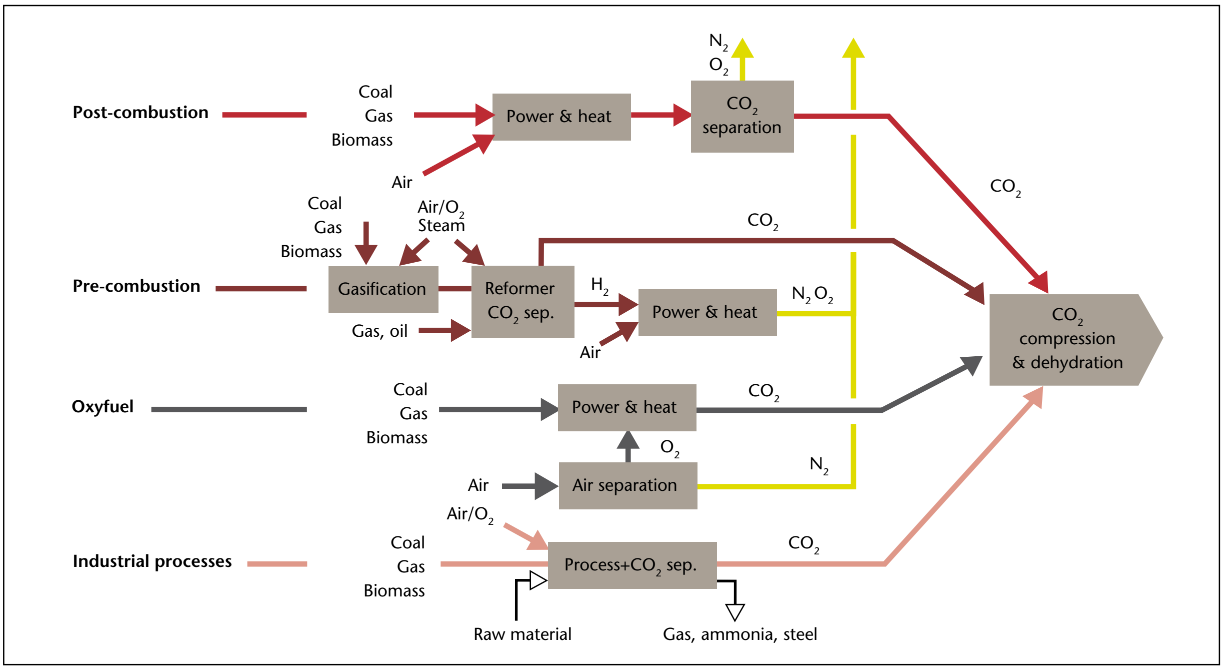


Figure 14: CCS involves removing $CO_2$ from exhaust gases, transporting it by tanker or pipeline, and storing it in underground reservoirs, deep beneath the sea, or as solid carbonates [1].

Figure 15: The three main processes for $CO_2$ capture [2].



The four main options for geological $CO_2$ storage are in saline aquifers, depleted oil and gas reservoirs, active oil wells, and coal mines. The last two of these, known respectively as enhanced oil recovery (EOR) and enhanced coal bed methane (ECBM), are especially attractive because $CO_2$ is used to increase the amount of oil and natural gas that can be economically recovered from existing reserves.

Ocean storage can take place either by dissolving $CO_2$ in seawater, typically at depths below 1,000 m, or by creating a lake of liquid $CO_2$ on the seafloor at depths below 3000 m. $CO_2$ can also be stored in the form of solid inorganic carbonates [1]. While some projects are already demonstrating the feasibility of large-scale geological storage, ocean and carbonate $CO_2$ storage is still in the research phase.

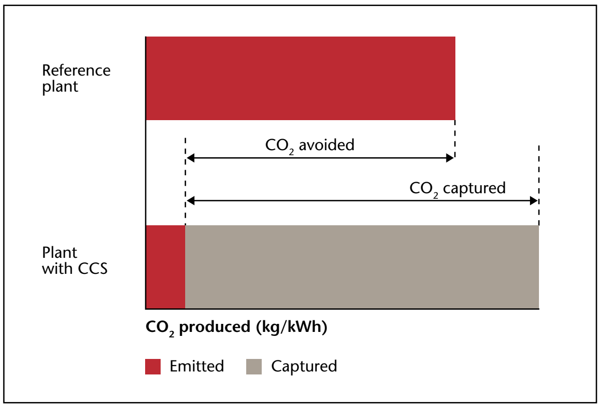


Figure 16: The energy needed to capture, transport and store $CO_2$ means that a power plant equipped with CCS (lower bar) has to produce more $CO_2$ per unit of product than a plant without CCS (upper bar). With effective $CO_2$ removal, however, there is a net reduction in $CO_2$ emissions to the atmosphere [1].

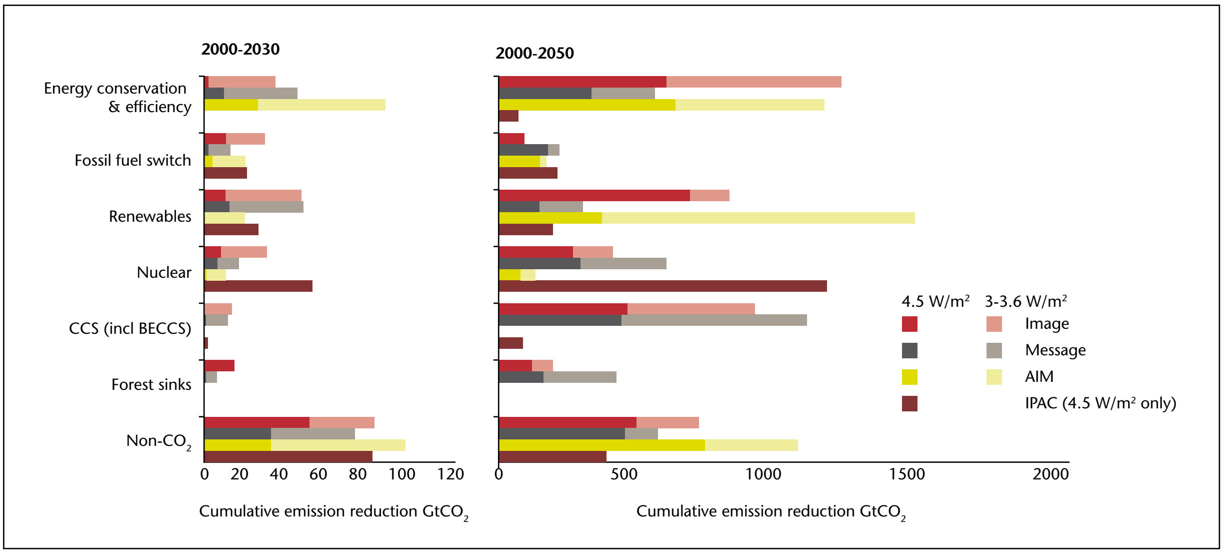
## 6.2 Economics of CCS

Capturing, transporting and storing $CO_2$ carries an energy penalty: a plant with CCS will consume roughly 10–40% more energy than a similar plant without CCS [1]. The net reduction in $CO_2$ emissions to the atmosphere therefore depends upon the fraction of $CO_2$ captured, the increased $CO_2$ production necessitated by the energy penalty, and any $CO_2$ leakage during transport and storage (Figure 16).

Capture is the most energy-intensive process in the whole CCS chain. With almost all the other CCS subsystems having already reached commercial maturity, capture accounts for 60-80% of the total cost of a CCS system (Table 4), and reduces the competitiveness of CCS compared to other near-zero $CO_2$ emission technologies. Costs vary considerably between countries and technologies, in both absolute and relative terms. The cost of CCS in tandem with combined-cycle gas (CCGT) or gasification (IGCC) systems is even less certain, since these have not yet built at full commercial scale; however the latter is less expensive than the former from a CCS point of view. CCS costs are projected to fall, however, with further R&D and economies of scale as more plants are built.

The IPCC Fourth Assessment Report states that additional CCS could reduce cumulative global $CO_2$ emissions by up to 10 Gt during the period 2000-2030, and by up to 600 Gt during 2000-2050 (Figure 17).

Figure 17: Cumulative emission reductions from a range of mitigation measures for the periods 2000-2030 (left) and 2000-2050 (right).
The various predictions for each mitigation measure derive from four different climate models (AIM, IMAGE, IPAC and MESSAGE). In each case, the shorter (darker) bar shows the $CO_2$ reduction needed to reduce radiative forcing to an intermediate level of 4.5 W/m², while the longer (lighter) bar shows the extra $CO_2$ reduction needed to achieve a lower level of 3.0-3.6 W/m².
Note that AIM and IPAC do not consider mitigation through forest sink enhancement, and AIM does not include CCS. “BECCS” refers to CCS applied to bio-energy plants, which would produce net negative $CO_2$ emissions [3].



## 6.3 Leakage risks and environmental impact

Captured CO$_2$ can leak into the atmosphere at many points in the CCS chain: during transport, injection and long-term storage. Transport of CO$_2$ is one of the best-established technologies in the chain, and the reported leakage rates are very low. The median value is 1.4 t/y CO$_2$ lost per km of pipeline [2] – similar to that reported for hydrocarbon pipelines.

For appropriately chosen and managed geological reservoirs, data from existing engineered systems, natural analogues and mathematical models suggest that the fraction of CO$_2$ retained is very likely (90-99% probable) to exceed 99% over 100 years, and likely (66-90% probable) to exceed 99% over 1,000 years [1]. Since the number of existing CO$_2$ storage sites is still very low and the technology has been in existence for only a few years, these figures rely on the identification and characterisation of both short-term and long-term leakage pathways. We need more observations to increase the reliability of the estimates.

Large-scale injection of CO$_2$ into the ocean could make the seawater more acidic, with damage to local marine life. And if a large quantity of CO$_2$ were to escape from geological storage or a sea-floor lake of liquid CO$_2$, concentrations of CO$_2$ greater than 7-10% by volume in air would pose immediate danger to human life and health.

## 6.4 European CCS research

The European Community is active in CCS R&D, and many European research institutes and energy companies are taking part in international research programmes. The Fifth and Sixth Framework Programmes (FP5 and FP6) of the European Commission have funded several projects involving public research institutes and the energy industry. Table 5 shows projects supported under the first round of FP6; most of these are still in progress.

| Project | EU funding (million €) | Coordinator |
|---|---|---|
| ENCAP | 10.7 | Vattenfall, Sweden |
| CASTOR | 8.5 | Institut Francais du Petrole, France |
| CO$_2$SINK | 8.7 | GeoForschungsZentrum Potsdam, Germany |
| CO$_2$GeoNet | 6.0 | British Geological Survey, UK |
| ISSC | 2.0 | University of Stuttgart, Germany |

Table 5: CCS projects funded under the first round of FP6

Source: Modified from European Commission, 2004 [4].

In 2005 the EU established the European Technology Platform for Zero Emission Power Plants (ZEP). ZEP aims to develop a portfolio of technologies that will allow zero-emission fossil-fuel power plants to be operating in Europe by 2020. Among other technologies, ZEP will prepare a strategic research agenda and a roadmap for CCS. ZEP has 25 members from industry, research institutes, authorities and NGOs [5, 6].

The CCS and coal is an important combination, e.g. IGCC, as it is less expensive to extract CO$_2$ upfront from the gasification stage than from the flue gas as in case of CCGT. US Future-gen initiative and the CO$_2$ pumping in the Texas oil fields are interesting developments internationally. Energy systems of some large developing countries such as China, India and South Africa have strong coal dependence and therefore CCS could play a critical role in mitigating their GHG emissions while maintaining their coal dependence in future.

Europe is currently a world leader in many energy technologies. The US and Japan are expected to create significant competition in the future, however – not least because of their high levels of government support,

Table 4: Current costs of CCS system components. Source: updated version of a similar table from IPCC, 2005 [1].

| CCS system component | Cost range | Notes |
|---|---|---|
| Capture from coal- or gas-fired power plants | 15-60 US$/tCO$_2$ net captured | Net costs of captured CO$_2$, compared to the same plant without capture |
| Capture from plants manufacturing hydrogen or ammonia, or processing natural gas | 5-50 US$/tCO$_2$ net captured | High-purity CO$_2$ sources requiring only simple drying and compression |
| Capture from other industrial sources | 25-115 US$/tCO$_2$ net captured | Range reflects a number of different technologies and fuels |
| Transport | 1-8 US$/tCO$_2$ transported | Per 250 km of pipeline or ship transport for flowrates of 5 (high end) to 40 (low end) MtCO$_2$/y |
| Geological storage | 0.5-8 US$/tCO$_2$ injected | Excluding potential revenues from EOR or ECBM |
| Geological storage: monitoring and verification | 0.1-0.3 US$/tCO$_2$ injected | Including pre-injection, injection, and post-injection monitoring; depends on regulatory requirements |
| Ocean storage | 5-30 US$/tCO$_2$ injected | Including offshore transport of 100-500 km, excluding monitoring and verification |
| Mineral carbonation | 50-100 US$/tCO$_2$ net mineralised | Range for the best case studied. Includes additional energy use for carbonation |

which exceed those allowed under the present European competition rules [6].

The future CCS research environment also depends on European emission policies. A working group on CCS under the European Climate Change Programme (ECCP) recently recommended that CCS should be recognised under the EU emissions trading scheme. The European Commission is planning to address this in the third quarter of 2007 [6].

At the global level, several European countries are active in the Carbon Sequestration Leadership Forum [7]. At the moment these nations are Denmark, Germany, France, Italy, Norway, the Netherlands, the UK and the European Commission.

## 6.5 European research goals

As with any technology that is moving towards widespread commercial use, CCS involves many sub-technologies at different stages of maturity. Of these, the biggest economic challenge – and the one that is likely to determine the commercial future of CCS compared to other $CO_2$ mitigation options – lies in capturing the $CO_2$ in the first place.

Much European CCS research therefore aims to reduce the costs of post-, pre- and oxy-fuel combustion capture technologies. Many of the projects listed in Table 6 aim to halve capture costs over the next 4-5 years, reducing capture costs to US\$30-40/t$CO_2$ and making CCS much more competitive with other technologies.

On the storage side, European demonstration projects are underway in various types of geological formation: saline aquifers, basalts, carboniferous sandstones, coal mines and depleted oil fields (Table 7). Ocean storage is not being explored much.

## 6.6 Danish CCS research

Three research institutions and energy agencies in Denmark – DONG Energy, GEUS and DTU – are active in global and European initiatives on CCS (Table 8).

The construction of the world's largest post-combustion capture test facility at the Danish coal-based power plant Esbjergværket has received much national and international attention. The facility has been in operation since March 2006 and consists of an absorber, a desorber/stripper, a reclaimer and support systems. It has a capture capacity of about 1 t/h of $CO_2$. The facility is set up to examine the performance of new absorbents and determine ways to improve performance and efficiency. The original absorbent was MEA (monoethanolamine); subsequently two new absorbents have also been tested.

## 6.7 Conclusions

CCS has moved to centre stage over the last five or six years as an important technology for large-scale $CO_2$ emissions mitigation. However, CCS currently carries an energy penalty of around 25% – and a corresponding increase in operating costs – due to the additional energy required to capture, transport and store the $CO_2$. Reducing the cost of $CO_2$ capture is the technological crux, since this stage contributes around 60-80% of the total cost of CCS. Many global research initiatives are currently attempting to reduce the costs of capture, especially through finding better and more energy-efficient adsorbents. Global research is gradually moving towards pre-combustion carbon capture, which offers potentially lower costs.

## 6.8 Recommendations for Denmark

CCS is a promising technology for greenhouse gas mitigation, so investing in CCS R&D could prove to be good for Danish industry in the short and medium term. There are opportunities to market CCS globally, including in large developing countries like China and India. Denmark's strength in technologies such as very-high-efficiency coal combustion for power generation, research on new adsorbents for $CO_2$ capture, and pre-combustion $CO_2$ capture through solid oxide fuel cells and oxygen membranes all have excellent market potential, and should therefore be pursued.

For developing countries, CCS adsorbents that can handle dirty flue gas containing SOX and NOX could also be an interesting research opportunity.

Collaboration with large consumers of coal, such as the USA, China, India, Australia and South Africa could provide good business opportunities, since a less expensive CCS could make an attractive GHG mitigation option.

| Project | Country | Goals/results |
|---|---|---|
| CASTOR | EC | Develop post-combustion absorption liquids with thermal energy consumption of 2 GJ/t$CO_2$ at 90% $CO_2$ recovery. Cost would be €20-30/ t $CO_2$ avoided, depending on fuel type. |
| $CO_2$ Capture Project | UK | Develop technology to halve the cost of $CO_2$ capture from \$60-80/t to \$30–40/t. Best technologies: chemical looping, BIT and HMR. |
| ENCAP | Sweden | Develop technologies to capture at least 90% of the $CO_2$ in a gas stream, at a cost below €20/t. |
| AZEP (Advanced Zero Emissions Power Plant) | Switzerland | Develop an oxy-fuel gas turbine. |
| Hammerfest natural gas power plant with $CO_2$ and NOX capture | Norway | Construct and operate a 100-MW gas-fired power plant with $CO_2$ capture. |
| RWE IGCC power plant | Germany | Commission a CCS power plant with a capacity of 400-450 MW and a capital cost of just under €1 billion by 2014. |
| ADECOS (Advanced Development of the Coal-fired Oxy-fuel Process with $CO_2$ Separation) | Germany | Design and evaluate oxy-fuel coal-fired power plants of 1,000 MW and 600 MW capacities. |

Table 6: European $CO_2$ capture research initiatives [8].

| Project | Country | Goals/results |
|---|---|---|
| CASTOR | EC | Storage in depleted oil field in Spain (0.5 million t/y $CO_2$), depleted gas formation in Austria (potentially 0.3 million t/y), saline aquifer in Norwegian Snøhvit field (0.75 million t/y) and enhanced gas recovery in the Netherlands (0.4 million t/y). |
| $CO_2$ Sink | Germany | Injection of 30,000 t/y $CO_2$ into saline aquifer. |
| $CO_2$ Store | Norway | Monitoring of $CO_2$ injection into saline aquifer in the Sleipner field in the North Sea (around 1 million t/y $CO_2$). |
| Salah Project (BP/Sonatrach/ Statoil) | Algeria | 1 million t/y $CO_2$ injection into carboniferous sandstone reservoirs. |
| Weyburn II | Canada and EC | Oilfield injection of 1.8 million t/y $CO_2$ has the potential to increase oil recovery by up to 60%. |
| Snøhvit LNG Project | Norway | 0.7 million t/y $CO_2$ extracted from natural gas will be stored in a sandstone formation. |
| EU GeoCapacity | Denmark | Assessing European capacity for geological storage of $CO_2$. |
| RECOPOL | Poland | Assessing feasibility of $CO_2$ storage in the Silesian coal basin. |

Table 7: European $CO_2$ storage research initiatives [8].

| Project | Dates | Core technology | Danish participation |
|---|---|---|---|
| CENS<br>($CO_2$ for EOR in the North Sea) | 2001- | Post-combustion capture and $CO_2$ pipeline infrastructure in the North Sea for EOR. | DONG Energy, with Kinder Morgan. |
| GESTCO | 1999-2003 | Research on storage in Europe. | GEUS: surveys in Denmark. |
| $CO_2$ Store | 2002- | Research on storage; case study in Kalundborg, Denmark. | Dong Energy: operates Asnæs power station near Kalundborg.<br>GEUS: Feasibility studies. |
| No$CO_2$ | 2003- | $CO_2$ capture and storage technologies. | DTU: Absorption with alkanolamines. |
| CASTOR | 2006- | Research on post-combustion capture and storage. | DONG Energy: Capture research; hosts the world's largest post-combustion capture test facility at Esbjergværket.<br>GEUS: geological surveys in eight East European countries. |
| GeoCapacity | 2006- | Assessing European capacity for $CO_2$ storage; setting up collaboration with China. | GEUS: Project coordinator. |
| Assessment of $CO_2$ storage potential in Indian subcontinent | 2006- | Potential for CCS in Indian subcontinent. | UNEP Risø Centre: Production of flowsheets and CCS economics for the Indian subcontinent. |
| Design of $CO_2$ capture units using aqueous alkanolamines | 2007- | $CO_2$ capture technology. | DTU: New research. |

Table 8: Danish participation in some major CCS initiatives [8].

# 7.1 Energy supply technologies

*This chapter presents the status of current R&D for selected energy supply technologies. Each technology is examined in terms of security of energy supply, effect on climate change and industrial potential, in each case from Danish, European and global perspectives.*

## 7.1 Wind

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### *7.1.1 General status*

Renewable energy can help to solve several important problems for society: improving security of energy supply, reducing $CO_2$ emissions, and providing sustainable energy to lift people in developing countries out of poverty.

There is a pressing need for renewable technologies in all regions of the world. Strong and continuing economic growth in Asia has created an energy deficit. The USA wants to move away from the dominance of the petroleum industry. In Europe, the European Commission has set a target of 20% renewable energy by 2020. Many other countries are setting their own renewable energy targets.

As a result, worldwide prospects for renewable energy seem unlimited. There is great demand for technologies that are either ready for the market or will be commercially available within a short time. Wind energy is one such mature option with great potential.

### *7.1.2 The Danish case*

Today, more than 15% of Denmark's energy originates from renewable sources. Wind turbines in 2006 produced power equal to 17% of the total Danish electricity demand (Figure 9). Biomass and waste incineration also contribute significantly, and in total the Danish dependence on oil has been reduced to about 40%.

Natural gas provides 23% of the country's energy supply, and coal accounts for 20%. The degree of energy self-sufficiency is more than 150%, and Denmark is a net exporter of oil and natural gas from its resources in the North Sea.

No other country approaches Denmark's use of wind energy, so Danish experience in managing such a high proportion of wind power is unique.

| **Installed wind capacity** | **3,137 MW** |
|---|---|
| Power from wind | 6,108 TWh |
| Wind generation as a percentage of national electricity demand* | 16.8% |

Table 9: Key wind energy statistics for Denmark, 2006.

*2006 was a poor wind year in Denmark. In other years with stronger winds, the same installed capacity would have generated more than 20% of Danish electricity demand.

At the end of 2006, the Danish government adopted new political initiatives to promote renewable energy and reduce $CO_2$ emissions. For wind energy, these initiatives support the national objectives set as a result of a political agreement reached in 2004: construction of new offshore wind farms, and a second repowering scheme to replace poorly-sited wind turbines with new turbines in better locations. The agreement also introduced a market-oriented pricing system for wind power, and more R&D and demonstration projects for advanced energy technologies.

The 2006 initiatives are more ambitious and more specific about the use of renewable energy in Denmark. By 2025, the goal is to double – from 15% to 30% – renewable energy's contribution to Danish energy, at the same time reducing the use of fossil fuels by 15%. Wind power will make up a large part of this increase, providing an estimated 50% of Danish electricity by 2025. To stabilise Denmark's overall energy consumption at its current level, the target for energy reduction will be increased to 1.25% annually. A doubling of total Danish investment in energy R&D and demonstration projects by 2010 will create new technologies and energy-saving opportunities.

The Danish government has stated that new wind energy capacity, both onshore and offshore, should have a firm economic foundation. Other factors that will be considered when planning new wind capacity include physical location and impact on the environment, including landscape; the criteria used to assess these will be updated periodically.

In December 2005, the Danish Energy Authority undertook a new plan for siting the next generation of offshore wind farms between 2010 and 2025. A working group was formed to look at future Danish offshore wind turbine development. Two other working groups were also set up: one to identify sites for future onshore turbines, and the other concerned with the siting of prototype turbines for field testing. All three working groups will limit their deliberations to wind turbines above 150 m in height.

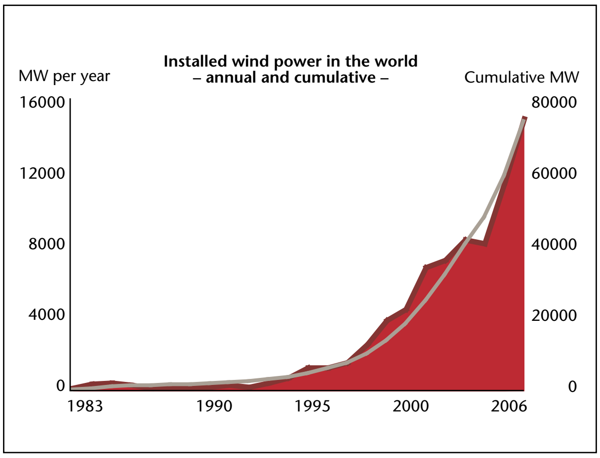
The Danish municipalities have recently been reorganised into larger units, and the former regional authorities will be handing over their responsibility for wind turbine planning to the new, larger municipalities. This reorganisation has influenced the following recommendations from the working group for siting on land:

- a large concentration of turbines at selected locations is favoured over a broad scattering of turbines across every type of landscape;
- the new, larger municipalities should maintain a leading role in the planning process;
- consideration must be given to wind turbine neighbours and to various technical and planning matters, such as the supply of power, energy, and climate policy;
- national authorities must provide background information, planning tools, and knowledge about wind resources and natural constraints.

The two working groups for offshore siting and positioning of prototype turbines published their final reports early in 2007. They identified some important issues:

- manufacturers have a strong need for sites with realistic wind conditions where they can test new turbine designs properly before launching them commercially;
- testing turbines on land is cheaper than offshore testing, and works well for many phases of offshore turbine development;
- turbine testing is especially important in Denmark, because the country exports wind turbines to many different markets with varying requirements;
- the number of test sites on land for very large turbines is limited, so these sites must be used continuously with different turbines. The test period for each turbine varies from a few months to several years.

Figure 18: Growth in global installed wind power from 1983 to 2006 – annual and cumulative [1].



| Year | Installed GW | Increase% | Cumulative GW | Increase% |
|---|---|---|---|---|
| 2001 | 6.8 | (52) | 24.9 | (35) |
| 2002 | 7.2 | 6 | 32.0 | 29 |
| 2003 | 8.3 | 15 | 40.3 | 26 |
| 2004 | 8.2 | -2 | 47.9 | 19 |
| 2005 | 11.4 | 42 | 59.4 | 24 |
| 2006 | 15.0 | 30 | 74.3 | 25 |
| Average growth over 5 years | 17.1% | | 24.4% | |

Table 10: World market growth for wind power from 2001 to 2006 [1].

The working group that is identifying offshore sites is considered to be an update of a group formed under Denmark's 1997 Action Plan for Offshore Wind Power. Since 1997, however, many conditions have changed. The working group must identify several sites that have the potential for more than 4,000 MW offshore wind power to be installed between 2015 and 2025. It is estimated that this amount of wind power can supply about half of Denmark's future electricity consumption.

### *7.1.3 International development*

Today's global installed wind power capacity is about 75 GW (Figure 18 and Table 10). For some years, world wind capacity has been doubling every three to four years, and this is expected to continue until at least 2011 [1].

Over the past 30 years wind energy has proved itself as a viable and increasingly economic means of generating electricity. It is particularly interesting to look at Spain and Germany, where market incentives were introduced in the early 1990s. Spain now has a capacity of 10 GW and Germany has 20 GW, together amounting to about 40% of total capacity worldwide.

Wind now provides about 8% of Spanish electricity, and has created a new manufacturing industry. The Spanish government plans to double installed wind capacity, to 20 GW, by 2010. Germany now has by far the highest installed wind capacity of any country in the world, and gets 7% of its electricity from wind. These are remarkable figures, especially considering that offshore wind has been slow to get off the mark in Germany and repowering of old, small, turbines has not yet started.

The power of market incentives is apparent from the success stories of Spain and Germany, and also from the oscillatory market experienced in the USA in line with the availability of the Production Tax Credit (PTC). The PTC is an important incentive for US investment in wind power, but it tends to be renewed only for short periods and has frequently lapsed.

It is clear that a market for wind turbines can be created through economic incentives, and that industry will respond in terms of both production volume and technological innovation. Production volume has increased over time, but the size of wind turbines has grown even more dramatically, from 50 kW in the late 1980s to about 5 MW today (Figure 19). At the same time the costs per MW and per kWh have fallen, and both availability and quality have improved.

Figure 19: Global annual wind power development with a forecast to 2011 [1].

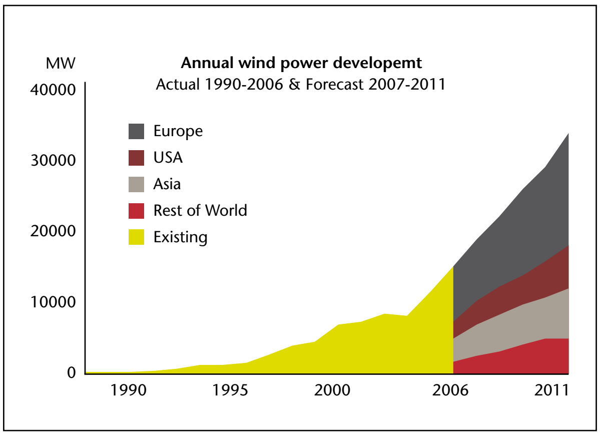
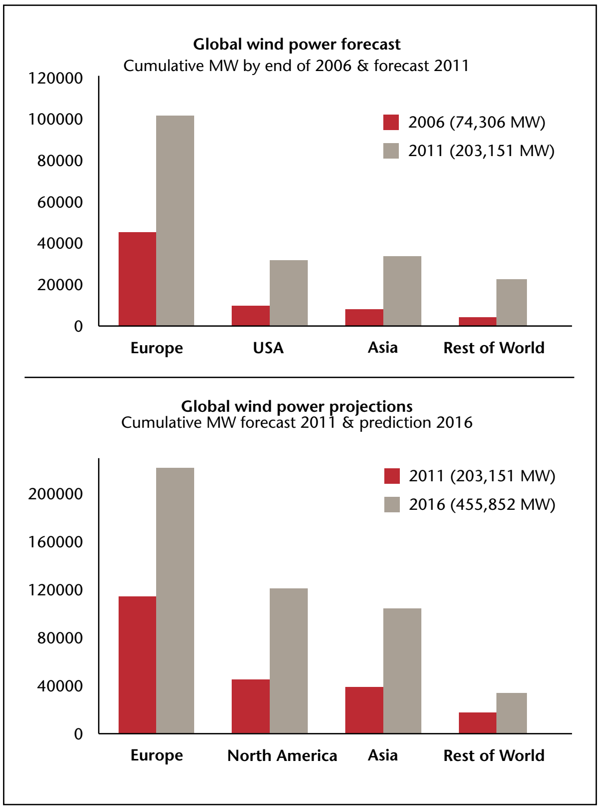


Figure 20: Predicted development of installed wind capacity by continent [1].



World market shares for the manufacture of wind turbines in 2006 were approximately: Denmark 35%, Germany 22%, Spain 18%, USA 15%, India 7%, and China 3%. The world's largest wind turbine manufacturer is the Danish company Vestas, with a market share of 28.2% in 2006.

### *7.1.4 Trends and perspectives*

Despite this technological development, and rapid growth in a few countries, wind today provides only a small percentage of the world's electricity.

As Figure 20 and Table 11 show, European countries and the EU as a whole are leading the deployment of wind energy. 51% of all new wind turbine installations in 2006 took place in Europe. Not coincidentally, many European countries lead the world in their concern for security of energy supply and climate change.

| GW | 2006 | 2011 | 2016 | 2020 | 2030 |
|---|---|---|---|---|---|
| Europe | 48.6 | 111 | 211 | - | - |
| America | 13.6 | 42 | 116 | - | - |
| Asia | 9.0 | 38 | 98 | - | - |
| Other | 3.1 | 12 | 31 | - | - |
| World | 74.3 | 203 | 456 | 1200 | 2700 |
| % of electricity demand | 0.82% | 2% | 4% | 12% | 23% |

Table 11: Forecasts for wind energy development.

Today the industry produces wind turbines that take an active part in the control and regulatory functions of power systems, in contrast to older turbines that did little to support the stability of the grid. Turbine manufacturers will continue to develop these capabilities in response to new requirements in the grid codes – the rules that govern how generating equipment interacts with the transmission grid – for "fault ride-through" and power quality, and the increasing importance of short-term wind forecasting.

It is important to differentiate between onshore and offshore development. There are logistical limits to the development of large turbines for land use. Visual intrusion and environmental considerations make it difficult to build very large wind farms on land. Offshore sites avoid these disadvantages and provide better wind conditions, but are more expensive to build.

Economically, wind turbines are approaching the point where they can compete economically with conventional power production. This is the case for grid-connected MW-class wind turbines, especially taking into account the external costs – including environmental and health costs – of fossil-fuel and nuclear generation. Huge numbers of smaller turbines, from 500 W to 50 kW, are used for local electricity production, pumping water or desalination, mainly in areas where the cost of conventional energy is very high. Despite their numbers, though, these small turbines have a total capacity estimated to be less than 1% of their larger relatives.

An important way to remove trade barriers and disseminate research results is to establish international standards for wind technology. Both national and European R&D programmes have supported this approach, and Denmark places a high priority on active participation in new standards through the IEC and CEN/CENELEC.

For wind energy to meet its anticipated target of 4% of the world's electricity by 2016, a number of R&D projects will have to produce successful results. The following sections set out these R&D targets

*Turbine technology and integration*

Developments in turbine technology, control systems and power transmission will include:

- gearless direct-drive turbine designs based on variable-speed and direct-drive multi-pole generators;
- high-voltage direct current (HVDC) transmission systems, energy storage technologies, compensation units and control technology for wind power plants;
- "intelligent" wind turbines that use computer controls to optimise their operation to suit local conditions and interact with other energy sources;
- systems to control variables such as rotational speed and power output according to wind, grid and market conditions; and
- control systems for large-scale integration of wind turbines into the grid.

*Meteorology, siting and power forecasting*

The increasing sizes of wind turbines and wind farms will require new meteorological methods and models, especially:

- measurements at great heights, such as by LIDAR from satellite and ground stations;
- better forecasts of wind power production several days ahead;
- understanding of the nature of wind and turbulence, and how this affects the siting of turbines offshore, in remote and steep areas, and in complex terrain; and
- wake modelling for large wind farms.

*Aerodynamics*

Improving the efficiency of wind turbines calls for developments in aerodynamics, including:

- aerodynamic and aeroelastic wind turbine control;
- methods and standards for optimising blade design; and
- new materials and designs for very large rotor blades.

*Structure and materials*

New composite materials will be developed for turbine components, including glass, carbon and natural fibres embedded in polymeric resins, and new designs with optimised weight/performance ratios. New methods for production, characterisation and numerical modelling will also be needed for the new blade materials. Properties of materials will be optimised in relation to their functions. Important research areas are:

- production processes for polymer composites;
- mechanical properties (strength, stiffness, fatigue lifetime) and damage mechanisms;
- modelling at microscale and continuum mechanical levels;
- characterisation and qualification using both destructive and non-destructive techniques;
- structural monitoring and state surveillance using acoustic emission; and
- new material combinations, such as natural fibres with organic resins, and hybrid combinations.

From the beginning of modern wind turbine development in the early 1980s, full-scale testing has been central to the development of new blade designs. Now basic materials knowledge, mathematical modelling and testing of sub-assemblies have reached the point where they are able to replace some or most of the full-scale tests, which are time-consuming and expensive. The new methods mark an important step forward, and are expected to lead to considerable changes in turbine technology, with lighter, more efficient machines as a result. Future developments will include:

- predicting the performance of turbines built with new materials;
- combined simulation and test methods for very large turbines; and
- full-scale blade testing (flapwise, edgewise, combinations, static tests, fatigue tests) will be replaced by component and specimen testing (buckling strength, shear, sandwich constructions, beam bending, fracture mechanics, bending tests, basic materials tests), and by new micro- and nano-scale design of new materials.

### *7.1.5 International R&D plans*

Globally there are many plans for wind energy R&D. Here we will focus on two: one European and one from the USA.

UpWind is an EU-supported Integrated Project (IP), and the largest EU initiative in wind energy R&D to date. UpWind looks towards future wind power, including very large turbines (8–10 MW) standing in wind farms of several hundred MW in total, both on- and offshore. The challenges inherent in creating such power stations necessitate the highest possible standards in design; complete understanding of external design conditions; the use of materials with extreme strength to weight ratios; and advanced control and measuring systems – all geared towards the highest degree of reliability, and, critically, reduced overall turbine mass. Wind turbines larger than 5 MW and wind farms of hundreds of MW necessitate the re-evaluation of the core unit of a wind energy power plant, the turbine itself.

UpWind will develop the accurate, verified tools and components the industry needs to design and manufacture this new breed of turbine. The project will focus on design tools for the complete range of turbine components. It will address the aerodynamic, aero-elastic, structural and material design of rotors, and critical analysis of drive train components.

In 2006, European companies supplied about 75% of the global market for wind power technology. UpWind will help to maintain this position and meet EU renewables targets.

In the USA, the Department of Energy (DoE) has laid out a five-year plan for wind energy R&D that follows three paths:

Onshore power, with a focus on low-wind-speed technology and machines in the range 2-6 MW. The main barrier is power transmission, and the goal for 2012 is \$0.03/kWh at sites with a mean wind speed of 13 mph.

Offshore power, focusing on both shallow and deep water, with turbine sizes of 6 MW and larger. The main barriers are cost and regulation, and the goal for 2012 is \$0.05/kWh.

Emerging deployment: here the focus is not on wind alone, but also on hydrogen and clean water. The barriers are cost and infrastructure. The goals for 2020 are turbine designs optimised for electricity, hydrogen production and desalination.

### *7.1.6 Horns Rev II and Rødsand II offshore wind farms*

Large offshore wind farms, such as the pioneering installations at Horns Rev and Nysted (Rødsand) in Denmark, have played a leading role in the development of large wind turbines. Horns Rev, which has 80 Vestas wind turbines of 2 MW each, was completed in 2002. This was followed by Nysted, with 72 turbines of 2.3 MW each from Bonus (now Siemens Wind Power), which was completed in 2003. These were followed by medium-sized offshore wind farms in Ireland and Great Britain. Many countries now have offshore projects in the planning and construction phases, including turbines of up to 5 MW capacity and rotor diameters of 125 m.

In Denmark the two existing large offshore farms will be followed by two neighbouring developments, each of 200 MW and taking up an area of about 35 km$^2$. Tendering for Horns Rev II and Rødsand II is now complete.

Horns Rev II will be located about 10 km west of the existing wind farm, and will be commissioned during 2009. The tender fixed the price of electricity from this farm at DKK 0.518 (\$0.096) /kWh for the first 50,000 full-load hours, corresponding to about 12 years of operation.

Rødsand II will be about 3 km west of the existing Nysted site, with commissioning expected during 2010. The tender fixed the price of electricity from Rødsand II at DKK 0.499 (\$0.090) /kWh for the first 50,000 full-load hours, corresponding to about 14 years of electricity production.

### *7.1.7 Conclusions*

Wind energy has developed rapidly over the past 25 years. Some companies have stayed in the market throughout this period, but many large new players have entered only recently. Wind energy has developed into a very significant player in the post-Kyoto era of $CO_2$ reduction.

The growing wind energy industry is increasingly able to support its own R&D costs, but generic long-term research and research of common interest for society and industry still needs public support.

### *7.1.8 Recommendations for Denmark*

In January 2007 the Technical University of Denmark (DTU) merged with a number of research institutions, including Risø National Laboratory. Some years ago Risø formed a consortium with DTU, Aalborg University and DHI (the Danish Hydraulic Institute) to strengthen Danish competence in all aspects of wind energy R&D, including offshore wind turbines. The new merger may bring organisational advantages to the consortium.

It is important that research institutions, industry and public programmes, both now and in the long term, continue to support wind energy through incentives such as support for research projects, prototype development and, together with the energy supply companies, demonstration projects. The latter, in particular, should receive emphasis that reflects the importance Europe attaches to wind energy, as well as the interests of Danish industry. Public support is moving in this direction, with the traditional energy research programme being replaced by a combined R&D and demonstration programme. The Public Service Obligation Programme for Environmentally Friendly Energy Technologies recently underwent a similar change.

In short, Denmark's public R&D system needs to master the complete chain: from knowledge, through theory, research and development, to innovation.

7.2

## 7.2 Fuel cells

SØREN LINDEROTH, RISØ DTU; HELGE HOLM-LARSEN, TOPSOE FUEL CELL, DENMARK; BENGT RIDELL, GRONTMIJ, SWEDEN

### *7.2.1 Introduction*

Fuel cells (FCs) are expected to be important as future sources of both power and heat. Fuel cell technology is developing rapidly around the world. Fuel cells will be highly efficient, clean, quiet, scalable, reliable, and potentially cheap. They will be able to use different kinds of renewable fuels, efficiently and in small as well as large plants. Integration of high-temperature fuel cells and gas turbines would be interesting for larger power units.

Various kinds of fuel cells are being developed worldwide for commercial use in portable, transport and stationary applications (Figure 21 and Table 12). Most current R&D focuses on two types: polymer electrolyte membrane fuel cells (PEMFCs) and solid oxide fuel cells (SOFCs).

Danish industry and universities are significant in fuel cell R&D, all the way from fundamental research, through component development and manufacture, to systems and integration. Denmark is especially involved in PEMFCs and SOFCs.

### *7.2.2 PEMFCs*

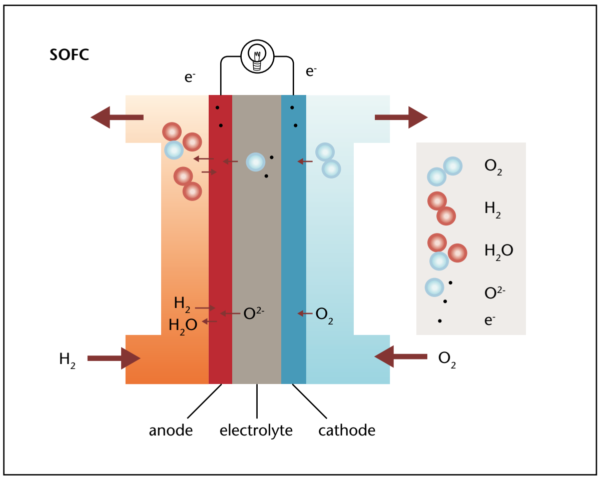


Figure 21: Principle of a fuel cell. The electrochemical reaction between the fuel (in this case hydrogen) and oxygen (air) takes place via an oxygen ion membrane. The reaction yields free electrons which provide a source of electric power.

Low-temperature fuel cells, notably PEMFCs, are useful for converting high-purity hydrogen into electricity and heat. Electrical efficiencies reach nearly 50% using hydrogen. Today the PEMFC seems the type of fuel cell most likely to replace car engines. PEMFCs are already being used in commercial uninterruptible power supplies (auxiliary power units, APUs), such as those made by the Danish company Dantherm. PEMFCs are very sensitive to impurities, especially carbon monoxide (CO).

Other varieties of fuel cells known as high-temperature PEMFCs (HT-PEMFCs) and phosphoric acid fuel cells (PAFCs), operating at temperatures above 120°C, can better handle these problems. PAFCs have been pro-

Table 12: Fuel cells fall into two types: low-temperature, which operate at temperatures below 400°C, and high-temperature for temperatures above about 400°C.

| **Fuel cell type** | **Polymer electrolyte membrane** | **Phosphoric acid and high-temperature PEMFC** | **Molten carbonate** | **Solid oxide** |
|---|---|---|---|---|
| Short name | PEMFC | PAFC/HT-PEMFC | MCFC | SOFC |
| Electrolyte | Proton-conducting polymer | H3PO4 | K-Li-CO3 | Doped Zr2O3 |
| Operating temperature | 50-80°C | 120-180°C | ~650°C | 600-1000°C |
| Advantages | Works at ambient temperature<br>High power density<br>Quick to start up<br>Solid electrolyte | Reliability<br>Tolerates >1% CO<br>Long experience | Internal reforming<br>Fuel flexibility<br>High-temperature waste heat<br>No noble metals | Internal reforming<br>Fuel flexibility<br>High-temperature waste heat<br>Solid electrolyte<br>Very durable<br>No noble metals |
| Disadvantages | Very sensitive to CO<br>Water management<br>Limited durability<br>Low-temperature waste heat | Relatively low efficiency<br>Limited durability<br>Loss of phosphoric acid electrolyte | Requires expensive alloys<br>Corrosive liquid electrolyte<br>$CO_2$ needed in the air to the cathode<br>Low power density | Planar format: sealing problems<br>Tubular format: low power density<br>Thermal cycling<br>Slow to start up |

duced for decades by companies including UTC in the USA, but cost and durability issues have hampered their commercial break-through.

HT-PEMFCs, which are a kind of PAFC with a polymer matrix, are gaining much interest. They may experience similar problems to those of PAFCs, but their cells and stacks may be easier to assemble. Their higher operating temperatures make HT-PEMFCs potentially more interesting than low-temperature PEMFCs for cars, because the heat exchange becomes simpler.

Methanol may also be used directly as a fuel for PEMFCs, which are then sometimes referred to as DMFCs (direct methanol fuel cells). NEC and Toshiba expect to commercialise DMFCs, primarily for portable applications such as laptop computers and personal digital assistants (PDAs). DMFCs are ideal replacements for batteries in portable equipment. Their energy density is four to five times that of batteries, and they can be refuelled easily. In Denmark, the company IRD Fuel Cells has advanced knowledge of DMFCs.

The ability of methanol to cross existing polymer membranes, plus higher losses at the electrodes, means that DMFCs have lower electrical efficiencies than ordinary PEMFCs: typically less than 30%, compared to standard lithium-ion batteries, which have equivalent efficiencies in the 90% range. Fuels other than hydrogen and methanol need processing before they can be used in PEMFCs, and this extra step reduces the electrical efficiency to 35% or less.

### *7.2.3 SOFCs*

High-temperature fuel cells (solid oxide fuel cells, SOFCs) are fuel-flexible, highly efficient and environmentally clean. They can run on fuels such as natural gas, biogas and methanol, thanks to their ability to reform hydrocarbons within the cell itself. An SOFC operating on natural gas could be termed a direct natural gas fuel cell.

Other attractive features of SOFCs include CO tolerance (because CO is simply another fuel), no liquid electrolytes, no water management issues, and high-temperature surplus heat that is suitable for CHP or energy recovery using steam turbines.

Recent years have witnessed substantial improvements in the performance and durability of SOFCs, mainly through advances in manufacturing technology. The internal resistance has been reduced significantly, allowing the operating temperature to be decreased from 1000°C to 750°C. This, in turn, has made it possible to use cheaper materials. Risø National Laboratory is one of the leading developers of SOFCs, in collaboration with Topsoe Fuel Cell A/S for stack development and commercialisation.

In the USA the major SOFC R&D programme is the Solid State Energy Conversion Alliance (SECA), which brings together government, industry and research institutions. There are six industry teams with the goal of developing 3-10 kW$_e$ SOFC prototypes by 2010. SECA is managed by the National Energy Technology Laboratory and Pacific Northwest National Laboratory, with an annual budget of approximately €50 million. The long-term goal of SECA is to develop a commercial SOFC at a cost of €400/kW that can be used on its own as an APU and also as a building block for large coal-fired power plants. SECA's ambitious goals have influenced R&D standards in other parts of the world.

Europe has been somewhat behind the USA in formulating an overarching SOFC strategy. However, the EU's Seventh Framework Programme (FP7) is expected to promote SOFCs as an important part of its strategy for hydrogen and fuel cells. Europe also has a number of national strategies, notably in Denmark, Germany and the UK, working on both SOFCs and PEMFCs. Europe is trying to set up a Joint Technology Iniative (JTI) on fuel cells and hydrogen technologies in order to improve the EU competitiveness in this field.

### *7.2.4 Applications*

The many application areas for fuel cell fall into three main markets: stationary, transport, and portable.

The stationary market includes small (1-5 kWe) CHP units for single households; 10-100 kWe CHP units for apartment buildings, office buildings, and uninterruptible power supplies (UPSs) for banks and data transmission; 100-1000 kW$_e$ CHP units for district heating; and multi-MW units for power generation, possibly combined with gas or steam turbines to increase electrical efficiency.

For the foreseeable future, stationary fuel cells will have high investment costs, which will need to be balanced by high efficiency and fuel flexibility. This means that the first markets for stationary fuel cells will be in applications that run for a large proportion of the year, such as CHP systems in hospitals, offices, breweries and other industrial applications.

In the transportation sector, auxiliary power units (APUs) for trucks, cars and boats are seen as an important market for fuel cells within the next 5-10 years. One attractive application is in long haul trucks, where fuel cells could supply heating and electricity for refrigeration, ventilation, lighting and entertainment systems during overnight stops.

Fuel cells may become important elsewhere in the transportation sector, though they will face competition from efficient diesel engines. A likely area of application is in hybrid cars, buses, trucks and trains, which are driven by DC electric motors powered by fuel cells and batteries. Various types of fuel cells may be used here, depending on the application and the available fuel.

Portable applications are close to the market, and several products have been demonstrated for use in portable computers, mobile phones and PDAs. The fuel cells of choice are PEMFCs fuelled by hydrogen or methanol, though there is also extensive R&D to develop SOFCs for battery replacement, where their fuel flexibility would be valuable.

Demonstrations of fuel cells in stationary applications are taking place all over the world. MCFCs are furthest advanced in this area, with demonstration programmes in countries including Japan, the USA, Germany and Italy. PEMFCs are also being tested, especially in Japan. The Danish Micro-CHP Demonstration Project, in which consumers will test a large number of fuel cells under real conditions, is a prime example of such testing and demonstration activities.

As fuel cell technology approaches market readiness, real-world testing and demonstration becomes more important, as does certification of fuel cell systems. In Denmark, a national centre for the testing and certification of fuel cell systems at Risø National Laboratory would be of great value, considering the importance of fuel cells to Danish industry and the country's future energy economy. Such an institution would also have the potential to become a European centre of excellence for the testing of fuel cells and related technologies.

### *7.2.5 Market and cost development*

The main drivers in favour of fuel cells are:

- high electrical efficiency, even in small sizes;
- ability to use renewable, locally-produced fuels, and thus reduce dependence on imported fossil fuels;
- siting near the point of use eliminates or considerably reduces distribution losses for both heating and electricity;
- lower $CO_2$ emissions;
- important as an enabler for other renewable energy sources such as wind;
- can be used to help the developing world meet its increasing demand for energy; and
- creates employment opportunities for skilled labour and a basis for export of value added goods.

The first breakthroughs in commercial markets will probably be in areas where the limitations of existing technologies give fuel cells a significant advantage. Likely candidates are battery replacement, APUs and perhaps UPSs. Later, when costs have fallen to the point where fuel cells are more competitive with other conversion technologies, various kinds of CHP will be commercially important.

Replacing car engines with fuel cells is an idea that has charmed many developers, but it is a big challenge. Such a move would require a reasonable hydrogen infrastructure, and competition from today's technologies is severe. When fuel cells do reach automotive applications, hybrid propulsion systems will appear significantly earlier than pure fuel cell engines.

### *7.2.6 Projections to 2030*

Fuel cells will not have a perceptible effect on the overall pattern of power generation until 2010 at the earliest, but substantial growth has already begun. By 2015 many developers foresee production capacities in the 100 $MW_e$/y range, and forecasts for 2025 are in the $GW_e$/y range. In the very long term, if the technology progresses as currently foreseen, the worldwide potential for fuel cells in power generation is more than 100 $GW_e$/y.

The first commercial fuel cells are now appearing in portable applications and backup power systems. The market is expected to expand into residential and industrial distributed power systems within the next 5-10 years. Fuel cells in the transportation sector will begin with their use as APUs in about 2020, followed by fuel cell hybrid vehicles in approximately 2025 (Figure 22).

### *7.2.7 Contribution to $CO_2$ reduction*

The high electrical efficiency and reduced transmission losses promised by fuel cells translate directly to lower $CO_2$ emissions. The amount of $CO_2$ reduction depends on the scenario chosen, including the fuels used, but the potential savings run into millions of tonnes of $CO_2$ per year in Denmark alone.

It can also be argued that the transition from central generation to distributed generation will increase consumer awareness of energy efficiency and $CO_2$ emissions, thus leading indirectly to a more environment-friendly attitude to electricity generation.

Further $CO_2$ reductions from fuel cells will require carbon dioxide capture and storage (CCS). Sealed SOFCs have the advantage that it is easy to remove carbon dioxide from the exhaust, because the gas streams leaving the anode and cathode remain separate. The anode gas contains water, $CO_2$ and unconverted hydrogen. One approach to exhaust cleanup uses a membrane to remove the hydrogen, which is then recycled to the inlet of the fuel cell. An alternative is to oxidise the hydrogen, using oxygen extracted from atmospheric air by another type of membrane. In each case the result is a gas stream containing only water and carbon dioxide. The carbon dioxide can then be separated by cooling to condense out the water.

### *7.2.8 Danish and European strengths*

Denmark and other European countries have well-known capabilities for R&D and efficient industrial production. Some European research institutions are already world leaders in some areas of fuel cell technology.

Europe probably lags behind North America and Japan in PEMFC research. The US company UTC is the undisputed leader in PAFCs, while in HT-PEMFCs Europe has a strong position through the German company BASF. MCFCs are being developed and demonstrated in MW sizes worldwide, and research on PAFCs and MCFCs is decreasing significantly. SOFCs are now being developed worldwide, with much effort and competition in research, development and demonstration projects.

SOFC development is dominated by 5-10 international groups with global aspirations. Of these, the largest European SOFC developer is Topsoe/Risø, which employs more than 100 people on SOFCs. Key to the success of this group are the unique competences of Risø and Topsoe, plus national support via the Danish strategy for hydrogen and fuel cells.

### *7.2.9 Promoting fuel cells*

Strategies to make fuel cells commercially viable need not differ from those for other environmental technologies. In the early phases, support for R&D is essential.

Next, once a workable prototype has been developed, funding should be available for testing and demonstration; this stage weeds out the worst development bugs in a controlled environment, and subsequently allows the project to gain public acceptance. This phase often requires several cycles of prototypes and tests. The objective of support during this phase is to facilitate the process for the developer. The importance of testing and prototyping cannot be over-emphasized, and it is the ability to support this activity on a national level that is likely to create winning technologies.

When the technology is ready for commercial application, an incentive programme should be put in place to persuade consumers to choose the new technology. This incentive may be phased out once production volumes of fuel cells are comparable to those of competing technologies.

On a more general level, access to the electricity grid should be made easier for distributed generators. Barriers to distributed generation – in the form of grid availability, costs or bureaucracy – will seriously hinder the benefits of sustainable power production and lower $CO_2$ emissions that fuel cells can provide.

It is essential to demonstrate fuel cells in several applications, to show the public that the technology works.

Very often fuel cells and hydrogen are linked together to form a hydrogen economy vision. However, a pure hydrogen economy is quite uncertain. It is important to note that hydrogen and fuel cells can be well decoupled as both have their own markets in the short and medium term.

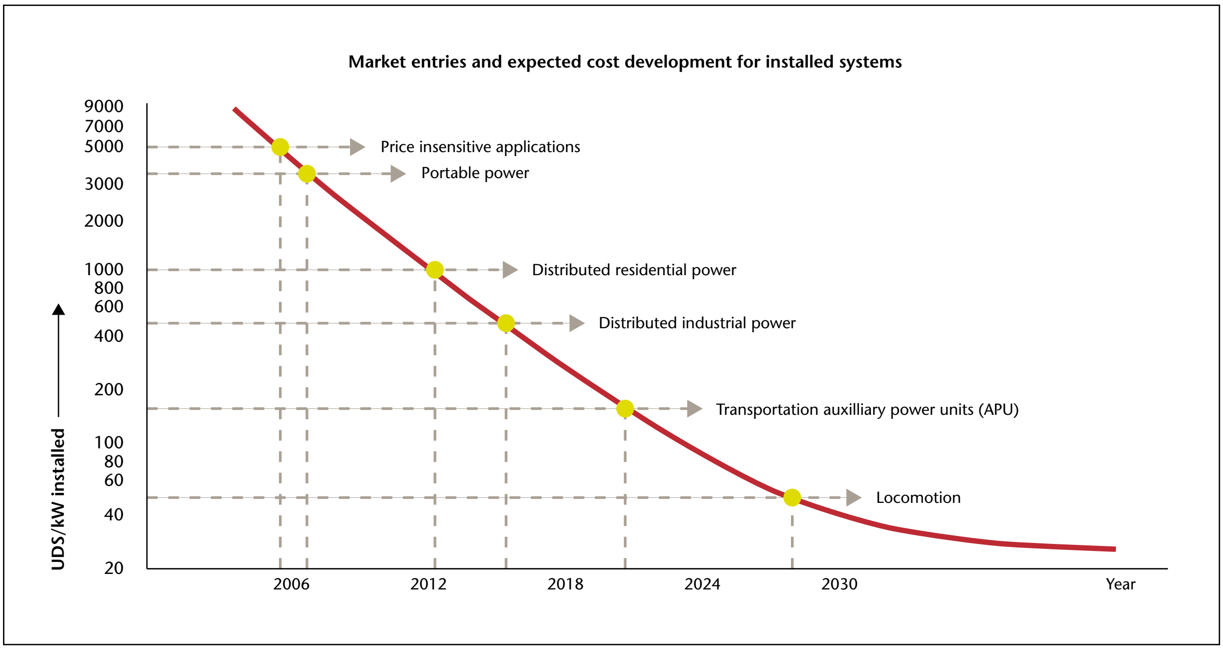
### *7.2.10 Conclusions*

Fuel cells are now at the point of breakthrough as the most versatile and environment-friendly energy conversion technology. They have strong links with other renewable technologies, such as wind, solar and wave power, and they will be central to any future "hydrogen society", with its promise of a release from dependence on fossil fuels. Denmark is playing a significant role in the development of fuel cells, all the way from fundamental research to consumer applications.

### *7.2.11 Recommendations for Denmark*

The priority given to fuel cells and hydrogen in Denmark has created strong research and industrial teams whose influence extends worldwide. We recommend that these areas are strengthened even further, through policies that support research, education, development, pre-commercial demonstration, and early-stage commercialisation. Denmark should quickly create a national centre for the development and testing of fuel cells and hydrogen technologies at Risø National Laboratory, with strong links to industry, end users and other test centres worldwide. Risø should participate as strong as possible in the JTI and the Research Grouping around the JTI.

Figure 22: Expected development of fuel cell system costs and entry points for different applications.



7.3

## 7.3 Hydrogen

ANKE HAGEN, RISØ DTU; JENS OLUF JENSEN, TECHNICAL UNIVERSITY OF DENMARK AND BIRTE HOLST JØRGENSEN, NORDIC ENERGY RESEARCH, NORWAY

The growing scientific, political and public awareness has led to increased funding of hydrogen related projects, the establishment of a number of national and international hydrogen platforms (e.g. European Hydrogen and Fuel Cell Technology Platform: HFP), and the presentation of hydrogen strategies throughout the world. This chapter feels the pulse of the development of a European Research and Innovation area in hydrogen (often in combination with fuel cells) with a view on the position of Danish research and innovation system

Hydrogen is an energy carrier, not an energy source. Although it is the most abundant element in the universe, it has to be produced from compounds that contain it. The use of hydrogen in industry has a history of more than 100 years. Today hydrogen is mostly used for the production of chemicals such as ammonia (fertilizer), methanol, but also for the production of iron and steel, in the electronics industry etc.

Hydrogen can be produced by many technologies, based on fossil and sustainable fuels (Table 13). Thermal and thermochemical processes use heat in combination with co-reactants to release hydrogen and are the most mature technologies. By far the largest process is steam reforming of mainly methane (natural gas); it accounts for more than half of the hydrogen production in the world. However, also other feedstocks can be reformed, e.g. liquid hydrocarbons as ethanol from biomass conversion. The same applies to gasification, which for example can use coal or biomass. Thus, the degree of sustainability of the hydrogen production strongly depends on the feedstock used.

Electrolytic processes use electricity to produce hydrogen. The hydrogen produced has a high purity and can be used in special applications. Evaluating this route with respect to environmental impact, the source of electricity is of main interest, here renewable sources such as wind and nuclear power can be considered. Electrolysis is experiencing an increasing support and will therefore be discussed later.

Photolytic processes offer a challenging, long-term potential for a sustainable hydrogen production and have to be further developed.

| **Process** | | **Example feedstocks** |
|---|---|---|
| Thermal/ thermochemical | Reforming/partial oxidation | Natural gas |
| | | Ethanol |
| | Gasification | Coal |
| | | Biomass |
| | High-temperature water splitting | Water |
| Electrolytic | Electrolysis | Water |
| | | Water + $CO_2$ * |
| Photolytic | Photobiological water splitting | Water |
| | Photoelectrochemical water splitting | Water |

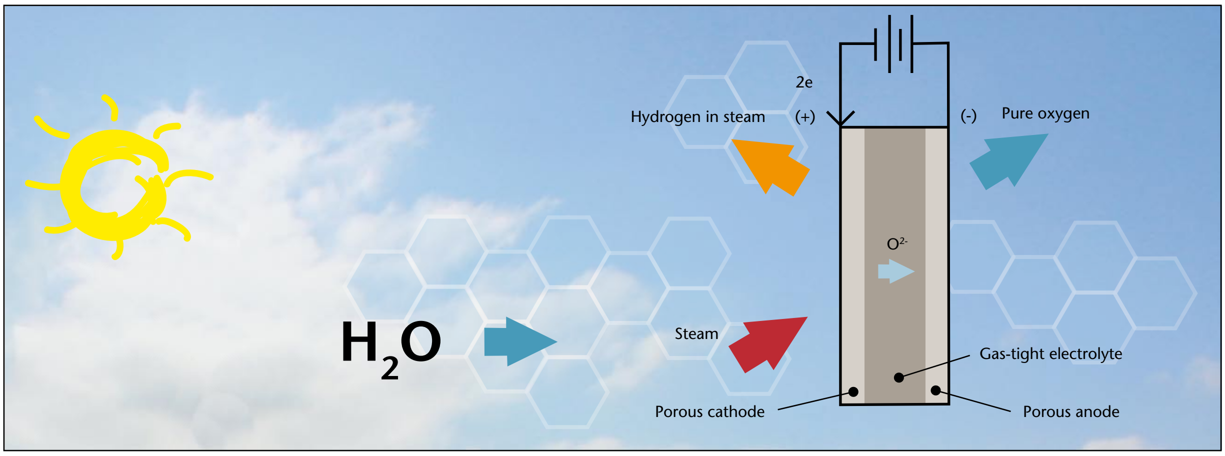
* Simultaneous formation of hydrogen and carbon monoxide (=synthesis gas)

Table 13: Important hydrogen production processes.

### *7.3.1 Water electrolysis*

The concept of hydrogen as an energy carrier involves many technologies of which fuel cells perhaps are what many people think of first. Another key element is electrolysis, the technology that uses electrical energy to split water into hydrogen and oxygen, regardless whether the electricity is produced by wind, photovoltaic or even nuclear technology (if very high temperatures are available, thermal water splitting is possible, but this technology is

Figure 23: Steam electrolysis on a solid oxide electrolyser cell [1].



| Type | Alkaline | Acid | Polymer electrolyte | Solid oxide |
|---|---|---|---|---|
| Charge carrier | OH- | H+ | H+ | $O^{2-}$ |
| Reactant | Water | Water | Water | Water, $CO_2$ |
| Electrolyte | Sodium or potassium hydroxide | Sulfuric or phosphoric acid | Polymer | Ceramic |
| Electrodes | Nickel | Pt, polymer | Pt, polymer | Nickel, ceramics |
| Temperature | 80°C | 150°C | 80°C | 850°C |

Table 14: Electrolysis cells and their characteristics based on [2].

not well developed). Electrolysis will likely play an important role in any future non-fossil energy scenario, not only in the hydrogen society. This is due to the option to convert a mixture of water and carbon dioxide into synthesis gas via electrolysis followed by further conversion to a synthetic fuel, which can be larger molecules like methanol, di-methyl ether, gasoline or diesel via well-established catalytic processes.

An electrolyser is based on the same principles as a fuel cell, but the process is reversed, i.e. electricity is used (Figure 23). Typically, water is split into hydrogen and oxygen with the two gaseous products being produced at the two different electrodes. Therefore, no further separation is necessary. The electrolyte separating the two electrodes might be either liquid (alkaline or acid) or solid (polymer electrolyte or solid oxide). It has the function of transporting the ionic species and has to be electrically insulating. The high electrical efficiency of a fuel cell (max. 83%) is often pointed out. In practice the electrical efficiency is much lower due to different losses, rarely much over 50%. With electrolyser cells, the efficiency can be close to 100%, when the system is operated at the (thermodynamically determined) thermo-neutral potential (i.e., the cell voltage where the heat produced equals the heat necessary for the splitting of water). Today, the conversion efficiency of commercial electrolysers is in the range 65-85% (based on the higher heating value).

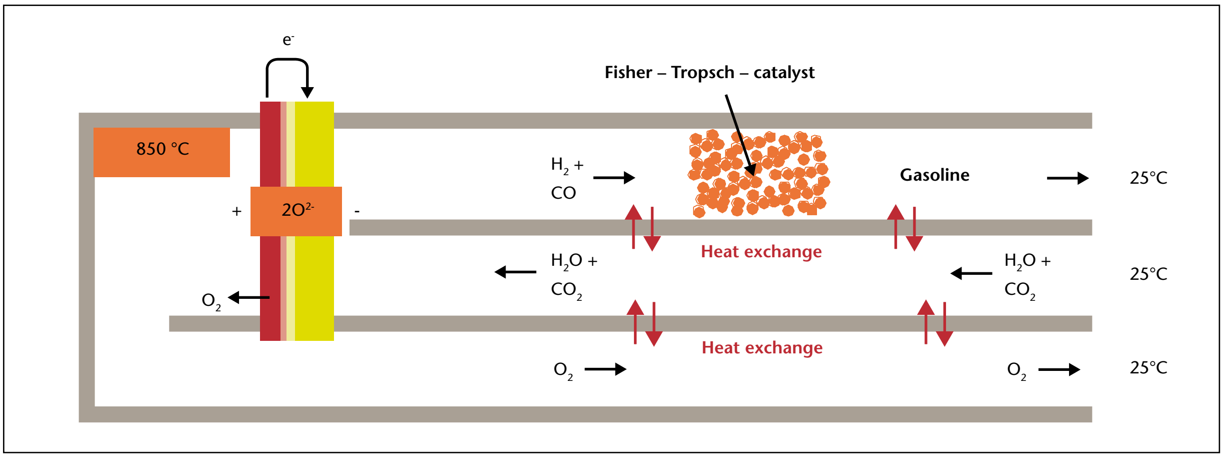
Like fuel cells, electrolysers are grouped and named after their electrolytes (Table 14). The classical type is the alkaline electrolyser cell (AEC). It is the counterpart to the alkaline fuel cells with an alkaline electrolyte of potassium hydroxide. The reason why the alkaline electrolyser has been much more successful than the alkaline fuel cell is a higher stability. Moreover, they can be manufactured of quite inexpensive materials, and the oxygen formation kinetics is fair.

Proton exchange membrane electrolyser cells (PEMEC) are reaching market these years as smaller units. They can be very compact with high current densities.

Conventional low temperature water electrolyser units with capacities from 1 kW to 125 MW are commercially available. The Electrolyser Corporation Ltd. (Canada) and Norsk Hydro Electrolysers AS (Norway) and DeNora (Italy) are well-established manufacturers of electrolysers. Other manufacturers have also established themselves in Europe, e.g. Hydrogenics Corporation [3].

Another type is the solid oxide electrolyser cell (SOEC). Like solid oxide fuel cells it is based on a ceramic oxide ion conducting electrolyte and therefore the working temperature is within the range of 600-1000ºC. The high working temperature has the significant advantages of the oxygen electrode kinetics being very fast and the temperature allowing to operate the cell at the thermo-neutral potential and thus to obtain a high electrical efficiency. The SOEC is not yet at a commercial stage.

Figure 24: Syngas production and subsequent synthesis of synthetic fuel. Water and carbon dioxide are supplied to the electrolyser (SOEC stack) and hydrogen and carbon monoxide are formed. When passing over the catalyst on the way out, synthetic fuel is produced.



Another interesting idea, which is only possible on high temperature SOECs, is to produce synthesis gas, i.e. a mixture of hydrogen and carbon monoxide, which are the starting materials for the synthesis of numerous chemicals or synthetic fuels, like methanol, methane and synthetic gasoline. Apart from water, carbon dioxide should then be led to the cell, and the products are synthesis gas and oxygen (Figure 24, see previous page). With a proper catalyst different fuels can be synthesized by the well-known Fischer – Tropsch process afterwards [4]. This concept shows that electrolysis is not only relevant in relation to a future hydrogen society.

### *7.3.2 Hydrogen R&D*

In a world wide perspective, the United States have probably the most significant hydrogen and fuel cell programs. Driven by the interest in reducing the dependency on foreign oil by developing the technology needed for commercially viable hydrogen-powered fuel cells – a way to power cars, trucks, ho mes, and businesses – that produce no pollution and no greenhouse gases, the $US 1.2 billion worth President's Hydrogen Fuel Initiative was launched in 2003 [5]. Through partnerships with the private sector, this initiative seeks to develop hydrogen, fuel cell, and infrastructure technologies. Other partnerships like the 'Freedom Car' and 'Freedom Fuel' support development and demonstration of hydrogen related technologies as well. The management of funds to meet challenges such as development of cost competitive hydrogen production and storage technologies is realized by the Department of Energy (DoE) that has planned to spend a budget of $US ~290 million in 2007 and ~309 million in 2008.

The future role of hydrogen and fuel cells in the European energy policy is closely related to the development of a strategic energy technology plan and hence also to a strong European Research and Innovation Area within these technologies. The development of a hydrogen economy, with $H_2$ produced from renewable energy sources, is a long-term objective of the European R&D agenda, and substantial funds have been allocated over the years to pave the way. A Joint Technology Initiative (JTI) for Fuel Cells and Hydrogen will be established in order to realize a public-private partnership on the European level. The budget will be in the range of 80-100 million Euro/year.

Figure 25: CUTE project [9].

At EU level, research funds for hydrogen and fuel cells have increased over the years in the Framework Programmes [6]. Several European demonstration projects have focused on niche markets, including hydrogen production from renewables and conversion in remote locations, auxiliary back-up power for residential homes, and the CUTE/ECTOS demonstration project of 33 hydrogen powered buses in 10 cities with 10 hydrogen fuelling stations and a total budget of 100 million € (Figure 25) [9].

Various initiatives have been made to coordinate activities in hydrogen and fuel cell technologies at European level to overcome fragmented R&D across countries and sectors, including European networks of excellence, the launch of the European Technology Platform for Hydrogen and Fuel Cells in January 2004 [7] and the networking of national and regional programmes in the context of the ERAnet HY-CO [8].

The European Technology Platform for Hydrogen and Fuel Cells was one of the very first technology platforms in Europe. Though led by the industry, it is strongly supported by the EU Commission, which encourages the process and closely coordinates its activities in this area. A Strategic Research Agenda as well as a Deployment Strategy were endorsed by the managing body of the platform, the Advisory Council, in December 2004. An Implementation Panel was established in 2006, under the direction of the Advisory Council of the HFP and in consultation with the Member States Mirror Group to take the strategy for research and demonstration of hydrogen and fuel cells technologies to the implementation stage by 2010-2015 [10]. This will require an estimated investment of 7.4 billion € between 2007-2015. The Implementation Plan is intended to provide recommendations for the core contents of a possible Joint Technology Initiative (§171) as well as form part of the 7th Research Framework Programme (FP7).

The ERA-NET HY-CO was launched in 2004 with more than 18 national and regional research funding agencies. The aim of the ERA-NET is to make a common knowledge platform for research funding agencies supporting hydrogen and fuel cell research and innovation and to make common transnational calls. A number of Action Groups have been established which prepare and launch calls within a number of prioritised topics aligned to the HFP Strategic Research Agenda and Deployment Strategy on the one hand and relevant to the national research needs and strategies of the involved actors on the other. The first calls are planned in 2007.

At national level, the Danish Energy Authority, together with other energy research funding agencies, published a strategy for research, development and demonstration in hydrogen and fuel cells in 2005. The strategy was the result of a participative process with all key stakeholders from research, the energy sector, the manufacturing industry and public authorities and includes the areas in which Danish knowledge producers have core competences and where commercial prospects are perceived to be best on global markets. The strategy estimates a total investment of 1.5-2.0 billion DKK over a 10-year period.

In 2006, the Danish partnership for Hydrogen and Fuel Cells was established with the aim to promote the technological development in this area and has assembled representatives from all important players.

A first important step to realise this strategy has been made by the proposed governmental RD&D programme for new energy technologies with an estimated public investment of 477 MDKK for the period 2007-2010 [11].

Also at operational level, progress has been made to make a coordinated effort in the launch and implementation of research and development projects in the field. The scientific quality of all energy research and development projects is assessed by the Strategic Research Council. Financiers and reviewers from the various funding systems meet regularly to exchange views on the good research project, administrative procedures and implementation.

Most importantly, a national hydrogen technology platform with the participation of public authorities, research institutes and private companies is steadily developing ambitious research, development and demonstration projects in selected key hydrogen and fuel cell energy technologies. These include for example:

- Lolland Community Testing Facilities (Lolland CTF) for emerging and sustainable energy technologies, more specifically The Hydrogen Community Lolland. The test facility comprises hydrogen produced by two 4kW electrolysers made by the Canadian company Hydrogenics and used for micro combined heat and power (PEMFC delivered by IRD Fuel Cells). The test facility is an integrated part of a step-wise demonstration plan for micro CHP.
- Hydrogen Innovation & Research Centre (HIRC), is a knowledge center that seeks to support introduction of hydrogen related activities in Denmark; for example the H2PIA-vision of a hydrogen based society.

These framework conditions aim to strengthen the Danish knowledge communities in creating strong and internationally competitive competences. At the same time, they facilitate coordination and transnational cooperation with other international bodies in and outside Europe as a national bottom-up contribution to a strong European Research Area in hydrogen and fuel cell technologies.

To conclude, the future European strategic energy technology plan is yet to be developed for the different technologies, with varying degrees of development and learning curves. Hydrogen and fuel cells are not expected to be implemented in the short-medium perspective and other intermediate technologies such as bio energy technologies are expected to be promising bridges from a fossil based economy to a hydrogen based economy. However, the European hydrogen and fuel cell knowledge communities have over the last years worked hard to overcome fragmentation across national boundaries and to build a competitive European Research and Innovation Area in hydrogen and fuel cell technologies. Research and deployment strategies have been made by all relevant stakeholders from research, industry and the Member States, strategies which have been framed by advanced national strategies such as the Danish hydrogen research and demonstration strategy and which likewise have aligned and influenced national activities.

### *7.3.3 Conclusions*

The long-term vision of the hydrogen economy will take several decades to be achieved. Initially, governmental support of R&D will play a key role in order to achieve the “technology readiness” needed to allow industry to make decisions on commercialization in the 10 year timeframe. Key milestones for technology development, improvement, or demonstration have to be defined and refined as technologies evolve and economics and systems analyses progress.

A continued critical evaluation and discussion of hydrogen based scenarios is necessary to establish a truly sustainable and economically viable energy system.

### *Recommendations for Denmark*

- A broad national partnership including all important players from industry, academia and politics is necessary that continually evaluates the national and international achievements and adjusts Danish research efforts accordingly;
- strong support of further development of core competences, for example electrolysis;
  - improvement of long-term stability of electrolysis cells at high performance;
  - cost competitive materials and production technologies, demonstration units when research has advanced sufficiently;
- establishment of international co-operations to complement Danish strengths within hydrogen technology;
- implementation of hydrogen technologies into a renewable future energy system containing for example links between wind, solar and hydrogen production as well as CCS.

7.4

## 7.4 Photovoltaics

PETER SOMMER-LARSEN AND POUL ERIK MORTHORST, RISØ DTU; PETER AHM, PA ENERGY A/S, DENMARK

### *7.4.1 Introduction*

Photovoltaic (PV) devices, otherwise known as solar cells, convert light directly into electricity. PV technology is modular and contains no moving parts.

The great majority of PV systems take the form of building-integrated (BIPV) installations, which supply power to customers connected to the public electricity grid. Such systems are integrated into residential, public and commercial buildings, and other structures like road traffic noise barriers.

Grid-connected centralised power stations or solar farms are the second large-scale application of PV. A third application, off-grid systems for both residential and non-residential applications, forms a valuable and reliable source of electricity in remote areas where main power is not available. Applications include households, telecommunications, water pumping, refrigeration and many more.

Solar cells are commonly divided into at least three categories. First-generation solar cells are made from crystalline silicon. Second-generation PV uses thin-film technology, including amorphous silicon, CIS and CdT. Third-generation technologies combine organics and semiconductors.

First-generation solar cells are currently dominant: crystalline silicon constitutes about 90% of the world market, and this situation is expected to continue until at least 2015. Second-generation solar cells are increasing in market share, with high-efficiency cells produced for high-value applications including satellites. Third-generation cells are still mostly at the research stage, though they are expected to be commercially available by the end of 2007.

Energy conversion efficiency is an important figure when comparing PV technologies. Efficiencies are typically reported under standard test conditions (STC): solar irradiance of 1000W/m$^2$, solar reference spectrum AM1.5G, and a temperature of 25 °C.

Individual solar cells are generally assembled in series to create modules, which are then connected in series and parallel to form panels. A full system contains one or more panels, plus “balance-of-system” (BOS) components including support structures, inverters, cables and switches.

The power output of solar cells, modules and panels is rated in peak watts ($W_p$) at STC. The energy generated by a PV system with a given $W_p$ capacity depends on factors including the amount of sunshine and the orientation of the solar panels. An optimally-placed 1000 $kW_p$ system generates an average of 850 kWh a year in Denmark and 1800 kWh a year in southern Europe.

The cost of solar power is continuously monitored by Solarbuzz [1]. Lowest retail prices for PV modules are (June 2007) €3.20/$W_p$ for first-generation cells and €2.20/$W_p$ for second-generation cells. The cost of solar electricity in cents per kWh obviously depends on the capital cost of the system, including installation, and on the expected lifetime. It is often loosely stated that in sunny areas, the price of power from first-generation PV systems with a warranty lifetime of 25 years is similar to peak prices for grid power from the utility company, though still considerably higher than average utility prices.

### *7.4.2 Technology status*

Global R&D effort in PV technology is concentrated in Japan, the USA and Europe. Each of these regions has a number of technology roadmaps, R&D plans and exploitation plans. The International Energy Agency supports the global development of PV technology in its PVPS work [2].

The EU-supported PV Technology Platform [3] is working on various aspects of PV technology, including research. The PV Technology Platform has a wide range of participants, with an emphasis on industrial partners, and is expected to advise the European Commission on future European-level PV RTD needs.

In a European context, the status of PV technology, its potential and R&D challenges were addressed comprehensively by the EU-supported publication *A Vision for Photovoltaic Technology* compiled by the Photovoltaic Technology Research Advisory Council (PV TRAC) [3].

These R&D challenges are analysed in more detail in a study called the PV Strategic Research Agenda (SRA), which has recently been published [3].

PV R&D programme managers in the EU-supported PV ERA-NET network are now strengthening the coordination of national PV R&D, including transnational joint calls for project proposals.

The costs of an installed system are shared between the PV modules, BOS costs including the inverter, and installation. Prices for installed systems vary from country to country, with a minimum of €6/$W_p$ in 2005. The industry needs to cut costs at every point along the value chain, but especially in the PV modules themselves, which currently account for 70% of the total cost of a typical PV system.

The aim is by 2016 to have cut module production costs from the current €2/$W_p$ to below €1/$W_p$ [4]. Based on the fall in costs up to 2006, this is a realistic target. New manufacturing technology is expected to cut the cost of solar-grade silicon, the raw material for first-generation PV cells. As an example, the Norwegian REC group [5], the world’s largest supplier of solar-grade polycrystalline silicon, is building a new plant based on low-cost fluidised bed technology and expects to start delivery by 2008. The new plant will double REC’s production capacity, with considerable cost savings. There is also huge cost reduction potential in improving the production yield of silicon wafers and decreasing the wafer thickness [4].

The quest for higher efficiency is another important aspect of PV R&D. As Table 15 shows, this is being pursued in several ways. Efficiencies up to 40% have been demonstrated using multi-junction thin-film cells and solar concentrators. High-efficiency single-crystal cells have also been made from ultra-pure silicon.

Table 15: Highest reported PV efficiencies [6]. Measurements are at STC except otherwise stated.

| Technology | Cell | Module | Notes |
|---|---|---|---|
| First-generation | | | |
| Mono c-Si | 24.7% | 22.7% | |
| Poly c-Si | 20.3% | 15.3% | |
| Mono c-GaAs | 25.1% | 15.3% | |
| Second-generation | | | |
| Amorphous Si | 9.5% | 8.2% | |
| CIS | 18.8% | 13.7% | |
| CdTe | 16.5% | 10.7% | |
| Third-generation | | | |
| Dye-sensitised | 10.4% | | Up to 6% reported* |
| Organic | 3.0% | | |
| High-efficiency | | | |
| GaInP/GaAs/Ge | 32.0% | | Multi-junction |
| GaInP/GaInAs/Ge | 39.3% | | Multi-junction, concentrator (179 suns)* |
| Mono c-Si | 26.8% | | Concentrator (96 suns) |

* Not confirmed

Concentrating the sun's energy allows expensive solar cells to be replaced by cheaper reflectors and lenses, and also increases the efficiencies of semiconductor PV devices. Future solar farms may concentrate sunlight to up to 1,000 times normal solar irradiance ("1,000 suns"). The High-Performance Photovoltaic Project managed by NREL aims to achieve 33% module efficiency by combining concentrators with multi-junction solar cells.

Compared to a monocrystalline silicon cell, a multi-junction cell harvests and converts a larger part of the solar spectrum by stacking several *p-n* junctions made from different semiconductors (Figure 26). The theoretical maximum efficiency (at STC) of a single-junction cell is 31%, whereas the theoretical limit for an infinite-junction cell is 66%. Multi-junction cells from SpectroLab Inc. show practical efficiencies up to 39%.

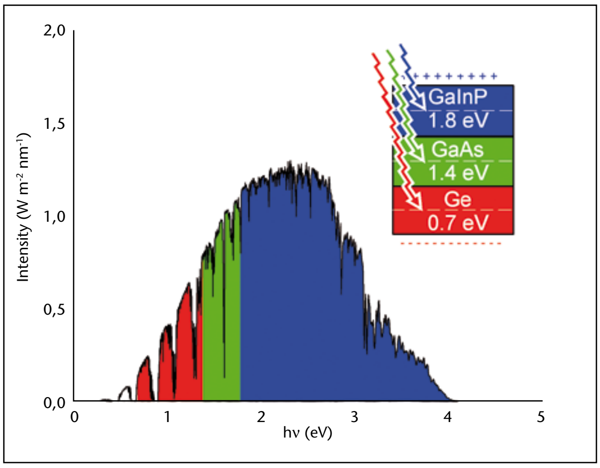
Other potential ways to increase efficiency are carrier multiplication and hot-carrier extraction. In carrier multiplication, high-energy photons absorbed by quantum-dot materials create multiple electron-hole pairs. This allows photon energy in excess of the semiconductor band gap to be converted into increased current, rather than dissipated as heat as it is in a monocrystalline silicon cell. Hot-carrier extraction exploits the same energy difference by tapping off energetic electrons before they thermally relax to the bottom of the conduction band. Hot-carrier extraction can increase the voltage of the cell as well as its efficiency.

Third-generation solar cells comprise dye-sensitised solar cells (DSSCs), which are also known as photoelectrochemical cells (PECs), and polymer solar cells. DSSCs have a 20-year history and show efficiencies comparable to amorphous silicon cells. Manufacturer G24i expects its 30 MW DSSC production line to be operating within the year [7].

Polymer solar cells (Figure 27, see next page) are less mature, but are approaching the efficiency of amorphous silicon cells. Konarka [8] is installing a production line, but has not published information on when it will be operational. Key goals for polymer solar cells are 5% module efficiency and a working life of several years. If these can be achieved, polymer solar cells will be commercially competitive, thanks to their low production costs and ability to be produced in extremely high volumes. The production cost of polymer solar cell modules could be as low as €0.1/$W_p$.

The German Federal Ministry of Education and Research announced the establishment of a research initiative for organic photovoltaics in June 2007. The initiative's total funding is 360 million € – of which 60 million € is government funding. The initiative comprises industry leaders BASF, Bosch, Merck and Schott and it aims to develop solar cells made of organic polymers with a 10% degree of efficiency and a life span of 2 to 3 years that can be used in mobile devices such as mobile phones or laptops. The initiative shall also contribute to the development of systems for stationary use with an improved power output.

Figure 26: This triple-junction PV cell has three semiconductor layers, each of which absorbs a different part of the solar spectrum. Photons with energies higher than the band gap of 1.8 eV are absorbed by the GaInP layer. Photons with energies below 1.8 eV pass through the GaInP to the GaAs layer below, which absorbs visible light from 1.4 to 1.8 eV. Near-infrared light passes through the GaAs and is in turn absorbed by the bottom Ge layer. The layers are connected in series.



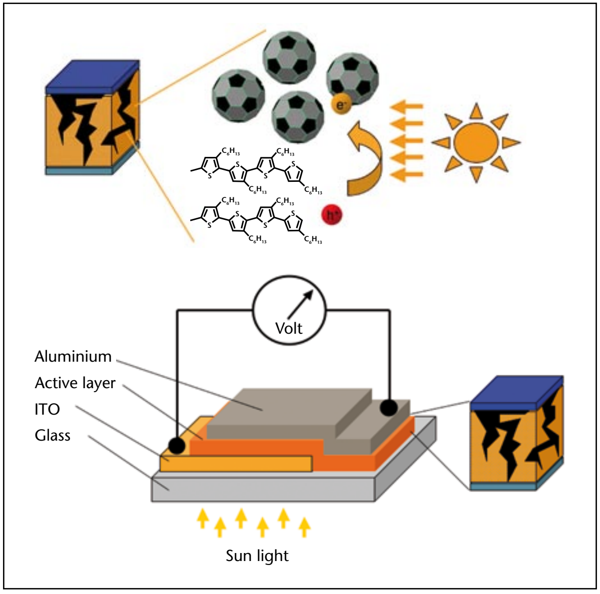
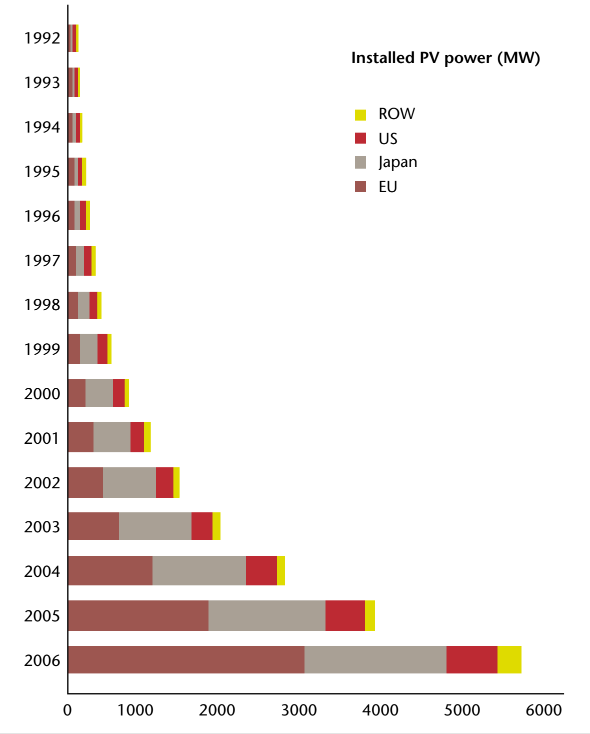


Figure 27: Bulk heterojunction polymer solar cell. The photovoltaic layer is a mixture of a hole conducting polymer, poly(3-hexylthiophene), and an electron-conducting $C_{60}$ phase. Photons absorbed in the polymer create charge separation and subsequently electron transfer to the $C_{60}$. The hole and the electron diffuse towards the electrodes in their respective phases.

### 7.4.3 Market development

Solar cells were the fastest-growing renewable energy technology market in 2005, with a global annual growth rate of more than 40%, and this trend continued in 2006. Growth has been dominated by grid-connected distributed systems in Germany and Japan. In Germany, subsidies have boosted the demand for solar cells to the extent that prices rose, though they fell slightly in the second half of 2006. Germany presently has an installed PV capacity of about 30 $W_p$/inhabitant, compared to Denmark's 0.5 $W_p$/inhabitant.

Figur 28: Cumulative installed PV capacity.



The global market is dominated by monocrystalline (35%) and polycrystalline silicon (45%), but thin-film solar cells are quickly gaining market shares, competitiveness and production capacity. Further technological breakthroughs in third-generation photovoltaics are expected, with some of these technologies expected to enter the market before the end of 2007.

Learning rates (see 7.4.4) for PV have levelled out at around 20% in the past decade. The trends for learning rates and global installed capacity show that within ten years PV will catch up with wind power in terms of both generating capacity and price. Ten years is also the time frame within which many countries are aiming to abolish subsidies for PV.

Although the availability of high-purity silicon is presently a bottleneck, production is expected to meet market demands before the end of 2007.

Figure 28 shows the world's cumulative installed PV capacity for the period 1992-2006 [9]. As noted above, first-generation cells still dominate the market, which until now has been concentrated in Japan, the USA and Europe. China, Taiwan, Korea, and India are now emerging as both large markets and strong solar cell manufacturers.

The European Photovoltaic Industry Association (EPIA; [10]) and Greenpeace have made projections about the PV market to 2025 and even 2040 [11]. They predict 433 $GW_p$ of installed PV capacity by 2025, corresponding to 2.5-3.5% of global electricity demand and creating a market worth €114 billion that would employ more than 3 million people. By 2040, according to the EPIA and Greenpeace, PV could be supplying 16-24% of the world's electricity.

An EU White Paper for a Community Strategy and Action Plan set a target for PV of 3 $GW_p$ installed capacity by 2010, corresponding to 1% of Europe's electricity demand. By the end of 2006 the EU already had 2.5 $GW_p$ installed, and the target will be met in 2007. By 2010 the EPIA wants PV installations in 7 million European homes, and 2.7 $GW_p$ of new capacity in the EU every year.

Global PV production volume was reported to be 1.5 $GW_p$ in 2005. Of this, Japan produced 55%, the USA 10%, and Europe the remaining 35%. The EU market for PV technology was worth more than €5 billion in 2005.

### 7.4.4 Cost trends

We can estimate the future cost of PV systems using the method of experience curves, developed by the Boston Consulting Group in the 1970s [12]. This theory says that every doubling of the total number of units produced (*cumulative production*) decreases the costs of manufacturing and marketing a single unit by a percentage that is approximately constant for a given product or industry. This *learning rate* is typically in the range 10-30%.

The experience curve does not take into account changes in the market or technological breakthroughs. It merely reflects the fact that mass production brings economies of scale, while manufacturing costs also fall as companies gain experience in making a particular product.

The EU-supported Photex project estimated an experience curve for PV [13]. Using price per $kW_p$ as the basis, the project estimated that learning rates were in the range 0.20-0.23. In other words, doubling the total installed PV capacity reduces the price per $W_p$ for new solar cells by 20-23%. The Photex estimate used data for the years up to 2001. A more recent estimate using IEA data gives a learning rate of 0.16-0.18, which agrees reasonably well with the Photex results.

Manufacture and installation of PV systems has grown at an average annual rate of around 40% over the last five years, so the total PV capacity is presently doubling every second or third year.

Figure 29 shows the trend in PV module production costs if we assume:

- a learning rate of 20%;
- installed capacity growth of 40% annually until 2008, followed by a linear decline to 30% annually by 2016; and
- PV modules cost \$3.5/Wp in 2001.

The actual price of PV modules followed the predicted price curve nicely until 2002-2003. Since then, however, strong demand and production capacity constraints have held prices almost constant (the current price of a module is approximately \$3.5/$W_p$). Big increases in manufacturing capacity this year should cause prices to fall soon; the question is whether they will drop back to the original curve, or follow a “delayed” curve that is shifted two or three years to the right. Bearing this uncertainty in mind, and the fact that the experience curve is not a precise forecasting tool, we might expect PV module prices of \$0.75-1.1/$W_p$ in 2016 (based on 2001 prices). By 2016 the total cumulative capacity is predicted to be 106 GW, compared to approximately 5 GW at present.

These estimations apply to the cost of modules, but not the additional BOS costs. However, experience from a number of countries [14] shows that BOS costs tend to follow the same experience curve as the modules themselves. In general BOS costs are around 35% of total PV system costs, so with module prices of \$0.75-1.1/$W_p$ we can expect system costs in 2016 to be \$1.2-1.7/$W_p$ (2001 prices).

### *7.4.5 $CO_2$ savings*

The energy payback time (EPBT) for PV is often claimed to be excessive compared to other renewable energy technologies. Recent estimates, however, suggest an EPBT in Europe of 2-5 years, depending on location. Of the energy needed to manufacture and install PV systems, less than 20% is accounted for by the BOS components. The bulk of the energy is used to make the PV modules, and of this fraction, 60-70% is used in the production of silicon. PV systems emit no greenhouse gases during operation. The EPIA and Greenpeace projected PV capacity for 2025 corresponds to annual savings of 350 million tonnes of $CO_2$.

### *7.4.6 Key policy measures*

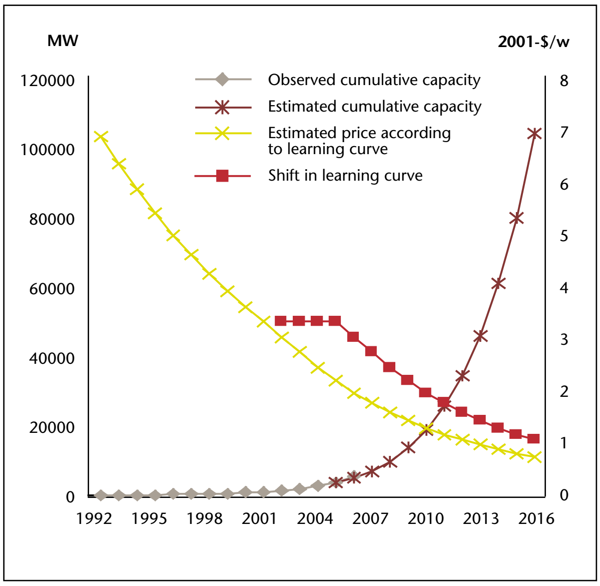
On the global scale, the objective is to create growth in the PV industry to the point where it competes on equal terms with other generating technologies (“grid parity”). The societal benefits are energy independence, new high-tech jobs, and lower $CO_2$ emissions.

Possible incentive mechanisms for PV growth are:

- feed-in tariff (FIT): producers are guaranteed a price for the electricity they produce over an extended period, typically 20 years;
- net metering: producers are paid the current market price. A reversible electricity meter is the preferred option for homeowners exporting small amounts of power to the grid; and
- investment support: subsidies, tax rebates or low-interest loans. Many European countries use investment support because PV technology is relatively expensive.

Germany introduced the first large-scale feed-in tariff system in 2004 under the *Erneuerbare-Energien-Gesetz* (EEG) law. This is based on a 20-year flat-rate contract; the values of new contracts decrease by around 5% every year, to reflect falling market costs. Spain, Italy, Greece and France also use FIT schemes. The typical value of FIT is €0.40-0.50/kWh.

Figure 29: Using experience curve analysis to estimate trends in PV prices up to 2016.



Net metering has become a permanent incentive in Denmark, with a current value of around €0.2/kWh. Many countries also provide investment support or installation subsidies, as did Denmark in the SOL-1000 project.

As the long-time world leader in PV, Japan has built a market for residential BIPV that requires no incentives beyond net metering. National subsidies for grid-connected PV in residential housing stopped in mid-2006, but despite this Japan reported more than 70,000 residential installations in 2006, more than half of which had been implemented without national subsidies. In the post-subsidy period Japan's PV industry expects a setback of 5-10%, to be followed by a return to growth.

In Denmark, a realistic target for installed PV capacity is 75 MWp in the period up to 2016. It is estimated that reaching this target will require installation subsidies to decrease gradually over a six-year period, and that the accumulated subsidy value will be DKK 50 million (around €7 million) on a total investment of about DKK 200 million (around €30 million).

### *7.4.7 The Danish view*

Denmark published its strategy for PV in 2005; Energiforskning.dk gives details of the supporting R&D programmes [15]. The Danish Energy Authority represents Denmark in PV ERA-NET. The accumulated Danish experience from a number of PV incentives such as SOLBY and SOL-1000 is well described in a recent report [14].

Solar cells are not produced in Denmark, though several companies supply and integrate systems. One company also has the potential to produce solar-grade silicon. Denmark has particular strengths in inverters, an essential support technology that converts the DC power produced by solar cells into AC household current.

Net metering is now a permanent incentive in Denmark, and this allows long-term planning of PV investments. The national installation subsidy ended with the conclusion of the SOL-1000 project, though one energy company, EnergiMidt, continues to offer customers a rebate on PV systems.

Building integration is one area that has the potential to minimise PV costs through replacing existing building elements with solar cells. Second- and third-generation technologies typically have shorter lifetimes than first-generation cells, and this will present special challenges for building integration.

In third-generation PV, Risø DTU hosts one of the world's strongest research groups on polymer solar cells [16]. Third-generation solar cells bring opportunities to integrate PV into other products via printing and plastics processing, and a number of Danish industries already have many of the skills needed to do this. The Risø group is working on all aspects of polymer solar cells, including materials, stability, and processing. A dedicated process line allows the testing of various approaches to module production. Demonstration on a larger scale is anticipated in 2008, with subsequent commercialisation of the R&D results.

The global fall in PV system costs will help to make PV electricity attractive in Denmark. EPIA and Greenpeace estimate that by 2025, PV electricity prices will be below €0.2/kWh in Denmark and other regions with similar solar irradiance.

It is important to maintain Danish PV industrial competence by securing a national market for first- and second-generation PV. Together with R&D funding, a national market gives industry the opportunity to build up skills and test the value of new production techniques at relatively small volumes. Two incentives to strengthen the Danish market are recommended below.

### *7.4.8 Conclusions*

PV is the fastest-growing renewable energy technology in Europe though market volumes are still low. The market is dominated by crystalline silicon solar cells, but the competitiveness of thin-film solar cells is quickly increasing. Based on growing market demands, production capacity increases, production costs decreases, and technology leaps, solar electricity is forecast to reach grid parity after 2016. Even before that, falling prices will make PV an attractive source of power in Denmark. PV is in the middle of a technological and commercial breakthrough, and new generations of technology promise a continued bright future. It is important to maintain Danish industrial competence in PV by securing a national market.

### *7.4.9 Recommendations for Denmark*

Denmark should:

- follow up on the SOL-1000 project with a new project having a target of 75 MW installed PV capacity by 2016. The new project should use two incentives: net metering, and a gradually decreasing installation subsidy;
- encourage installation of PV in new public buildings, perhaps through requirements to the building regulation clusters;
- make sure that all the relevant public R&D programmes take PV into account, and maintain the present mix of funding for demonstration, research and international involvement;
- ensure that Danish R&D strategies and market incentives in PV are ready to respond to future advances in PV technology, and the new opportunities these may create for Denmark. In the light of the recent 360 million € German initiative on organic photovoltaics, the Danish R&D system must prepare for massive investments in highly profitably energy technologies like PV.

7.5

## 7.5 Bioethanol for transport

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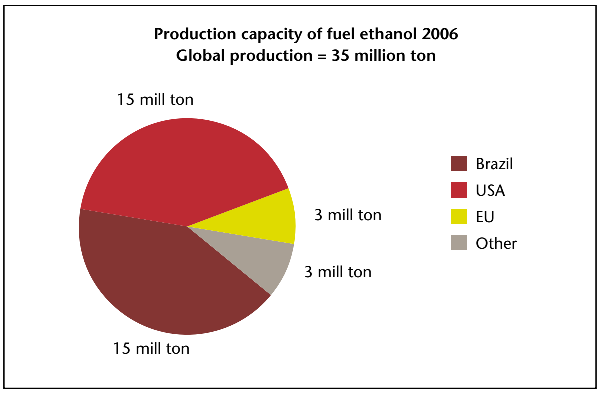
### *7.5.1 Introduction*

Bioethanol – ethanol made by the fermentation of sugars derived from biomass such as sugar cane or grains – is by far the commonest biofuel today. Bioethanol is one of the most promising sustainable alternatives to gasoline (and MTBE), since it can be handled through the existing infrastructure. The high oil prices are presently the driving factors for pushing bioethanol into the transport sector.

Ethanol can be blended with gasoline or used in its pure form, taking advantage of its higher octane number and heat of evaporation compared to gasoline. Vehicles with ordinary gasoline engines can use a blend of gasoline with 10% ethanol (E10) while modified "flexi-fuel" engines can use E85 (85% ethanol and 15% gasoline). Neat ethanol (E100) can also be used in gasoline-type (Otto) engines with high compression ratios, and in diesel engines with the addition of an ignition enhancer. The target of EU is in 2020 to replace 10% of fuel consumption in the transportation sector with bio-fuel.

Bioethanol is defined as either *first-generation or second-generation bioethanol,* depending on the feedstock used to produce it. First-generation bioethanol derives from starch (wheat or maize) or simple sugar-containing raw materials such as sugar cane or sugar beet. Second-generation bioethanol is made from lignocellulosic materials such as wood, straw, waste paper or household waste. Nearly all the fuel ethanol produced today is first-generation, notably the huge quantities of starch-based bioethanol now being made in the USA. Much progress has also been made in the last five years on the second-generation ethanol production, however.

Figure 30: World bioethanol production.



### *7.5.2 Market development*

Historically Brazil has been the only major producer and consumer of ethanol as a transport fuel, but the last ten years have seen rapid development in the USA, China and the EU. In the USA, a range of public interventions have significantly increased the demand for ethanol, while the supply side has been stimulated through tax credits, grants and loans. As a result, annual production in the USA has grown from around 3 million tonnes in 1996 to around 15 million tonnes in 2006 (Figure 30) [1], with capacity for a further 9 million t/y planned or under construction [2]. This makes USA the world's largest producer of ethanol.

The situation is similar in the EU, where several Member States are actively supporting the introduction of ethanol, in particular in Germany. Tax exemptions – in part or in full – and the mandated use of ethanol have stimulated demand, while a mixture of tax incentives, capital grants and access to EU Common Agricultural Policy provisions have encouraged the supply side [2]. Bioethanol production in the EU has more than tripled between 2000 and 2005, to the current figure of around 0.7 million t/y [7]. Total EU production capacity in 2006 was estimated at 1.2-3.0 million tonnes [3]. European production is concentrated in Spain, France, Germany, and to a lesser extent in Sweden and Poland [3, 4, 5].

Brazil, the main producer of ethanol until now, has also shown a significant increase in production capacity. The official target is a 40% increase in production between 2005 and 2010 [2], mostly for export to Europe and the USA. Brazilian ethanol production is very competitive because of the country's low input costs, large and efficient plants, and the use of sugar cane, with its easily-converted sugars, as the feedstock [6]. To encourage domestic production, however, both the EU and the USA have imposed customs duties that significantly increase the price of imported Brazilian bioethanol [5].

Even though global consumption of ethanol has already increased significantly, high future growth is expected. The IEA (2006) has projected an average annual growth rate of 6.3% for liquid biofuels between 2005 and 2030, most of which will be in the form of ethanol [2].

### *7.5.3 Cost development*

First-generation bioethanol technologies have been used for decades and are now mature, with large cost reductions the last 20 years. Second-generation technologies are still at the demonstration phase, and there is not enough historical data to predict how their costs will change in the future.

Compared to other renewable energy technologies, bioethanol has seen a steep fall in costs as production volumes have increased. Figure 31 (see next page) shows experience curves (cost plotted against cumulative production) for Brazilian (first-generation) bioethanol, wind turbines and photovoltaics.

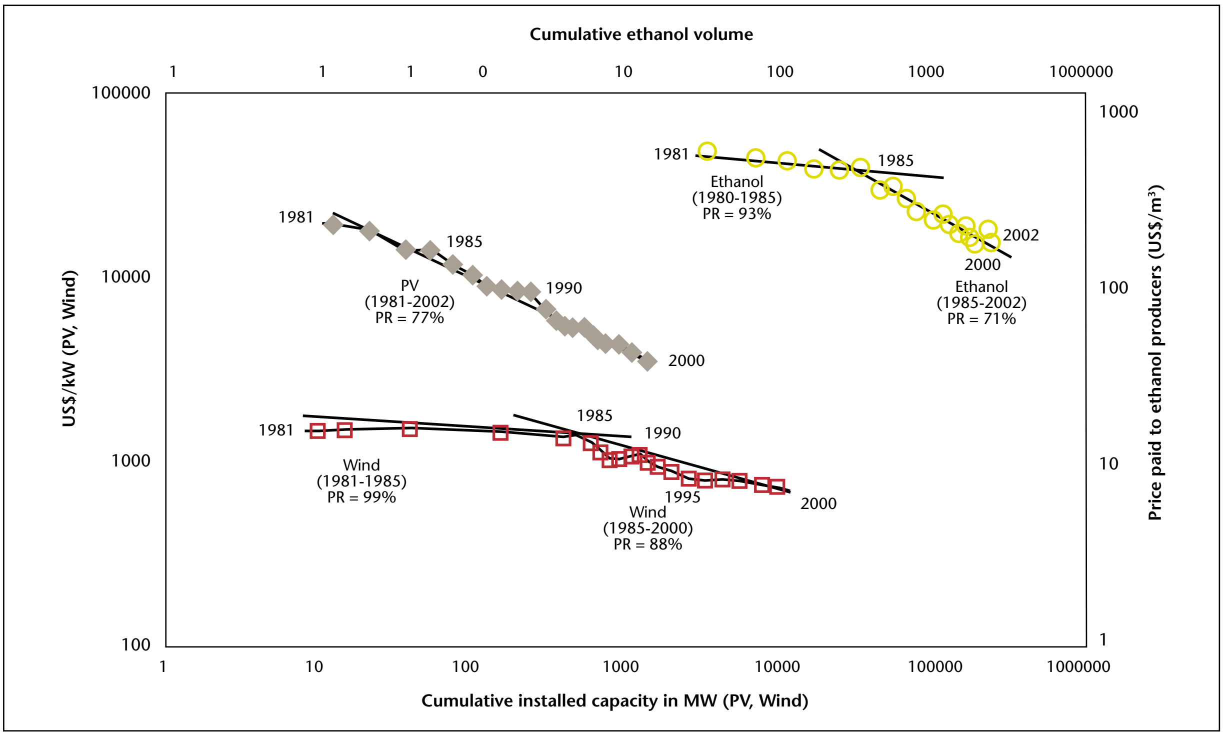


Figure 31: Historical data points and estimated experience curves for Brazilian bioethanol, photovoltaics (PV) and wind turbines. PR denotes the progress ratio (see text) [7].

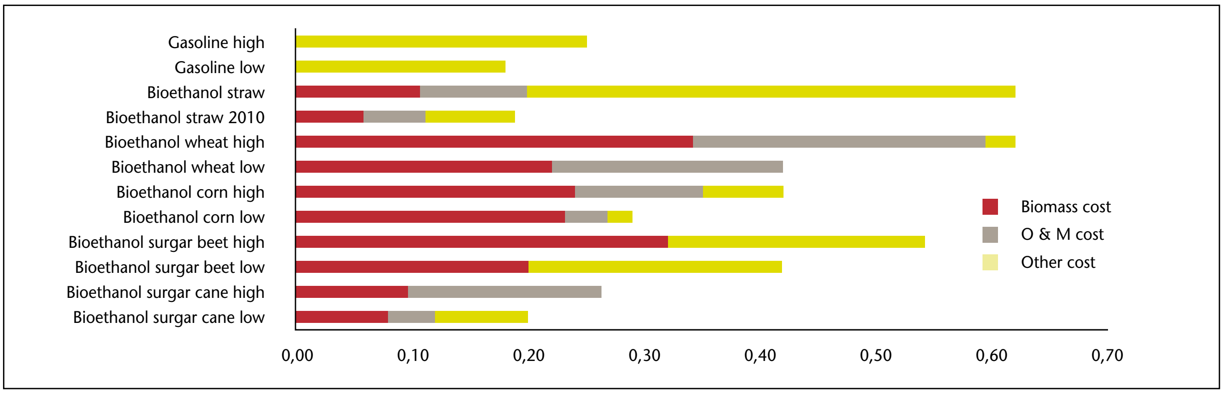
A log-log plot of unit production cost against cumulative production capacity often yields a straight line, known as an experience curve, that reflects increasing know-how and economies of scale as a technology takes off. Figure 31 shows that since 1985 this line has been steeper for bioethanol than for PV or wind power.

The slope of the experience curve can be used to calculate the "progress ratio": the new unit cost, as a percentage of the original figure, that applies when the cumulative production capacity has doubled. For Brazilian ethanol production the progress ratio is estimated at around 71% – in other words production costs fall by 29% for every doubling of cumulative capacity. Factors behind this sharp fall include big improvements in Brazilian agriculture, with better species of sugar cane and larger yields per hectare, as well as improvements in process technology.

Figure 32 shows that the cost of producing ethanol varies significantly between different feedstocks and technologies. The largest cost component of first-generation bioethanol is the feedstock. The energy and environmental balance of bioethanol is very sensitive to the source of feedstock and could even lead to negative balances.

Feedstock cost (delivered) accounts for 60-70% of the total manufacturing cost of corn-based ethanol in the USA, and this proportion will rise following the dramatic increase in corn prices during 2006. As a result, several new US bioethanol projects have been postponed. Corn

Figure 32: Production costs for gasoline and bioethanol from various sources (figures from Europe, USA and Brazil). Each fuel shows a low and a high cost scenario. Cost figures are on a volume basis, which partly disguises the cost gap between ethanol and gasoline (ethanol contains around one-third less energy than the same volume of gasoline) [8].



and wheat prices in the EU are normally higher than in the USA because of the EU intervention price of about €100/t. Current EU wheat prices of more than €140/t (delivered) could spoil the economics of many new first-generation bioethanol plants [9].

Making bioethanol from straw would cut feedstock costs as well as allowing the grain to be used for food. One cubic metre of ethanol from grain requires about 2.7 t of grain, which at €140/t costs €378. One cubic metre of ethanol from straw needs about 5 t of straw if only the $C_6$ sugars from the cellulose are converted, or about 3 t if the $C_5$ sugars from hemicellulose are converted as well; with straw at €50/t, the feedstock costs are €250 and €150 respectively per cubic metre of ethanol. At the moment, however, the extra process complexity of making ethanol from straw more than offsets the saving in feedstock costs.

### *7.5.4 Technological status*

#### *First-generation bioethanol*

In 2003, about 61% of the world's bioethanol derived from sugar crops: sugar cane (Brazil), sugar beet (France) and molasses. The remaining 39% was produced from grain, predominantly corn (USA) [10]. Thanks to intensive research on new enzymes to produce ethanol from starch, however, by 2006 nearly half the world's bioethanol was being produced in the USA from corn. Corn is also the main feedstock in Canada and China, whereas in Europe wheat, rye, barley, and triticale are used.

The first-generation bioethanol industry is characterised by large plants. Economies of scale for corn-based bioethanol plants have caused individual plant capacities to grow from about 75,000 $m^3/y$ to 150,000-300,000 $m^3/y$ over the last ten years. Most corn-based plants are located in the USA, but the largest plant, with a capacity of 600,000-700,000 $m^3/y$, is in Jilin, China [10].

Ethanol is easy to make from sugar cane, sugar beet and molasses, because these feedstocks contain $C_6$ sugars that can be fermented directly to ethanol using baker's yeast. For cereal starch, current ethanol technology is based on either wet or dry milling. In wet milling, the grain is steeped in a solution of sulphur dioxide at 50°C for 24-48 hours, followed by milling to loosen the germ and the hull fibres. In dry milling the grain is simply broken into fine particles to facilitate subsequent penetration of water. Both processes then follow the same three stages: liquefaction (thermal enzymatic hydrolysis); simultaneous saccharification and fermentation (SSF) using baker's yeast; and finally distillation to purify the ethanol.

New plants are mainly based on dry milling, because it is more energy-efficient than wet milling. Dry milling allows the liquefaction stage to operate with a solids concentration of 30-35%, compared to 20% for wet milling, and this reduces the energy required to produce one litre of ethanol by almost 50% [11]. The Danish company Novozymes has developed efficient enzyme systems especially tailored for dry milling processes, and production costs have fallen as a result [12, 13, 14].

#### *Second-generation bioethanol*

Second-generation bioethanol is also known as cellulosic ethanol, since it is produced from plant sugar components in straw, wood chips, grasses, waste paper and other "lignocellulosic" materials. Lignocellulose has a more complex structure than starch, so it requires more expensive methods to release and ferment the different kind of sugars. For ethanol production, the main components of lignocellulose are $C_6$ sugars from cellulose and $C_5$ sugars from hemicellulose.

In 2001, second-generation bioethanol was still at the research stage and far from industrial application. Today, lignocellulosic processing is well advanced, and the EU has three demonstration plants, in Sweden, Spain and Denmark (Table 16).

In Sweden a fully-integrated demonstration plant at Örnsköldsvik started up in 2004 with a capacity of 2 t/d of softwood as feedstock [15]. Between 2002 and 2006 Dong Energy built the first pilot-scale plant in Denmark [16]; originally designed to treat 1,000 kg/h of biomass, the plant will be further developed in 2007 to handle 100-4,000 kg/h. The Abengoa plant in Salamanca, Spain, produces both first- and second-generation bioethanol: around 195,000 $m^3/y$ from wheat and some barley, and 5,000 $m^3/y$ from wheat straw.

Outside the EU, Iogen Corp. in Canada has a pilot plant rated at 40 t/d [17]. In the USA, six commercial-scale second-generation plants to produce a total of 492.000 $m^3/y$ of ethanol are scheduled to start up in 2009-2010 [18].

Table 16: Demonstration plants for second-generation bioethanol.

| **Plant operator** | **Location** | **Capacity (t/d feedstock)** | **Hydrolysis method** | **Raw material** | **Reference** |
|---|---|---|---|---|---|
| Iogen | Canada | 40 | Dilute sulphuric acid + enzymes | Wheat/oat/ barley straw | www.iogen.ca |
| Abengoa | Salamanca, Spain | 30-40 | Steam pretreatment + enzymes | Barley straw | www.abengoabioenergy.com |
| Etek Etanolteknik | Örnsköldsvik, Sweden | 2 | Dilute sulphuric acid + enzymes | Softwood | www.etek.se |
| Dong Energy | Denmark | 2.4-24 | Hydrothermal treatment + enzymes | Wheat straw, household waste etc. | www.dongenergy.dk |

7.5

Second-generation bioethanol processes start with pretreatment, followed by enzymatic hydrolysis, fermentation of cellulose ($C_6$) and hemicellulose ($C_5$) sugars, and finally distillation. The nature of the pretreatment step depends on the raw materials (Table 16, see previous page).

The challenge in second-generation bioethanol is to increase yield while reducing energy demand, operating costs and capital costs [19]. Important research tasks include:

- pretreatment and depolymerisation of sugars for fermentation with minimum generation of inhibitors and without the use of chemicals;
- reducing enzyme costs and developing novel technology for operation at high solids levels;
- developing microorganisms to ferment $C_5$ sugars that are more tolerant to inhibitors and ethanol;
- process integration to reduce the number of process steps and to reduce water consumption; and
- recovery of lignin, a waste product that can be used as a fuel or as a source of chemicals.

All the demonstration and pilot plants mentioned above have pretreatment units that use a combination of high temperature and high pressure to open the tight structure of lignocellulosic materials, a necessary step before hydrolysis by enzymes. A side-effect of pretreatment, however, is the release of "fermentation inhibitors" – compounds that are toxic to the fermentation organisms or hinder enzymatic hydrolysis [19]. More research is needed to minimise the production of inhibitors during pretreatment, preferably without the need to add chemicals.

A low-cost method with minimal consumption of enzymes is needed for a breakthrough in second-generation bioethanol. The US National Renewable Energy Laboratory (NREL) has made a full review of process designs and economic models for ethanol from biomass [20]. The resulting research projects have aimed to reduce the cost of the cellulase enzymes needed to convert plant waste material into fermentable sugars. The award of $17 million to Novozymes and Genencor International for enzyme research reflects the importance of this target.

Novozymes has reported that it has reduced enzyme cost per unit of ethanol by a factor of 30, as defined by NREL, using dilute acid pre-hydrolysis as a pretreatment step [21]. Other researchers have developed a new method to handle high solids concentrations, based on hot water pretreatment [20]. As a result, second-generation bioethanol is now a practical proposition, but it still needs more research to reduce enzyme costs and increase efficiency.

Tolerant yeast strains exist that can ferment $C_6$ sugars from cellulose, but further development is needed to reduce the effect of inhibitors, and especially to ferment $C_5$ sugars under real process conditions, including high ethanol concentrations. High ethanol yield and the ability to handle a range of feedstocks are other important goals. Promising candidates include the genetically-modified yeast TMB 3400 [22] and a thermophilic bacterium [23].

Bioethanol production uses large quantities of water, which need to be removed and requires energy. Water use can be minimised by operating at high solids levels, to reduce the amount of water that has to be removed at the end of the process, and by re-using water within the process. Risø DTU has a patented process that produces biogas from the waste products and inhibitors in the fermentation broth. The resulting purified liquid is then recycled as process water [24].

The residue from the SSF stage is lignin, a complex polymer with a high calorific value. The energy obtained from burning lignin is similar to that needed for pretreatment and fermentation [20]. In the long term, lignin could also be used as a source of chemicals [25].

### *Integration and co-production*

One way to reduce the cost of bioethanol is through integration and co-production with other biofuels. In Sweden, the heat and electricity needed to produce ethanol from wheat are supplied by a CHP plant fuelled by biomass; including the fuel used for agriculture and transport, this system produces twice as much bioethanol as the amount of fossil fuel it consumes [26].

In Brazil, bioethanol from sugar cane is produced at prices competitive with those of gasoline. Most plants use bagasse, the lignocellulosic residue from sugar cane processing, to produce process heat and electricity. In this case fossil fuels are used only in harvesting and transporting the sugar cane, and the resulting ratio of ethanol to fossil fuels is about 8 in energy terms [27]. Bagasse can also be used as feedstock for second-generation bioethanol plants [21].

Denmark's second-generation pilot plant uses the Integrated Biomass Utilisation System (IBUS), in which bioethanol is produced alongside CHP from co-firing coal and straw. Straw handling and storage systems originally designed for CHP production serve the bioethanol plant as well. Surplus heat is used to evaporate wastewater, leaving behind byproducts such as carboxylic acids and unconverted sugars that can be sold as animal feed [19].

Co-production of first- and second-generation bioethanol, as done for the first time at the Abengoa plant in Spain, creates further opportunities for process integration. The ultimate plant will combine first- and second-generation bioethanol with CHP. Agricultural residues such as straw are attractive for bioethanol production, but the fact is that such residues are already in short supply – and relatively expensive – in some EU countries. Few places in the EU could provide the 750,000 t/y of straw needed to run a 150,000 m3/y ethanol plant, so future plants need the flexibility to handle a wide range of feedstocks, including straw, grain, energy crops, waste wood and household waste.

### *7.5.5 Emission reduction and energy security*

The net consequences of bioethanol production on energy security and greenhouse gas (GHG) emissions depend very much on the type of biomass used, the process technology used, and of-course on the type of fuel substituted. Some combinations of these factors score well on both points, while others perform poorly or even have negative consequences.

If bioethanol is made from waste materials, upstream energy inputs such as agricultural diesel and fertiliser can be charged to the primary crop, and do not detract from the energy balance of the bioethanol. The analysis of energy security and GHG emissions therefore depends only on a comparison between the bioethanol, plus its production residues, with the alternative downstream fate of the feed materials.

For first-generation bioethanol, on the other hand, the assessment must include all the upstream inputs for biomass production, plus the energy consequences of using the land to produce fuel rather than food, as well as the downstream effects.

First-generation ethanol processes based on grain starch show similar characteristics, regardless of whether their feedstock is wheat or corn. A comparison of results from six representative analyses [18] shows that primary energy (excluding the energy in the biomass) makes up about 80% of the energy contained in the bioethanol product. Thus, only about 20% of the energy in the bioethanol is effectively renewable.

However, only about 20% of the primary energy used comes from petroleum, while coal and natural gas make up the rest. This means that grain-based ethanol used as a transport fuel displaces an amount of gasoline or diesel equivalent to about 84% of the energy content of the bioethanol, while increasing the use of coal and natural gas.

This may be good for energy security, but the consequences for GHG emissions are modest: replacing gasoline with grain ethanol reduces GHG emission by about 13% [18]. Larger GHG emission cuts would be possible by using renewable energy for the fossil fuels currently used in bioethanol production.

Future second-generation bioethanol processes could be much more effective in reducing petroleum inputs and in particular GHG emissions [28]. Depending on the process technology and degree of energy integration, replacing gasoline with second-generation bioethanol could cut GHG emissions by 90% or more.

### *7.5.6 Conclusions*

Bioethanol is a promising transport fuel that occupies a fast-growing market. The USA and Brazil are currently the main producers, together accounting for 82% of all fuel ethanol. Only a limited amount of bioethanol is produced in the EU, but a wide range of policy instruments are available to governments wishing to promote its use.

All the bioethanol in commercial production today is of the first-generation type, meaning that it is made from starch (from corn or wheat) or sugar (from sugar cane or sugar beet). The technology needed to make first-generation bioethanol from starch has developed rapidly, thanks to intensive research in enzyme technology.

Second-generation bioethanol is made from materials that are of lower value but are more difficult to process, such as straw and wood waste. The necessary technology is not yet commercial but is developing fast, with several demonstration plants operating or under construction.

Plants that combine first- and second-generation bioethanol with CHP can cut both capital and operating costs. Future European plants should have the capacity to convert combinations of feedstock – such as straw, grain, energy crops, wood waste and household waste – to ensure a continued supply of raw materials.

The reduction in GHG emissions that results from the use of bioethanol in transport depend on the raw materials and conversion technology used, as well as on the type of fuel substituted. Most promising here is second-generation bioethanol, with an estimated 90% reduction in GHG emissions.

7.6

## 7.6 Thermal fuel conversion – pyrolysis, gasification and combustion

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### *7.6.1 Main drivers in the energy market*

The perfect fuel is cheap, available locally, in huge amounts, and easy and efficient to convert thermally into an energy form that may be applied in the modern day life, with only minor operational and environmental difficulties. However, such a fuel does not exist. Up until the early 1970s the world energy production was mainly based on fossil fuels and – in some parts of the world – on nuclear power.

Anyhow, the massive energy crisis in 1973, opened the public eyes to the fact that the supply of fossil fuels from the Middle East was highly uncertain. Later, an increasing level of $CO_2$ in the atmosphere, as well as several cases of documented environmental problems in relation to formation of acidic rain, introduced a significant environmental aspect in the energy supply debate. These aspects caused significant effort into the development of renewable energy sources and the thermal conversion techniques of $CO_2$-neutral fuels.

| Fuel | 1980 | 2002 |
|---|---|---|
| Coal | 25% | 24% |
| Oil | 46% | 38% |
| Natural gas | 19% | 23% |
| Nuclear | 3% | 7% |
| Renewables | 7% | 8% |

Table 17: Relative world energy consumption by fuel type, 1980 and 2002 [1].

Table 17 shows that the fraction of natural gas and nuclear energy supply to the world energy consumption has increased from 1980 to 2002, mainly at the expense of oil [1].

### *7.6.2 Fuels: Fossil fuels, biomass, and waste from human activities*

Coal is the most abundant fossil fuel, with widespread resources all over the world – enough to last several hundred years with the current consumption rate. Due to this, coal shows better price stability than oil and gas, and has gained renewed interest as an energy source over the past decade. Most of the energy supply in Denmark comes from combustion of pulverized coal, and the Danish power plants are leading in the world with respect to energy efficiency of these plants. Nevertheless, coal will only be an option for the future if it is possible to cost-efficiently reduce the emissions of $CO_2$.

It is important to realise that all fossil fuels, particularly natural gas, are limited resources, not only from a total energy capacity point, but also from an easy-access point-of-view, i.e. some of the major resources of e.g. natural gas are located in areas dominated by politically unstable regimes.

Biomass and waste may be used as a fuel in modern power stations, in some industrial processes to provide electrical power and heat, and in domestic stoves for cooking and heating purposes.

Biomass has a number of characteristics that makes it more difficult to convert thermally than fossil fuels. The low energy density is the main problem in the handling and transport of these fuels, while the main difficulty in using them as fuels, relates to their content of inorganic constituents. Thus, biofuels frequently need pre-treatment in order to reduce its storage, transport and handling costs, or to provide a homogeneous fuel with a higher energy density, suitable for automatic fuel-feeding in combustion systems. The actual pre-treatment process depends on the type of biomass as well as on the preferred combustion technology, and may e.g. involve baling (herbaceous biofuels), particle size reduction, and, if necessary, drying.

Waste – e.g. from human household activities – are being produced in increasing amounts in the modern society. It is characterized by a low heating value, and by being extremely inhomogeneous chemically and physically, which is the reason for applying grate-based incinerators to convert the part of the waste that is not either disposed or reused, thermally.

### *7.6.3 Conversion of solid fuels*

The basic idea in thermal conversion of fuels is to transform and utilize chemical energy bound in the fuel to e.g. supersaturated steam in steam cycle, from which electricity may be produced upon passage of a steam turbine. Anyhow, thermal conversion of solid fuels occur – in principle – either in one strongly exothermic step from fuel to fully oxidized species ($CO_2$, $H_2O$ etc.), or in multiple steps, initiated by an endothermic step, in which a calorific gas is produced, followed by multiple exothermic conversion steps. The difference between these extremes provides possibilities of heat and power production, combined with application of gaseous products for production of liquid fuels. Recently, several opportune concepts of combined thermal conversion and fuel production have been introduced.

### *7.6.4 Existing technologies*

Traditionally, biomass in the form of wood and straw, and domestic, agricultural, and industrial wastes has been converted in grate or stoker type boilers. These boilers are still used today when very in-homogeneous fuels like straw and MSW, are applied, when the boiler units are small, or when limited process and operation knowledge on a particular fuel are available. During the last couple of decades, combustion technologies like suspension-firing and fluidized bed have also been applied for biomass and waste. Compared to grate fired boilers, suspension-firing offers higher electric power generation efficiency, lower operating costs, and a better load adaptation. Fluidized bed technology offers the potential for high fuel flexibility and build-in reduction of harmful pollutants.

More recent conversion technologies, such as gasification or pressurized combined cycle combustion, have been under development through several years. However, with respect to electric power generation efficiency and operating costs they are still less efficient than suspension firing boilers. In Table 18, an overview of technology vs. fuels is provided together with key operational parameters of each technology.

Significant efforts are aimed at co-firing of herbaceous biomass together with coal on existing pulverized coal burners. Co-firing with coal has been successfully demonstrated at a number of power stations in Denmark, during the last 10-12 years. In addition to concerns on SCR-catalyst deactivation, the addition of biomass to PF-fired units may impede the utilization of fly ash for cement production.

Modern gasification technology with high quality standards for the product gas is a complex process. The product gas consists mainly of $H_2$, CO, $CH_4$, and $CO_2$, and is mostly intended for immediate use on site. Thus, the gasification unit is usually an integral part of the power generating plant. In the small unit size the product gas is mostly used in a combustion engine, while in larger units it is used in a gas turbine or combined cycle plant. In this way a high efficiency of biomass conversion can be obtained.

Gasifiers may be divided into three categories:
- Fixed bed gasifiers are mostly small scale units and appear in two types; either down-draft (<2 MW) or up-draft (<10 MW), differing mainly in the direction of gas flow through the biomass in the reactor. In an up-draft gasifier the raw gas contains important fractions of tar which need to be removed before using the gas. The down-draft reactor enables the cracking of the high hydrocarbon fraction but a drawback is the high gas temperature at the reactor outlet.
- The fluidised bed gasifiers, either stationary or circulating, are in the MW-range. The circulating variety, CFB, requires a size of more than 15 MW, in order to be commercially viable. The product gas is characterized by low tar content, and sulphur and chloride may be absorbed by the bed material. Thus, fluidised bed gasifiers apparently reduce significantly the problems associated with the utilization of agricultural biomass.
- Entrained flow gasifiers operate at very high temperatures, 1200-2000 °C, and require the biomass in form of very finely ground particles. Again there are a number of different types. A special feature is the utilisation of the high temperature heat in the raw gas, which is quenched after leaving the reactor.

Fixed bed gasifiers for biomass have mainly been used in a few relatively small units where the gas is used to

Table 18: Comparison of key furnace parameters for a number of common solid fuel combustion techniques. CSAF – Cross Sectional Area of Furnace, ABFB – atmospheric, bubbling fluid-bed, CFB – Circulating fluid-bed, PBFB – Pressurized bubbling fluid-bed, HR – PC – High-rank, pulverized coal, dry – dry bottom slag removal, wet – wet bottom. Slag removal (slag tap furnace), LR – PC – Low-rank, pulverized coal, dry bottom slag removal [2].

| Firing technology | Grate-firing | ABFB | CFB | PBFB | HR-PC (dry) | HR-PC (wet) | LR-PC |
|---|---|---|---|---|---|---|---|
| Fuels applied | Biomass, waste | Coal, biomass, waste | Coal, biomass | Coal, biomass | Coal, oil, natural gas, biomass, waste | Coal | Coal, biomass |
| Comb. temp. [λC] | 1100-1300 | 750-1050 | 750-950 | 750-950 | 1100-1500 | 1300-1600 | 1100-1300 |
| Furnace exit gas temp. [λC] | 1000-1100 | 750-1050 | 750-950 | 750-950 | 1050-1250 | 1000-1150 | 950-1150 |
| Gas velocity in furnace [m/s] | 4-9 | 0.5-5 | 5-8 | 0.5-3 | 5-10 | 5-10 | 4-8 |
| Residence time, gas [s] | 1-3 | 1-3 | 0.5-6 | 3-8 | 1-3 | 1-3 | 1-3 |
| Residence time, solid [s] | $10^3$-$10^4$ | $10^3$-$10^4$ | 500-$10^3$ | 80-400 | 1-3 | 1-3 | 1-3 |
| Air excess number [λ] | 1.3-2.5 | 1.2-1.4 | 1.12-1.3 | 1.2-1.5 | 1.13-1.3 | 1.15-1.3 | 1.2-1.5 |
| Thermal load per volume [MW/m$^3$] | 0.15-0.35 | 2-5 | 8-20 | 20-50 | 0.06-0.3 | 0.1-0.4 | 0.06-0.15 |
| Thermal load per CSAF [MW/m$^2$] | 0.5-2.5 | 1-2 | 2-8 | 10-20 | 2-6.5 | 4-6 | 2.5-5 |
| Pressure [bar] | 1 | 1 | 1 | < 20 | 1 | 1 | 1 |
| Average part. size [mm] |  | 1-3 | 0.15-0.25 |  | 0.01-0.1 |  |  |
| Comb. efficiency [%] | 92-97 | 92-95 | 98-99 | 95-99 | 96-99 | 98-99.9 | 96-99 |

generate electricity by an engine. Fluidized bed gasifiers for biomass are in the developing phase in several countries both for electricity and liquid fuels. Entrained flow gasifiers have been used to gasify coal for many years, but first recently have the development of pressurized biomass gasifiers been initiated.

### *7.6.5 Emissions and solid residues*

As the main composition of all fuels in principal can be presented as: $C_{\alpha}O_{\beta}H_{\chi}S_{\delta}N_{\varepsilon}$, it is obvious that all fuels upon oxidative thermal conversion with air ($N_2$+$O_2$), forms certain amounts of $CO_2$, $SO_X$, $NO_X$, $O_2$, $H_2O$, and $N_2$, together with minor amounts of e.g. gaseous Cl-species. The increasing $CO_2$-level in the atmosphere, is known to cause global heating, while $SO_X$ and $NO_X$, if emitted to the atmosphere may form e.g. acidic rain. Thus, the emission of these species must be decreased either directly by flue gas cleaning onsite at the plant or indirectly e.g. by substituting $CO_2$-emitting fossil fuels with $CO_2$-neutral fuels like biomass.

Emissions of pollutant species depends to some extent on the thermal conversion technology applied. Fluidized bed combustion is characterized by fairly low combustion temperatures (Table 18, see previous page), that are beneficial for conversion of fuel-N to $N_2$ and for capture of sulfur on dry limestone. Combustion on a grate involves slightly higher temperatures, but the reducing conditions just above the fuel bed facilitate conversion of nitrogen volatiles to $N_2$. Due to high temperatures, NO emissions from suspension firing are potentially much higher, but may be limited by the use of low-$NO_x$ burners that delay mixing of $O_2$ with the fuel. Concentrations of sulfur and chlorine species in the flue gas are mainly determined by the content of these elements in the fuel. Independent of the combustion technology they are mostly released as $SO_2$ and HCl. However, in fluidized bed and grate combustion a significant fraction of the sulfur and chlorine may be captured by the ash or released as aerosols.

Several techniques are available for $NO_X$- and $SO_X$-removal from flue gases, while there in principle are three different ways in which a reduction in the $CO_2$ emission from power generation by combustion can be achieved:

- increasing the fuel conversion efficiency;
- switching to a fuel with a lower fossil carbon content (including biomass);
- capturing and storing the $CO_2$ produced by fossil fuel combustion.

While the two first options will help reduce the $CO_2$-emission in a longer timeframe, the latter will make a significant and rather quick reduction in the $CO_2$-emission. The most obvious way forward is then to perform $CO_2$ capture from conventional suspension-fired units by flue gas scrubbing or doing so-called oxy-fuel combustion where combustion takes place in pure oxygen diluted with an external recycle stream of flue gas to reduce the combustion temperature.

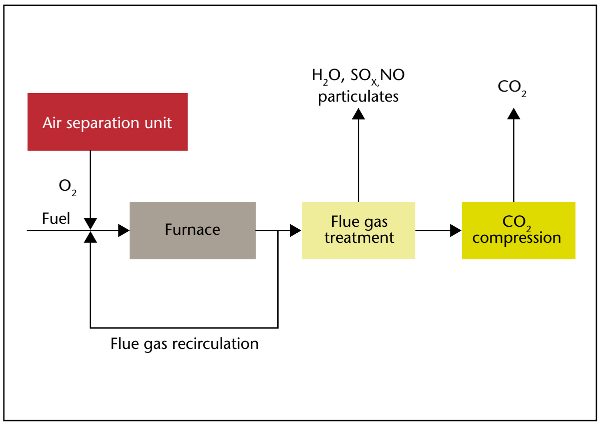
Capturing $CO_2$ from a dilute stream is rather expensive, but techno-economic studies indicate that the oxy-fuel combustion process, may be a cost-effective method of $CO_2$ capture. The oxy-fuel process is shown schematically in Figure 33. During oxy-fuel combustion a combination of oxygen typically of purity greater than 95% and recycled flue gas – consisting mainly of $CO_2$ and $H_2O$ – is used for combustion of the fuel. The recycled flue gas is used to control the flame temperature and make up the missing $N_2$ to ensure there is enough gas to carry the heat through the boiler. The oxy-fuel process may be applicable both as a retrofit technique for existing boilers and for new boilers. There are many new challenges to be faced for the oxy-fuel process compared to conventional combustion, including:

The characteristics of oxy-fuel combustion with recycled flue gas differ from combustion in air in several ways, including:

- different flame temperature requiring higher $O_2$ concentration in the burner to ensure ignition;
- increased radiative heat transfer due to the high levels of $CO_2$ and $H_2O$ in the furnace;
- changed corrosion rates of the heat transfer surfaces due to the changed gas atmosphere;
- the emissions of $NO_x$ and $SO_2$ may be lower in oxy-fuel combustion than for air firing, due to re-cycle of these compounds to the combustion chamber;
- gas cleaning processes for e.g. $NO_x$ and $SO_2$ – how will they respond to the changed gas composition.

It is interesting to note that if coal and biomass is co-fired and all $CO_2$ is captured it is possible to obtain below zero emission of $CO_2$ thereby reversing the green-house effect. The Swedish power company Vattenfall AB is engaging strongly in the oxy-fuel combustion process and is building a 30 MW demonstration plant in Schwarze Pumpe, Germany.

Figure 33: General flow sheet for oxy-fuel combustion [3].



### *7.6.6 Future challenges*

Biomass and waste applied for heat and electricity production should be converted in processes with a high efficiency and low operating costs. In addition, the processes need to be environmentally sustainable and to provide a net reduction in $CO_2$-emissions. R&D activities may support those objectives by supporting the following type of activities:

- improve the efficiency and decrease the operating costs for all types of biomass and waste thermal conversion units;
- develop tools to minimize operational problems (i.e., with fuel handling, corrosion and ash deposits), and, remove harmful emissions and to ensure an appropriate utilization of residual products;
- develop methods such that biomass and waste can be applied for power generation on high efficiency suspension-fired and fluidized bed boilers.

Another major future challenge is to develop gas-cleaning strategies to meet the stringent requirements of gas quality. Two methods deserve to be mentioned, namely the wet gas cleaning procedure developed by Babcock & Wilcox Volund (BWV) and the high temperature two-stage gasification as developed at the Technical Univerisity of Denmark. The methods are part of the 6 MWth CHP demonstration plant (Harboøre, Denmark) and the 75 kW staged gasifier (Wiking) at the Technical University of Denmark.

Thermal conversion of biomass has been investigated through several years as a possible source of renewable liquid fuels, storable and having the advantage of separating the fuel production from the utilisation. They can substitute fuel oil in any stationary heating or power generating application and have a heating value of about 40% of a conventional fuel. Thus, biofuels may well find use at peak loads at large power plants. The dominant use of liquid biofuels is in the transportation sector, at least in Europe. Oil from plants, especially rape seed, is obtained by pressing and extracting, and can be used directly in dedicated engines. In a subsequent process, a methylated ester is produced with a quality comparable to diesel fuel. It is marketed as “Bio-diesel” or is blended with standard diesel.

There are several incitements to provide alternative transport fuels based on biomass as a raw material. It will be a $CO_2$-neutral transport fuel, it will reduce the dependence on imported fossil fuels in the Western world and it is possible to further develop a domestic industry based on liquid fuels. Liquid transport fuels based on biomass can be produced by several different means such as biodiesel from rape, ethanol by fermentation and by the GTL-technology (Gas-To-Liquid). The GTL-technology has a potential to obtain a high efficiency with respect to biomass to liquid conversion efficiency, and it should be possible to develop the technology so that a broad range of solid input fuels can be applied. On the down side counts that GTL-plants are relatively large and complicated.

The GTL-technology uses natural gas or gas produced from solid fuels or from gasification of biomass, waste or coal, whereby it is converted to a gas rich in CO and $H_2$. This gas is then used for a synthesis of hydrocarbon liquids, by use of a catalyst. Depending on the catalyst type and operation conditions different products can be made such as ethanol, DME, higher alcohols, and Fischer-Tropsch gasoline or diesel. Often a pressurized oxygen blown entrained flow or fluid bed gasifiers is used to produce the synthesis gas. The gas supplied from the gasifiers to the catalytic synthesis does often need to be carefully conditioned in order to obtain an adequate $H_2$/CO ratio, and to be cleaned of species that can poison the catalysts.

The GTL-technologies are presently used in a large scale to produce methanol from natural gas, and for many years Fischer-Tropsch hydrocarbon production have been applied in South Africa. Because of the relatively high fossil oil prizes, GTL-technologies have gained renewed global attention, and in China plants for DME production from coal are being erected. Large-scale commercial production of transport fuels from biomass with the GTL technology is not done presently, but the increased awareness of the need to reduce $CO_2$-emissions, and the need to provide alternative transport fuels, do strongly favour this technology.

A broad band of research work need to be initiated to consolidate the GTL-technology for commercial application, improve energy efficiency and improve the possibilities to integrate the technology with other energy technologies. Possible research areas could be:

- further development of pressurized gasifiers to handle biomass and waste as well as co-gasification of biomass and coal;
- work on integration of the GTL technology with power production so that waste heat can be used efficiently for power and central heat production. Integration with other advanced technologies so outlet $CO_2$-sequestration can be obtained and that the gasification can be integrated with combined cycle power production;
- increase of plant efficiency by improving the efficiency of both the gasification and synthesis process;
- development of new catalysts, with higher tolerance towards poisoning, and improved control over product composition;
- development and test of motors, and distribution systems, for new fuel types.

## 7.7 Nuclear energy

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### *7.7.1 Market development*

Nuclear fission is a major source of energy that is free from $CO_2$ emissions. It provides 15% of the world's electricity and 7% of total primary energy consumption. Around 440 nuclear reactors are currently generating power in 31 countries, with largest capacity in Europe, the USA and southeast Asia. Non-electricity applications are few at present, but include process heat, hydrogen production, ship propulsion, and desalination.

High capital costs and low fuel prices mean that nuclear energy is used predominantly for base load electricity production. In Europe, for instance, nuclear accounts for 20% of generating capacity but provides 31% of all electricity generated. Only in a few countries such as France, where nuclear provides 78% of electricity, are some nuclear plants used for load following.

Most existing nuclear plants were built in the 1970s and 1980s. After 1990, nuclear power faced global stagnation. In the USA and in Europe the development of nuclear power halted, primarily because of the accidents at Three Mile Island in 1979 and Chernobyl in 1986, but also because of past poor economic performance, especially in the USA. Construction of nuclear power plants continued, however, in the far east, especially in Japan and South Korea.

Since 1990 global installed nuclear capacity has increased only slightly to its present figure of 370 $GW_e$. At the same time the economic performance of nuclear plants has continued to improve, mainly due to shorter outage times for fuel reloading and maintenance (Figure 34).

### *World projections*

Nuclear power has long been controversial, especially in Europe, with concerns over the safety of nuclear installations, radioactive waste, and proliferation of nuclear weapon materials. Globally, however, renewed interest in nuclear energy has been sparked by concerns for energy security, economic development, and commitment to reduce $CO_2$ emissions. Nuclear power is not vulnerable to even high fuel price fluctuations, and as it is based on uranium sources that are widely distributed around the globe, fuel supply is not strongly affected by geopolitical issues. In addition, because many years' worth of nuclear fuel can be stored in a small area, the presence of local uranium resources is not a pre-condition for nuclear energy security. In much of the industrialised world, nuclear is the only base-load option available today that combines low carbon emissions with the potential for large-scale expansion.

Ambitious plans for nuclear new build have been announced by China, India, and Russia, and many other countries are considering introducing nuclear power. 15 countries are currently building nuclear power stations, while about 25 more have plans for nuclear new build. In the USA, where no nuclear power plants have been ordered since the Three Mile Island accident, the Department of Energy (DOE) expects nuclear capacity in 2030 to have increased by 3 $GW_e$ through plant uprating and 10 $GW_e$ from new build [1]. The industry has announced plans for 30 potential new reactors in the USA.

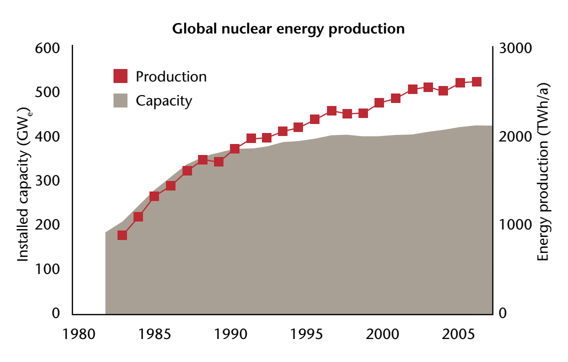
In its World Energy Outlook 2006 reference scenario, the IEA assumes that nuclear power production will have increased by 15% in 2030 [2]. This contrasts with earlier prognoses, in which nuclear was assumed to decrease after 2010. The IEA bases its new view on the assumption that more existing units will gain lifetime extensions, and that the need to reduce $CO_2$ emissions, concerns over security of supply and higher fossil fuel prices will all encourage nuclear.

Even more optimistic is the International Atomic Energy Agency (IAEA), which estimates that nuclear power will expand by 20-40% over the next 15 years [3]. The World Energy Technology Outlook 2050 (WETO-H2) study [4] assumes in its reference scenario that nuclear will increase strongly after 2020, with a four-fold capacity increase by 2050 that will allow nuclear to provide 25% of the world's electricity.

Key issues determining the prospects for a large expansion of nuclear energy are costs, safety, waste management, and proliferation risks; all must be resolved satisfactorily to ensure public acceptance [5]. Political risks – in energy policy changes, regulatory uncertainties, and financial risks in a liberalised energy market – will also affect the rate of nuclear expansion. A critical issue in many developing countries, but important everywhere, is the need for education and training to maintain competence in building and operating nuclear power plants.

In Europe, the short-term future of nuclear is uncertain and there is no common approach. Only Finland and France are currently building new nuclear power units. A

Figure 34: Installed nuclear capacity and annual energy production. Better plant utilisation means that production is growing faster than capacity.



number of mostly East European countries are considering expanding or introducing nuclear, while Germany, Belgium and Sweden have decided in principle to phase out nuclear. Great Britain is likely to decide in 2007 or 2008 whether to replace its aging fleet of second-generation nuclear reactors and coal-fired power plants with new nuclear or with other technologies. Denmark decided in 1985 not to build nuclear power stations.

In a recent Green Paper on energy development in Europe [6], the European Commission emphasised that the priorities are sustainability, security of supply, and competitiveness. Both nuclear and renewables are acknowledged as important energy resources, now and in the future. The EU's Action Plan to promote renewable energy and combat climate change sets a greenhouse gas emissions reduction target of 20% by 2020 [7]. Nuclear's role in cutting $CO_2$ emissions is acknowledged. The member states are free to choose their own energy mix, but it is not clear to what extent nuclear energy will affect individual member states' targets for $CO_2$ emissions reduction.

### *Cost trends*

Nuclear power is characterised by high construction costs and a relatively long construction period, typically of four to six years, but low operating and maintenance expenses, including fuel. The increased interest in nuclear power in many countries has led to an increase in the cost of natural uranium, but prices are likely to level down when new mines are commissioned and uranium exploration intensified. Capital costs excluding interest (overnight costs) are \$1,500-2,500/$kW_e$ [1, 5] for a first-of-a-kind unit. Costs for subsequent units of the same design are lower; a saving of 15-25% is the usual industry assumption.

The Finnish EPR (1.6 $GW_e$) unit now under construction has been estimated to cost €3 billion, or roughly \$2,000/$kW_e$ at the current exchange rate. Delays in construction and in detailed plant design, however, have brought about additional costs to the vendor (Areva). Operating costs have varied considerably in different countries, partly because poor performance sometimes has led to low availability. In recent years performance has generally improved, with availabilities of 80-90% becoming realistic. Such availability yields O&M costs including fuel of the order of \$15/MWh and an overall power cost of €28-45/MWh, making nuclear one of the cheapest options for carbon-free electricity generation [8]. A moderate carbon emission tax of \$10/t $CO_2$ would make nuclear competitive with electricity from fossil fuels.

The transition to a hydrogen economy may further increase demand for nuclear power as a $CO_2$-free primary energy source. In the WETO-H2 hydrogen energy scenario (which assumes important technological breakthroughs, especially in end-uses for hydrogen), hydrogen in 2050 is produced predominantly by the electrolysis of water, of which nuclear energy accounts for 40% [4].

Electrolysis of water is a modular technology that allows hydrogen production to be adjusted according to demand and electricity availability. The economics of the process are strongly influenced by the cost of electricity; costs of hydrogen have been estimated at €22-25 /GJ from nuclear and €30-50 /GJ from wind [4].

Hydrogen could also be produced on a large scale using heat from high-temperature nuclear reactors, through thermochemical reactions such as the sulphur-iodine cycle, which requires temperatures above 850°C. High-temperature reactors now being studied could allow the co-production of electricity and hydrogen.

### *7.7.2 Nuclear reactors*

Most nuclear power plants in the USA and Europe have second-generation light water reactors (LWRs), while the plants now being built in southeast Asia are of third-generation design. The Evolutionary Power Reactor (EPR) under construction in Finland by the Areva-Siemens consortium, and the Pebble Bed Modular Reactor (PBMR) reactor being developed in South Africa, are both of types referred to as Generation III+. From 2020-30 onwards, fourth-generation reactors are expected to provide improved fuel utilisation and economics.

### *Uprating and life extension*

Existing power stations have reactors with typical original design lifetimes of 25-40 years. Considering the age distribution of existing power reactors (Figure 35, see next page) this implies that substantial replacement capacity will be needed from around 2015.

Many countries have already introduced plant life management programmes aimed at increasing the capacity of nuclear plants, extending their operating lifetimes, or both. The condition for these measures is that the overall safety level is improved or at least maintained at the original level. For LWRs, power uprating as high as 20% [9] can be achieved through new fuel designs with higher enrichment allowing higher operating temperatures and hence greater thermal efficiency, and from improved steam turbines.

The USA has uprating projects totalling 4,000 $MW_e$ in progress or planned. Among the European countries, Finland has increased the capacity of its four units by 450 $MW_e$, and by 2011 Sweden will have increased the capacity of its ten units by 1,300 $MW_e$.

Periodic safety reviews have demonstrated that many plants can be operated safely and efficiently for longer than was foreseen when they were designed; lifetimes of 60 years are likely in many cases. There is a significant economic advantage in doing this, since by the end of the original design life most plants are fully amortised and it is much cheaper to extend the working life than to build a new plant. In the USA, about 40 units in the last five years have had their operating licenses extended from 40 to 60 years, and 20 more units have applied for life extensions.

*Generations III+ and IV*

The EPR and the PBMR mentioned above are both reactors of the general type known as Generation III+. The EPR is characterised by a simple system design with increased redundancy and physical separation of the safety systems. Safety features include double containment and a core catcher at the bottom of the reactor vessel. The EPR has high thermal efficiency due to its high secondary system pressure. Anticipated availability is also high, because shutdowns for planned maintenance are of short duration, and the reactor needs to be refuelled less frequently than older reactors of the same power rating. The design lifetime is 60 years.

The PBMR is a high-temperature, graphite-moderated, gas-cooled reactor. It has a high thermal efficiency due to the high operating temperature. The PBMR is characterised by a high level of safety due to the large heat capacity of the moderator. The flow of helium gas coolant is sustained by natural circulation if power to the circulation pumps is lost, so the potential for a destructive loss-of-coolant accident is low.

The first three generations of nuclear reactors do not represent fundamental technological shifts, but rather an evolution based on experience from previous designs. Fourth-generation reactors, on the other hand, have new and demanding performance goals. These include more efficient use of fuel, less waste, better economic performance, improved safety and reliability, enhanced proliferation resistance, and better physical protection. Meeting these ambitious goals requires that substantial efforts are devoted to research, technological development and demonstration of the novel concepts.

The key technologies for Generation IV are fast neutron reactors with a closed fuel cycle and high or very high operating temperatures. In 2000, the US DOE launched the Generation IV International Forum [10], with currently 12 participating countries plus EURATOM, to collaborate on new designs. The Forum is focusing on six designs:

- Sodium-cooled Fast Reactor (SFR)
- Gas-cooled Fast Reactor (GFR)
- Very High Temperature Reactor (VHTR)
- Supercritical Water-cooled Reactor (SWR)
- Lead-cooled Fast Reactor (LFR)
- Molten Salt Reactor (MSR)

Four of these are fast reactors, which allow for much improved utilisation of the uranium fuel. The sodium-cooled fast reactor is the most mature technology, and so may be deployed in the medium term. However, additional technology development is needed to further improve safety and to develop high-performance materials.

The gas-cooled fast reactor is an attractive alternative to sodium-cooled reactors because of its potential for higher-temperature applications and hydrogen production.

The very high temperature reactor, with temperatures above 950°C, is seen as a promising candidate for the production of hydrogen or synthetic fuels.

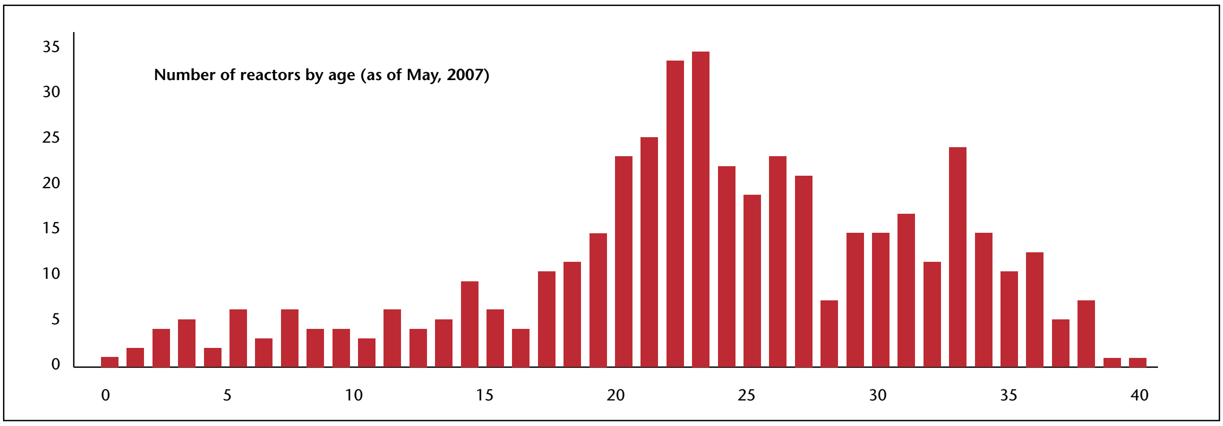
The supercritical water-cooled reactor design is a further development of the pressurised water reactor. Lead-cooled fast reactors are considered to be the most promising for proliferation-resistant nuclear power; Russia has some experience with small (100 MWe) reactors using lead alloys as the coolant. The molten salt reactor is probably the least mature design of the six, but is valued for its potential to operate with a thorium fuel cycle.

### 7.7.3 Fuel cycle

In the long term, the potential of nuclear power depends on how effectively the world's uranium resources are used. Today's thermal reactors with a "once-through" uranium fuel cycle use less than 1% of the energy in the fuel; most of this energy comes from the fissile isotope $^{235}$U, which makes up 0.7% of natural uranium.

Fast reactors – based on fast neutrons instead of thermal neutrons – operating with a closed fuel cycle may effectively utilize also $^{238}$U, which makes up 99.3% of natural uranium. In the closed fuel cycle plutonium produced in

Figure 35: Age distribution of current nuclear power reactors. With a typical design life of 25-40 years, most of the reactors now operating will need to be shut down or replaced soon unless their lives can be extended.



the fast reactor as well as unused uranium is recycled, so that uranium reserves are used much more efficiently.

Fuel can be conserved, and waste volumes reduced, by reprocessing spent fuel. When also minor actinides are effectively recycled the heat output of the remaining high-level waste is reduced considerably, allowing underground waste repositories to be made much smaller.

Through advanced separation of radionuclides after reprocessing, and subsequent transmutation, many of the radionuclides that present potential risk to humans can be removed. Transmutation of the separated radionuclides can be performed in two types of reactors: fast-spectrum critical reactors and accelerator-driven subcritical systems (ADS). Of the two, accelerator-driven transmutation is the less mature, and its economics are less certain. The main incentive for partitioning and transmutation, however, is to use fuel more efficiently.

The potentially most dangerous radionuclides in unprocessed spent fuel are also generally those least likely to escape from an underground repository. Whether a repository contains unprocessed spent fuel or high-level waste (HLW) from reprocessing therefore makes little difference to the radiological risk to the population [11].

*Uranium resources*

The length of time for which the world's uranium resources will last depends on the technology we use (Figure 36).

Identified uranium resources total 4.7 Mt, at prices up to \$130/kg. Used in typical LWRs this would provide about 2,400 EJ of primary energy, which would be enough for nearly 100 years at the 2004 rate of use [12].

Probable uranium reserves that have not yet been discovered increase the total to 14.8 Mt (7,400 EJ), which would cover a much longer period even if our use of nuclear power expands considerably. There are also "unconventional" uranium resources such as phosphate minerals. In these resources uranium is a by-product and is estimated to be recoverable for \$60-100/kg [13].

With fast reactors operating in a closed fuel cycle – reprocessing spent fuel to remove the plutonium produced – reserves of natural uranium would last for several thousand years at current consumption levels, and centuries at higher levels of use. This recycling option increases uranium resource efficiency by a factor of 30 [14], yielding about 220,000 EJ of primary energy reserves from conventional uranium resources. If breeder reactors were used to burn all actinides extracted from spent fuel, as well as recycled or depleted uranium, the uranium utilisation efficiency would further improve by a factor of eight [12].

Nuclear reactors can also be designed to run on thorium, of which the proven and probable resources are about 4.5 Mt [13]. The thorium fuel cycle is more proliferation-resistant than the uranium cycle, since it produces fissionable $^{233}$U instead of fissionable plutonium. In addition to $^{233}$U, the thorium cycle produces $^{232}$U as a by-product, which has a daughter nuclide emitting high-energy photons making the material difficult to handle. India has large reserves of thorium, but the commercial feasibility of the thorium cycle will remain uncertain until there has been more technical development. Norway does not have nuclear power but has large thorium reserves and is currently exploring the possibilities to exploit these resources.

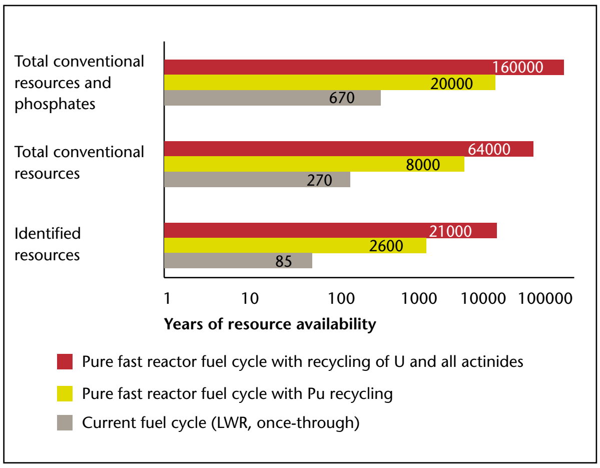


Figure 36: The number of years for which we have uranium resources depends on how we use it (2004 utilisation level) [12].

*Proliferation and global nuclear energy partnership*

The enrichment of uranium, spent fuel reprocessing, and separation of pure plutonium must be considered in the context of preventing proliferation of nuclear weapons. The Treaty on Non-Proliferation of Nuclear Weapons (NPT), which has been ratified by nearly 190 countries, operates a safeguard system to control fissile material that may be used in weapons. Compliance with the NPT is verified and monitored by the IAEA.

Improving proliferation resistance is a key objective in the development of next-generation reactors and advanced fuel cycles. A recent example of enhanced international efforts is the Global Nuclear Energy Partnership (GNEP) proposed by the USA [15].

In a once-through fuel cycle, stocks of plutonium build up in the spent fuel, but only become accessible when the fuel is reprocessed. Disposal of spent fuel without reprocessing therefore limits opportunities for proliferation.

Recycling through fast reactors, as we have seen above, increases considerably the utilisation efficiency of uranium, but also introduces opportunities for plutonium to be diverted to non-peaceful purposes. Reprocessing therefore needs careful safeguards.

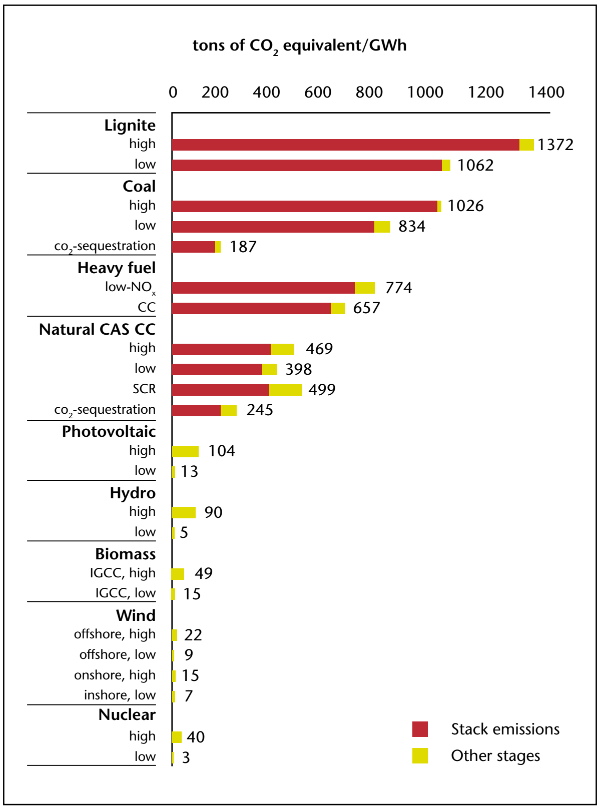
*Waste management and disposal*

The main objective of nuclear waste management is to protect human health and the environment, now and in the future, without imposing undue burdens on future generations.

Several countries have underground repositories for low- and medium-level radioactive wastes, but as yet there are no repositories for HLW such as spent LWR fuel. Deep geological repositories are the most extensively studied option, but neither the technical nor the political and societal issues have been fully resolved. The technical feasibility and the long-term post-closure safety have been extensively studied for different geological host media under generic conditions. The studies show that safety targets set for geological disposal can be met, while site specific safety assessments are still needed.

In 2001, the Finnish Parliament agreed to site a spent fuel repository near the Olkiluoto nuclear power plant. After detailed rock characterisation studies, construction is scheduled to start around 2013, with commissioning planned for 2020. Sweden is currently comparing several repository sites close to the Oskarshamn and Forsmark nuclear power plants. In the USA, the Yucca Mountain area has been chosen as the preferred site for a high-level waste repository. Extensive site characterisation and design studies are underway, although not without significant opposition, and Yucca Mountain is not expected to begin accepting HLW before 2017. France also sees deep geological disposal as the reference solution for long-lived HLW, and has set 2015 as the target date for licensing a repository to be opened in 2025. France further examines the possibility of transmutation of the long-lived actinides to reduce volume, heat load, and toxicity of the HLW.

Figure 37: Lifecycle greenhouse gas (GHG) emissions from various energy sources [17].



Fuel reprocessing does not eliminate the need to dispose of HLW, but it can reduce the amount of heat produced by the waste and shorten the length of time for which it remains potentially dangerous. A repository for HLW from reprocessing might therefore be designed to less stringent standards than a repository for unprocessed spent fuel.

*GHG emissions*

Total lifecycle GHG emissions from nuclear power are below 40 g $CO_{2eq}$/kWh, which is similar to those from renewable energy sources (Figure 37). According to one study, even low-grade ore deposits (0.03-0.06% uranium content) need only small amounts of energy for extraction and leaching of the uranium ore and $CO_2$ emissions from mining are only about 1 g $CO_2$/kWh generated [16].

The variation in GHG estimates stems mainly from the choice of uranium enrichment technology and the origin of the power needed for enrichment. Gas diffusion technology consumes much more energy than the alternative technology of centrifuging.

### *7.7.4 Conclusions*

Nuclear power does not form part of the Danish energy mix and at present there seems to be little political will to change this position. As a result, Denmark has relatively little expertise in nuclear power, and no university courses for nuclear engineers. Because accidental releases of radioactive material do not respect national boundaries, Denmark maintains limited preparations for a nuclear emergency besides monitoring for anthropogenic radioactivity in the environment.

Since nuclear power provides a substantial share of Europe's electricity, however, Denmark should ensure that it has the expertise to advise the government and the public on nuclear issues. In the long term this means running courses in nuclear technology, though the lack of prospects for nuclear power in Denmark will make it difficult to attract students.

Should Denmark in the future decide to introduce nuclear power, the country would face challenges across government, regulatory authorities, industry, research and education. While many of these challenges might be solved by acquiring expertise from countries with nuclear power, Denmark would need a new regulatory system to address the licensing and operation of nuclear power stations, as well as waste management.

### *7.7.5 Recommendations*

Denmark should maintain a nuclear expertise to advice the government and the public on nuclear issues, and to ensure an adequate nuclear emergency preparedness system.

Facing challenges of energy security and the commitment to reduce GHG emissions nuclear power might be reconsidered as an option for Danish energy planning.

7.8

## 7.8 Fusion energy

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### *7.8.1 Introduction*

The immense amount of energy radiated from the sun and other stars is created in the interior of these stars. At the high pressures and temperatures in the centre of the sun, fusion processes turn hydrogen into helium, simultaneously releasing huge amounts of energy. Although the solar fusion reactions depend on the sun's huge gravitational pressure, quite similar fusion processes can be used to produce energy on earth.

Of the terrestrial fusion processes, the most accessible is the fusion of two heavier isotopes of hydrogen: deuterium and tritium. A fusion reactor would "burn" these isotopes at moderate pressure and at a temperature of 150 million Kelvin – a very high temperature indeed, but one that is easily achieved in modern fusion experiments. The real challenge lies not in achieving the high temperature, but in sustaining this temperature efficiently. Only then can a fusion reactor produce more power than it consumes.

For the last 50 years many countries have had fusion research programmes. Scientists realised early on that building a reliable fusion power plant would be extremely challenging. On the plus side, however, the prospect of fusion power is very attractive. Fusion offers a safe, clean, zero-$CO_2$ energy source, burning fuel that is abundantly available everywhere.

### *7.8.2 Fusion power plants*

Like any other thermal power plant, a fusion power plant is based around a heating unit which turns water into steam. The steam drives turbines, which produce the mechanical power to turn the generators that create electricity.

The fusion reactor itself is inherently safe. The primary fuels, deuterium and lithium, are not radioactive. At any time, the reactor contains only enough fuel to feed the fusion processes for the next few seconds, and any irregularities would cause the fusion processes to stop immediately.

Most of the energy from the fusion processes is released in the form of fast neutrons. Around the fusion chamber itself is a blanket of material that absorbs the neutrons, converting their energy into heat that is carried away by circulating cooling liquid.

Some of these neutrons, however, will create radioactive isotopes in the reactor wall. To minimise disposal problems, materials for fusion reactors therefore need to be chosen so that the isotopes created have short half-lives. With the right materials, it is estimated that after about a hundred years the waste will be less radiotoxic than the ash from a coal-fired power plant of the same size. After storage for 50-100 years, the material could be reused in new power plants, and there is no long-lived radioactive waste.

The main cost of fusion energy will be in constructing the power plant, while the cost of fuel is negligible. Fusion power will therefore be most economical when run as base load, though it can easily contribute to a sustainable energy mix. Fusion plants will also be safe enough to be built in or near large cities, making it easy to use the surplus heat for space or process heating. Several detailed studies have concluded that the cost of electricity from fusion is likely to be comparable with that from other environmentally-responsible sources [1].

The fusion fuel, deuterium, can be extracted from water: 1 $m^3$ of water contains approximately 35 g of deuterium. The extraction process is cheap compared to the amount of energy the deuterium can provide.

The other necessary material, tritium, can be produced at the fusion power plant by bombarding lithium with neutrons from the fusion process. Lithium is a light metal that is common in the earth's crust and also occurs at low concentrations in seawater. Compared to the large amounts of energy released from the fusion processes, the cost of the fusion fuels will be negligible, and only small amounts are necessary. Denmark's total energy consumption for a year would require only a few tonnes of deuterium and lithium. Existing resources of lithium would be able to power the world for a million years, and deuterium reserves would last for 50 billion years.

At the burn temperature of 150 million K, the fuel is in the form of a plasma: the atoms are ionised and separate into free electrons and ions. In the reactor, strong magnetic fields are used to shape and confine the plasma. The magnetic field also reduces the thermal conductivity of the plasma by some 12 orders of magnitude, turning it into a better thermal insulator than Styrofoam and thus greatly reducing the power needed to sustain the high operating temperature. This amazing effect of the magnetic field will eventually enable net power generation in a fusion reactor.

Confining the plasma in a toroidal magnetic field is an old idea that still shows great promise, especially in the reactor design known as the tokamak, which has been developed quite successfully over the last 35 years. Current pilot plants include the world-leading Joint European Torus (JET), sited near Oxford, UK, which came into operation in 1983, as well as other experiments around the world. These tests have demonstrated the stable confinement of fusion plasmas at temperatures up to 400 million K, which is well above the optimum temperature for a fusion power plant. To achieve net power production, the reactor needs to be doubled in size (in linear dimension) compared to JET. This step is now being carried out

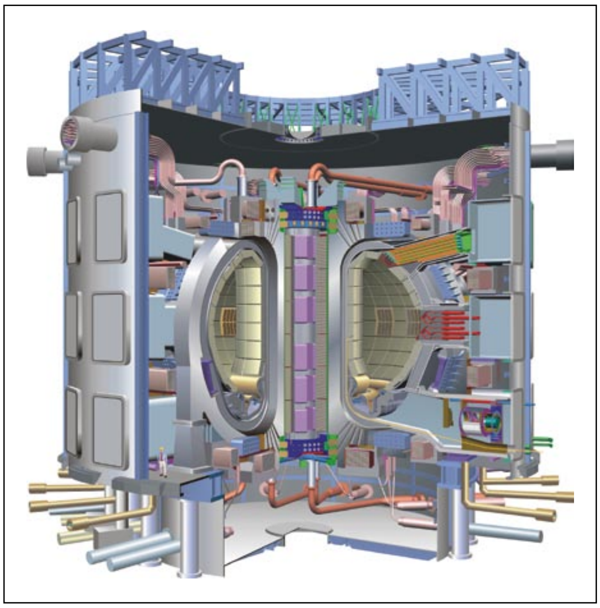


Figure 38: The ITER reactor.

through the ITER multi-partner fusion experiment. ITER means "The way" in Latin. Formerly interpreted to stand for International Thermonuclear Experimental Reactor, but this usage has been discontinued.

### 7.8.3 *ITER: ten times power multiplication*

Based on the success of tokamak experiments during the 1970s and 1980s, it was decided in 1985 – during a summit meeting between Mikhail Gorbachev and Ronald Reagan – to design and build a new, large tokamak fusion reactor, in an international collaboration involving the USA, Russia, Europe and Japan.

After years of design work, followed by several years of negotiations over where to site it, the ITER project was formally launched. In the meantime, the partnership in this international research collaboration has grown to an unprecedented level. The current partners – Europe, Japan, USA, Russia, China, South Korea and India – represent more than half the world's population.

ITER is designed to generate 500 MW of fusion power, ten times the power needed to sustain the high temperature in the reactor, for periods of up to 1,000 s (16 minutes). A future fusion power plant will be designed to generate 50-100 times the power used for heating, having a total fusion power about 6-8 times that of ITER. According to the present plan, ITER will start operating in 2017 with the goal of "demonstrating the scientific and technological feasibility of fusion power for peaceful purposes". As a research and development device, ITER is not equipped with generators to produce electricity. The ITER website gives more technical information [2].

Fusion releases the energy captured by the strong forces that keep nuclei together. Since this binding energy is typically a million times larger than that in the chemical bonds on which combustion processes rely, fusion is a very compact power source. The size of ITER can be estimated from Figure 38. Although large, the ITER reactor would fit comfortably inside the combustion chamber of a coal-fired power plant.

### 7.8.4 *European strategy for fusion energy*

In Europe, research for fusion energy is coordinated by EURATOM in collaboration with the Fusion Associates established in most European countries. A series of studies within the European fusion programme have examined the safety and environmental aspects as well as economic potential of fusion power, and have given input and support to European long-term planning.

The next step after ITER is likely to be a demonstration fusion power plant called DEMO. Europe has recently taken the first steps towards defining the strategy for such a demonstration power plant. DEMO will be the first experimental fusion power plant to deliver electricity to the grid. To make use of the results from ITER, the construction of DEMO will probably not start until some years after ITER starts operating, that is probably not before 2025.

At present, the expectation is that if ITER is successful, several DEMOs will be built simultaneously. Apart from Europe, the USA, Japan, China and India have all assigned an important role to fusion in their energy strategies. "China wants to be among the first countries to generate electricity from fusion," stated the Chinese government when it joined ITER. The USA says: "The President has made achieving commercial fusion power the highest long-term energy priority for our nation." But it is important to note that Europe is leading the dance in the field of fusion, both scientifically and technologically.

The strategies of all these countries plan to deliver the first fusion electricity to the grid around 2035, and the first generation of commercial fusion power plants may be in operation around 2045.

Figure 39 shows a possible scenario for the development of fusion power; this plan could be accelerated if adequate funds were available. Fusion may therefore be ready to make a large contribution to world energy production in the second half of this century, at a time when oil and gas reserves are likely to be running out and climate change and other environmental problems are reaching their full enormity.

To make progress as planned, in parallel to ITER it is necessary to carry out a strong programme of development, testing and qualification of materials for the DEMO reactor. This requires a test facility in which materials of construction can be subjected to high fluxes of "fusion" neutrons (neutrons with an energy of 14 MeV). As a result of the ITER negotiations, Europe and Japan reached an agreement on a strategy known as the "Broader Approach" (BA). This includes the design, followed in due course by construction and operation, of such an experimental materials centre: the International Fusion Materials Irradiation Facility (IFMIF).

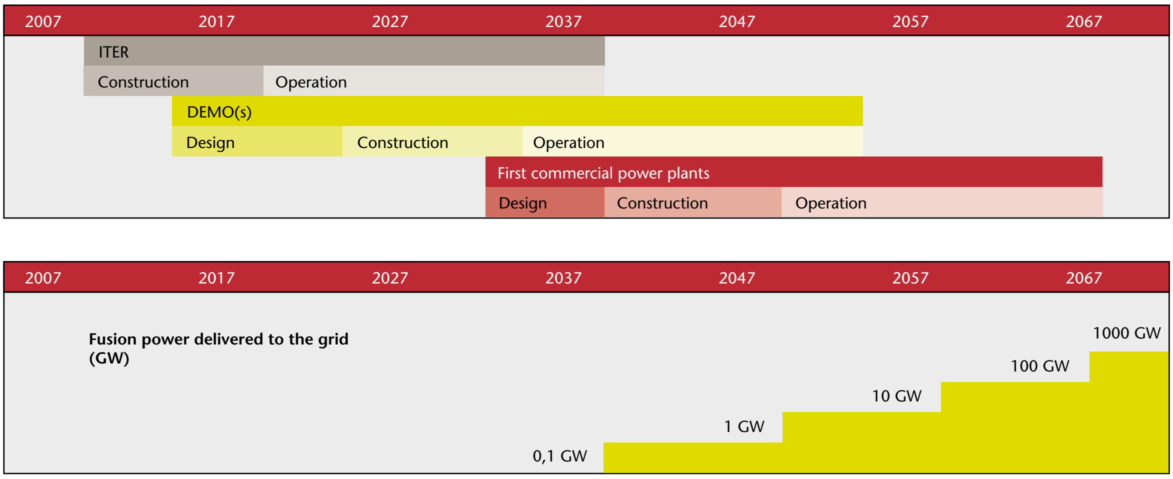


Figure 39: A possible scenario for the development of fusion power.

A conceptual power plant study (PPCS) was recently carried out in Europe by a group of fusion experts, together with a large number of experts from industry. The study considers reactors with a power of 1,500 $MW_e$, and evaluates the cost efficiency and other aspects of fusion energy. Earlier there was a common perception that future fusion plants would be gigantic in scale. More recent investigations like that of the PPCS have shown that 1,500 MWe is a realistic size for a fusion plant.

### *7.8.5 European and Danish strengths*

Over the last five decades, most developed countries have put significant effort into fusion energy research. Thanks to a focused research programme coordinated by EURATOM, Europe is a world leader in the field, but Japan and the USA also have significant fusion experiments, and China, India and South Korea are rapidly closing the gap.

The world's largest fusion experiment at the moment is the Joint European Torus (JET) in Oxford, UK. Thanks to experience with JET and its extensive and coordinated fusion research programme, Europe is the ideal host for ITER, In this role Europe will contribute approximately 45% of the €4 billion construction costs. The bulk of this budget will be tendered among European industry, which in some cases has been involved in fusion technology development for decades.

As a part of the European fusion research programme, Denmark makes significant contributions to the field. Two areas in particular stand out: modelling and prediction of turbulence and transport in fusion plasmas, and the unique technique of collective Thomson scattering (CTS) for measuring fast ions in the plasma.

### *7.8.6 Challenges*

Before the first commercial fusion power plant can be built, a number of physical and technological problems relating to plasma have to be solved, and some existing solutions need to be refined.

Among these are understanding the behaviour of plasma when a large number of alpha particles is present; the control of erosion where the hot plasma touches the wall of the combustion chamber; the development of materials for the inner wall capable of withstanding the neutron flux; development of tritium breeding blankets and tritium recovering systems; and technology for large superconducting coils, if possible based on high-temperature superconductors. These challenges will be addressed in both ITER and DEMO.

ITER will be the first experiment to use a plasma containing a large number of high-energy alpha particles from the fusion processes. These energetic particles may cause new instabilities in the plasma, possibly increasing the energy loss rate. Many plasma instabilities have already been investigated experimentally and theoretically, and in the present tokamak experiments the plasma can be controlled and maintained extremely well. However, these known instabilities limit the maximum plasma pressure relative to the magnetic field pressure. Other instabilities give rise to turbulence in the plasma which increases the energy loss from the plasma to the walls. Since the magnet coils are very expensive to build and operate, a good understanding of plasma instabilities and turbulent transport is extremely important in order to make fusion power plants as economical as possible.

The inner wall facing the plasma, called the first wall, is a technological challenge. ITER expects to use a first wall consisting of blanket modules of stainless steel covered by a layer of copper and a layer of beryllium. For DEMO, however, a tungsten-coated stainless steel wall is under consideration. The IFMIF facility mentioned earlier is necessary so that these materials can be studied. Properties to be measured will include the degradation of materials due to the neutron flux from the plasma.

Whether fusion power will be able to contribute significantly to our energy supply in the long term depends not only on finding satisfying solutions to the technical challenges mentioned above, but also on how economic it proves to be, and whether it will be accepted by society. The goal of the ongoing worldwide development programme is to demonstrate the technical and economical feasibility of fusion, so that our children will have the choice when they need it.

### *7.8.7 Spin-offs and opportunities for industry*

Developing a practical fusion power plant will require a broad range of technologies, many of which will have potential applications in other fields. These include large, high-field superconducting magnets, particle accelerators, a wide range of measuring techniques, advanced remote handling, special materials and more. Fusion research has already created spin-offs: a laser-based plasma diagnostic device used by Risø, for example, inspired a new technique to measure small-scale turbulence in the design of wind turbine blades. Similar spin-offs from fusion research will doubtless occur in the future.

The construction of ITER will demand significant contributions from industry. Many of the tasks will be large and complex, requiring companies to operate as consortia rather than alone. This collaboration, plus the high-tech nature of the work, should strengthen the general competence of the firms involved and the competitiveness of the countries they represent.

### *7.8.8 Recommendations for Denmark*

Fusion energy has great potential as a safe, clean, $CO_2$-free energy source, with fuel that is abundantly available everywhere.

Through their engagement with the international ITER project, Europe, Japan, the USA, Russia, China, South Korea and India have all shown that they are willing to make significant investments in developing this long-term energy source. Europe has taken the lead, mainly thanks to its strong research coordination and support from EURATOM, but also with considerable national support from several countries.

Risø DTU is the only place in Denmark where this research is taking place. The team at Risø is small, but by concentrating their efforts in a few areas its members are making their presence felt at European and international scale. Besides this scientific and technological contribution Risø also participates in the European coordination of ITER, with representatives in several of the decision-making bodies.

In 2005 Risø began a project to inform Danish companies about ITER and inspire them with the possibilities of becoming suppliers to the project. A strong Danish presence in the fusion research programme is likely to bring benefits through technology transfer, thanks to the highly advanced and international nature of ITER. Participation could also help Danish industry to win large orders for ITER and the following generation of fusion power plants.

A national strategy for Danish fusion energy research, and increased national funding, would strengthen these benefits and make it possible to include other scientific fields in the European fusion programme. Examples of these are superconductors, high-temperature materials, robotics and system analysis, where Danish scientists have special expertise. This expansion of the scientific contribution is particularly relevant after the merger of Risø and the Technical University of Denmark, although groups from other universities could also be included. And since EURATOM's funding mechanism is based on national co-financing, increased national support will attract larger EURATOM funding.

## 7.9 Geothermal energy

JØRGEN FENHANN AND HANS LARSEN, RISØ DTU; IDA LYKKE FABRICIUS, E&R, TECHNICAL UNIVERSITY OF DENMARK

The interior of the earth contains high temperatures and huge quantities of heat. Some of this geothermal energy probably dates back to the formation of the earth, but the rest is continuously created by the nuclear decay of natural radioactive isotopes ($^{238}$U, $^{235}$U, $^{232}$Th and $^{40}$K). This means that on a timescale of a million years geothermal energy is renewable, though in some situations it is possible to temporarily exhaust the energy available to a given geothermal plant. At least 76 countries use geothermal heating, and 24 countries produce electricity from geothermal energy.

### *7.9.1 Geothermal power*

As heat from the interior of the earth escapes through the continental crust, it creates an average temperature gradient of 20-30°C per kilometre, depending on the thermal conductivity of the rocks and sediments at any particular point. In some areas of the world, heat is transported to the surface by convection of hot or even molten rocks. This heat transport mechanism is much more effective than heat conduction, so in these localities high temperatures may be found at shallow depths.

In Europe, high temperatures occur at shallow depths in Italy, Turkey, Iceland, and oceanic islands including the Azores. Installed geothermal generating capacity in the EU has grown from 370 $\mathrm{MW_e}$ in 1970 to 893 $\mathrm{MW_e}$ in 2005, mostly in Italy and Iceland (Table 19). Portugal plans to double its existing 10 $\mathrm{MW_e}$, which is located in the Azores.

Western Italy has a long belt of land extending from Tuscany down to Campania, near Naples, in which temperatures often exceeding 200°C can be found close to the surface. All three Italian geothermal power plants are located in this region, which is also home to Europe's first geothermal power plant, installed at the Larderello field in 1904. The Larderello hot springs have been known for thousands of years, and were used by the Etruscans for bathing. Geothermal capacity in Italy is expected to increase by 100 $\mathrm{MW_e}$ by 2010 [1].

Table 19: Installed geothermal capacity in Europe [3].

| MW | 1970 | 2000 | 2005 |
|---|---|---|---|
| Italy | 368 | 590 | 665 |
| Portugal | 0 | 10 | 10 |
| Iceland | 2 | 170 | 203 |
| Turkey | 0 | 15 | 15 |
| Europe | 370 | 785 | 893 |

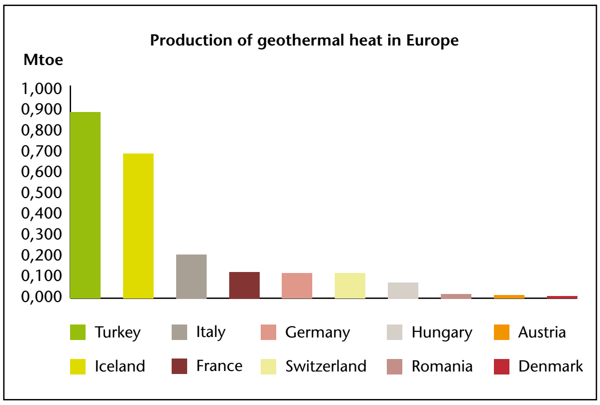


Figure 40: Geothermal energy for heating in Europe, 2005.

The 203 MWe of installed geothermal power in Iceland produced 1,658 GWh in 2005, or 19% of the country's electricity production. An additional 210 $\mathrm{MW_e}$ was installed in 2006, and a further 200 $\mathrm{MW_e}$ is under construction [2].

In its Alternative Policy Scenario, the International Energy Agency (IEA) assumes an installed capacity of 3,000 $\mathrm{MW_e}$ in OECD Europe by 2030 [4]. Up to 6,000 $\mathrm{MW_e}$ is possible according to the president of the European Geothermal Energy Council, speaking at the European Renewable Energy Policy Conference in January 2007.

### *7.9.2 Geothermal heating*

In areas where heat flow from the earth's interior is controlled by diffusion, so that near-surface temperatures are relatively low, geothermal energy may still have good potential. When heat pumps are used, small temperature gradients can be transformed into useful energy. As an example, geothermal plants in the city of Lund, southern Sweden, extract heat from water at 21°C pumped from boreholes 800 m deep. At present, the geothermal plants supply 40% of the district heating demand in Lund [5].

The main requirement for geothermal energy is thus not high temperatures but rocks that allow the flow of water, which in turn carries heat. The water may flow through fractures in the rock, or through porous sediments. Deep wells may reach really hot water (125°C at a depth of 4 km), but sediment porosity tends to decrease with depth, so both temperature and permeability must be taken into account. In Denmark, porous sediments with potential for geothermal energy are widespread, but up to now only two geothermal plants have been built: one in Thisted and one in Copenhagen [6].

European production of geothermal energy for heating has increased from 0.3 Mtoe in 1970, through 1.9 Mtoe in 2000, to 2.3 Mtoe in 2005. Most geothermal heat is produced in Turkey and Iceland (Figure 40). The renewable heating action plan for Europe [7] drawn up by the European Renewable Energy Council sets targets of 4 Mtoe in 2010 and 8 Mtoe in 2020.

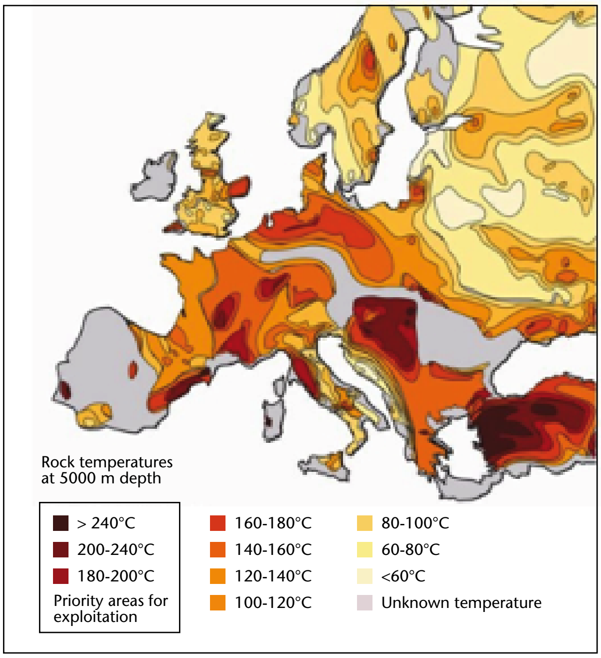


Figure 41: Hot dry rock temperatures at a depth of 5,000 m in Europe [9].

Geothermal energy today is used for district heating as well as for individual buildings, offices, greenhouses and factories. The German parliament building in Berlin and the Rijksmuseum in Amsterdam are both heated by geothermal energy.

Geothermal energy is increasingly used to heat and cool buildings, to the point that nearly two million heat pumps have now been installed in over 30 countries [2]. The first plant in Denmark opened in 1984 in Thisted. The second, which opened in 2005 at Margretheholm, supplies 1% of the total heat demand in Copenhagen [8]. The energy is derived from porous sandstone beneath Copenhagen, which could potentially supply 20% of the city's energy demand for a period of 450-600 years. Several other Danish cities have access to useful amounts of geothermal heat, and a third project is planned for Sønderborg, where it will cover a third of the district heating demand [6].

### *7.9.3 Future perspectives*

Today the technology to extract heat from underground aquifers is well known, but the energy available at shallow or moderate depths is limited, However, a huge energy resource exists at greater depths (Figure 41). At a depth of 5,000 m, Europe has an estimated 125,000 km$^2$ of rocks with temperatures of around 200°C.

The European Hot Dry Rock project within the 6th Framework Programme brings together partners from France, Germany, Italy and Switzerland. This 6 MW demonstration project uses widened natural fracture systems to inject water at high pressure; after heating, the water returns to the earth's surface via several production wells. Europe is currently the leader in this technology. The plant is being built at Soultz-sous-Forêt, France, [9]. Figure 41 shows that high-temperature geothermal energy is also available in Denmark.

A comprehensive assessment of enhanced geothermal systems was carried out at Massachusetts Institute of Technology (MIT) to evaluate the potential of geothermal energy in the USA. The USA has enormous geothermal potential, but has largely ignored this until now. The study concluded that with a reasonable investment in R&D, enhanced geothermal systems in the USA could provide 100 GWe or more of cost-competitive generating capacity, similar to the country's present nuclear capacity, within the next 50 years.

### *7.9.4 Conclusions*

Denmark has huge potential for geothermal energy, and high oil prices have encouraged an increasing number of cities to embark on geothermal projects. It is difficult, however, to predict the share of geothermal energy in the future Danish energy system.

### *7.9.5 Recommendations*

Growth in the use of geothermal energy in Denmark will be influenced by support for RD&D projects and changes in oil and gas prices. Danish manufacturers and consulting firms could benefit from domestic experience as a basis for geothermal projects abroad.

7.10

## 7.10 Hydro, ocean, wave and tidal

JØRGEN FENHANN AND HANS LARSEN, RISØ DTU

### *7.10.1 Hydro*

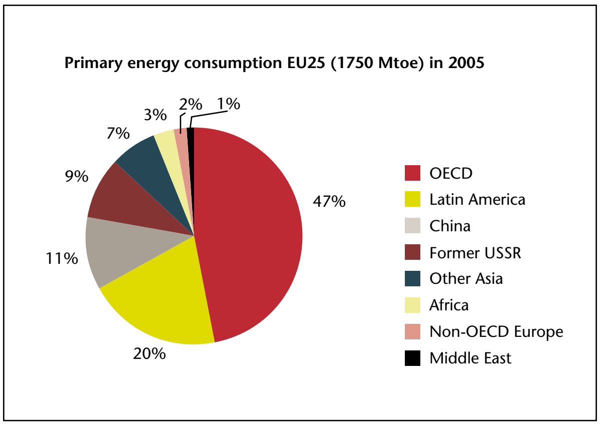
OECD and non-OECD countries currently produce roughly equal amounts of hydroelectricity (Figure 42). Little growth is expected in OECD countries, where most hydro potential has already been realised: on average, capacity has increased by just 0.5% annually since 1990. The OECD nations produced 1,343 TWh of hydroelectricity in 2003, the largest contributors being Canada (338 TWh), the USA (306 TWh) and Norway (106 TWh). Hydropower has little potential in the low-lying terrain of Denmark.

Large hydro remains one of the lowest-cost generating technologies, although environmental constraints, resettlement impacts and the limited availability of sites have restricted further growth in many countries. Large hydro supplied 16% of global electricity in 2004, down from 19% a decade ago. Large hydro capacity totalled about 720 GW worldwide in 2004 and has grown historically at slightly more than 2% annually. China installed nearly 8 GW of large hydro in 2004, taking the country to number one in terms of installed capacity (74 GW) [1]. With the completion of the Three Gorges Dam, China will add some 18.2 GW of hydro capacity in 2009 [2].

The socio-economic benefits of hydro include improved flood control and water supply. The socio-economic cost of hydro includes displacements and submergence. Further hydro can improve peak-capacity management.

Small hydropower has developed for more than a century, and total installed capacity worldwide is now 61 GW. More than half of this is in China, where an ongoing boom in small hydro construction added nearly 4 GW of capacity in 2004. Other countries with active efforts include Australia, Canada, Nepal and New Zealand.

Figure 42: Regional share of hydroelectricity production in 2003 [2].



### *7.10.2 Current power*

Ocean currents, some of which run close to European coasts, carry a lot of kinetic energy. Part of this energy can be captured by submarine “windmills” and converted into electricity. These are more compact than the wind turbines used on land, simply because water is much denser than air.

The physical characteristics of sea currents are well known. The available power is about 1.2 kW/m$^2$ for a current speed of 2 m/s, and 4 kW/m$^2$ for a current of 3 m/s [2]. Potential sites for exploiting current power are those where the current speed is faster than 1.75 m/s. The main European countries with useful current power potential are France and the UK.

### *7.10.3 Tidal power*

Ocean tides are driven by the gravitational pull of the moon. With one high tide every 12 hours, a tidal power plant can operate for only four or five hours per cycle, so power from a single plant is intermittent. A suitably-designed tidal plant can, however, operate as a pumped storage system, using electricity during periods of low demand to store energy that can be recovered later.

The only large, modern example of a tidal power plant is the 240 MW La Rance plant, built in France in the 1960s, which represents 91% of world tidal power capacity. An 18 MW tidal barrage was commissioned in 1984 at Annapolis Royal in Nova Scotia, Canada, and two systems of about 0.5 MW each have been built in Russia and China. Numerous studies have been completed for potentially promising locations with unusually high tidal ranges, such as the 8.6 GW scheme for the Severn estuary in the UK, but no decision has been made to build these [1].

### *7.10.4 Wave power*

Wave energy can be seen as stored wind energy, and could therefore form an interesting partnership with wind energy. Waves normally persist for six to eight hours after the wind drops, potentially allowing wave power to smooth out some of the variability inherent in wind power.

Wave power could in the long term make an important contribution to the world’s energy demand, if it can be developed to the point where it is technically and economically feasible. A potential 2,000 TWh/year, or 10% of global electricity consumption, has been estimated, with predicted electricity costs of €0.08/kWh [1]. Wave power is an energy source with a low visual and acoustic impact.

Oceanic waves – those found far offshore – offer enormous levels of energy; power levels vary from well over 60 kW per metre of wave front in the North Atlantic to around 20 kW/m at the foreshore [1]. A study of the area available for wave power along the coast of Portugal showed that a total length of 335 km could be used

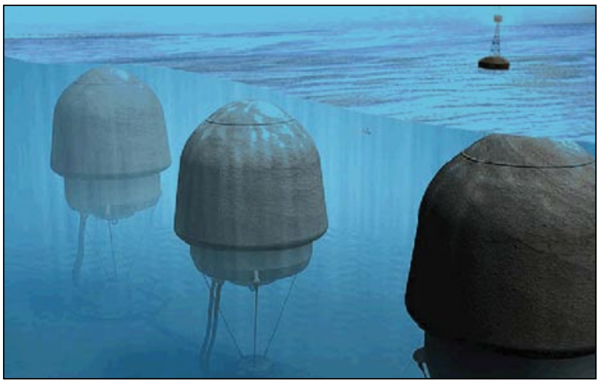


Figure 43a: Artist's impression of the AWS Ocean Energy plant.

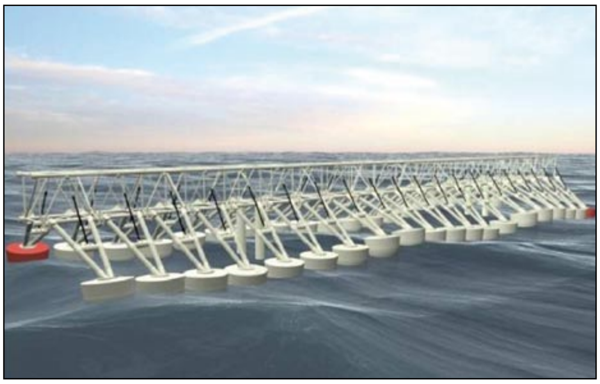


Figure 43b: The Wave Star generator is now being tested in Denmark as a 1:10 scale model. The full-size version will generate 6 MW.

without causing problems for fisheries, navigation, environmental protection or military zones [3].

Wave power is being investigated in a number of countries, particularly Japan, the USA, Canada, Russia, India, China, Portugal, Norway, Sweden, Denmark and the UK. At present, the front runners are Portugal and the UK.

In contrast to other renewable energy sources, the number of concepts for harvesting wave energy is very large. More than 1,000 wave energy conversion techniques have been patented worldwide, though they can be classified into just a few basic types: oscillating water columns (OWCs), overtopping devices, heaving devices, pitching devices, and surging devices.

The 400 kW OWC plant on the island of Pico in the Azores was constructed in 1999, and recently refurbished by the new Wave Energy Centre in Portugal [4]. Based on a device known as the Pico, this "wave energy breaker" project is now being developed commercially. The device will be integrated into a caisson breakwater head now under construction on the Douro estuary in Oporto, Portugal.

A 2 MW prototype of the *Archimedes Wave Swing* (AWS) heaving device was tested for seven months off the coast of Portugal in 2005. The AWS Ocean Energy company [5] is now developing a new model (AWS II). A 1.2 MW pre-commercial demonstrator will be installed in 2008 (Figure 43a).

The world's first commercial wave farm project is being led by a Scottish firm, Ocean Power Delivery [6], and installed during 2006 off the coast of northern Portugal. It consist of three 750 kW *Pelamis wave energy converters*, each 120 m long and 3.5 m in diameter, developed by OPD. This 2.25 MW scheme is the first stage of a planned 24 MW plant. It was located in Portugal because the Portuguese government has established a feeder market that pays a premium price for electricity generated from waves compared to more mature technologies such as wind power [7]. A full-scale prototype has been tested at the European Marine Centre (EMEC) in the Orkney Islands, Scotland. As well as the wave test facility, which started in 2003, a tidal test facility is now being built in Orkney.

The *Wave Dragon* is a wave power device developed in Denmark. It has been tested at the Danish test site at Nissum Bredning since 2003 as a 1:4.5-scale prototype. The first full-scale version (4-7 MW) is expected to be built in Wales in 2007 as the first part of a planned 77 MW plant.

A 24 m-long 1:10 scale model of another wave generator, the Wave Star, was installed in April 2007, also at Nissum Bredning (Figure 43b). The active parts of this device can be lifted out of the water to provide protection from storms, thus reducing the construction costs. A 120 m-long half-scale unit will be tested during 2008-2009 in protected water, and then in 2009-2010 inside a Danish offshore wind farm, where it can take advantage of the existing cable for power export. The full-size model will be 240 m long and will generate 6 MW [8].

### *7.10.5 Conclusions*

Denmark has been active in developing wave power technology such as the Wave Dragon and Wave Star. These demonstration projects are excellent starting points for the further development of this promising technology.

### *7.10.6 Recommendations*

To give Danish industry a chance to lead the development of competitive wave technologies, a public-private partnership is needed. Danish manufacturers and consulting firms should also have ample opportunities to contribute to offshore wave power projects around the world.

# 8

# Innovation indicators and future options

PER DANNEMAND ANDERSEN, RISØ DTU

## 8.1 Introduction

A number of internationally-recognised organisations have constructed scenarios to help examine the future of new and emerging energy technologies.

The best-known source for future trends in energy is the annual World Energy Outlook (WEO) from the International Energy Agency (IEA), which is part of the OECD [1]. The WEO is based on medium- and long-term energy projections using a World Energy Model (WEM).

The 2004 European Commission report *European Energy and Transport: Scenarios on Key Drivers* developed five scenarios: baseline; high oil and gas prices; low gas availability for Europe; de-linking of oil and gas prices; and soaring oil and gas markets [2]. In contrast to the IEA's WEO, this report was produced not in-house by the Commission but by a consortium led by energy experts from the Technical University of Athens. These experts have developed a global sectoral model of the world energy system known as POLES.

A third authoritative source is the Annual Energy Outlook (AEO) series drawn up each year by the US Energy Information Administration (EIA) [3]. The AEO includes forecasts of energy supply, demand and prices through to 2030. These projections are based on the EIA's National Energy Modelling System (NEMS).

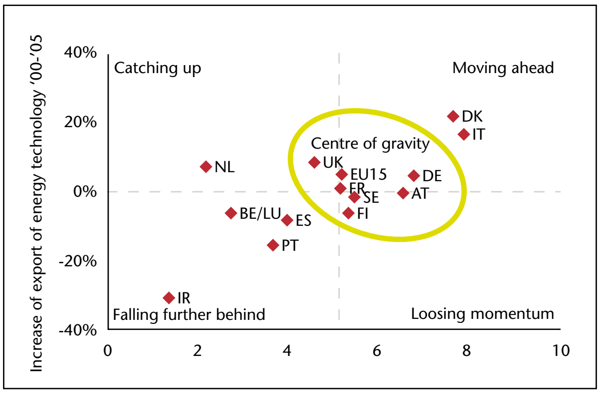
In all three of these scenario-based projections, the expected performance of new energy technologies is an input to the model, not an output. It is therefore necessary to use independent methods to predict how these technologies will develop. Often this is done by canvassing the opinions of experts in energy science and technology; a drawback to this approach is that experts often are unrealistically optimistic about their own areas of work.

In this chapter we will further analyse the potential of a range of technologies to contribute to these challenges in a Danish as well as a European context.

Based on the analyses presented in previous chapters, for each technology we will give an overview of:

- indicators from the innovation system (science, technology and markets);
- expectations for future development; and
- timescales for these expectations.

Figure 44: EU countries' exports of energy technology as a percentage of total exports in 2005, and the relative change (as a percentage of energy technology exports) from 2000 to 2005 [6].



## 8.2 Innovation system indicators

Industrial innovation, competitiveness, new jobs and exports are high on the political agenda in Europe and in other parts of the world. Energy is big business. The IEA estimates the cumulative investment in energy supply infrastructure in its reference scenario at $21 trillion ($21,000 billion) in the period 2005-2030. Europe's share of this is $2,395 billion [4]. For comparison, the EU's ambitious new energy policy assumes an extra cost of €80 billion in the same period, or, depending on exchange rates, around 3% of total energy investment.

As job creation is such an important topic, several energy technology actions plans and roadmaps have taken employment into account. The European Geothermal Energy Council (EGEC), for example, in its Geothermal Heating and Cooling Action Plan for Europe assessed the effect of increased geothermal development on energy costs, investment needs and jobs [5]. According to the EGEC, an investment in equipment of €21 billion between 2001 and 2020 would create the equivalent of 70,000 full-time jobs by 2020. Other industry organisations have put forward corresponding figures. From a macroeconomic point of view, however, job creation is not the aim of government science and innovation policy, and we will not discuss employment further in this chapter.

Exports are also of political interest in many countries, for two reasons: one concerned with macroeconomics, the other relating to technology transfer, often to developing countries. Europe is a net importer of energy (hence the concern over energy security) but it is a net exporter of energy technology. Energy technology export statistics are scarce, but according to one recent study, energy technologies accounted for an average of rather more than 5% of total exports from the EU-15 countries, including mutual trade (Figure 44) [6].

For countries such as Italy and Denmark, energy technologies provide almost 8% of total exports, while Danish exports of oil and gas amount to a similar percentage. Both Denmark and Italy also experienced significant growth in their exports of energy technologies in 2004 and 2005. At the other end of the scale is Ireland, with very low – and declining – exports of energy technologies. Belgium/Luxembourg, Spain and Portugal seem to be falling further behind the EU average, while the Netherlands, and to some extent the UK, are catching up.

Growth in jobs (or industrial productivity) and exports are affected by general national industrial competitiveness, and for new businesses areas and technologies also by the nature of the national innovation system. An innovation system can be defined as *"the elements and relationships which interact in the production, diffusion and use of new and economically useful knowledge"* [7]. Innovation studies recognise the concepts of national innovation systems (NISs) and also technology innovation systems (TISs). Energy technologies have in several cases been the subject of TIS studies [8].

When such importance attaches to innovation, it is natural to set up indicators that measure the effectiveness of innovation systems. The European Environmental Technologies Action Plan (EU ETAP) has involved a variety of work on defining and measuring "eco-innovation" [9]. From the definition of an innovation system above, we can see that it is about:

- knowledge creation;
- actors (industry, markets, institutions); and
- the actors' mutual interactions.

Based on models of technology innovation systems and the chain-linked model for innovation in firms, we can suggest a set of indicators for industrial innovation. The following paragraphs deal first with knowledge creation, and then with actors and their relationships.

### *8.2.1 Knowledge creation*

For knowledge creation three indicators are significant because they are relatively easy to measure: government expenditure, publications and patents.

#### *Government expenditure*

Government expenditure on R&D within specific areas of energy technology can be found in the IEA's Energy Technology R&D Statistics, which is based on information supplied by individual IEA member countries [10]. The quality of this data can be questioned, but it is the best available today.

For most energy technologies the IEA data goes back to the 1970s, but in the charts that follow we have included expenditure only for the period 1996-2005, and for newer technologies such as fuel cells and hydrogen, data has only been available since 2004 (and for fuel cells in Denmark, only for 2005). In the following figures EU comprises data for the individual member countries and not EU's framework programmes.

**Bibliometric search profiles**

Bibliometric searches are carried out in Science Citation Index and Derwent World Patents Index. Both of which are hosted online via STN International. The search has been carried out by Line Nissen and Susanne Munck.

***Wind:*** Science citation index: wind power(5w)plant? or wind(5w) turbine?
Derwent world patents index: wind power(5w)plant? or wind(5w) turbine?

***Fuel cells:*** Science citation index: fuel cell#/ti,st
Derwent world patents index: fuel cell#/ti

***PV:*** Science citation index: (photovoltaic# and (cell# or power or energy or conversion)/ti or (solar cell#)/ti
Derwent world patents index: (photovoltaic# and (cell# or power or energy or conversion)/ti or (solar cell#)/ti

***Nuclear:*** Science citation index: (nuclear power or nuclear energy or nuclear reactor# or fission power or fission energy or fission reactor#)/ti
Derwent world patents index: (nuclear power or nuclear energy or nuclear reactor# or fission power or fission energy or fission reactor#)/ti or X14-A01/mc or X14-A02/mc

***Fusion:*** Science citation index: (tokamak or iter or thermonuclear or fusion)(3w)(reactor# or fuel# or power or energy)
Derwent world patents index: (tokamak or iter or thermonuclear or fusion)(3w)(reactor# or fuel# or power or energy) or X14-A03/mc

***Geothermal:*** Science citation index: Geothermal and (energy or heat? or power or electricity or air condition? or ventilation or cooling)
Derwent world patents index: Geothermal and (energy or heat? or power or electricity or air condition? or ventilation or cooling)

***Tidal:*** Science citation index: (tidal and power)/ti,st or (tidal and energy)/ti,st
Derwent world patents index: tidal and (power? or energy)

***Wave:*** Science citation index: Set 1: (wave energy or wave power) and (plant# or generator# or turbine# or converter# or conversion). Set 1 combined with (engineering(s)(ocean or civil or mechanical or machanics or marine or manufacturing)/cc or energy/cc
Derwent world patents index: (wave or waves) and F03B0013?/IPC (adaptions of machines for special use)

***Hydrogen:*** Science citation index: (hydrogen fuel? or hydrogen production or hydrogen energy or hydrogen power?) or (hydrogen and (economy or society or storage))/ti
Derwent world patents index: (hydrogen fuel? or hydogen production or hydrogen energy or hydrogen power? or hydrogen storage)/ti

***Biofuel:*** Science citation index: (biofuel? or bio fuel? or biodiesel or bio diesel or biomass fuel? or bioethanol or bio ethanol)/ti,st or (biomass and (ethanol or diesel))/ti,st
Derwent world patents index: (biofuel? Or bio fuel? Or biodiesel or bio diesel or biomass fuel? Or bioethanol or bio ethanol or biomass ethanol or biomass diesel) and H06/dc or (biofuel? Or bio fuel? Or biodiesel or bio diesel or biomass fuel? Or bioethanol or bio ethanol or biomass ethanol or biomass diesel)/ti

***Biomass for heat and electricity:*** Science citation index: (biomass and (energy or heat? or combust? or power) not (hydrogen or bioethanol or bio ethanol or biofuel?)) and (energy? or agricultural(w)engineering)/cc or biogas
Derwent world patents index: ((biomass and (energy or heat? or combust? or power) not (hydrogen or bioethanol or bio ethanol or biofuel?)) or X15-E/mc or biogas.

It is important to remember that only OECD/IEA members contribute to these statistics, so countries such as China, India, Russia and Brazil are not included. This is a significant shortcoming in view of the considerable energy R&D efforts these countries have made in recent years.

*Publications and patents*
The number of publications and citations in particular areas of energy technology can be extracted from various databases (bibliometrics).We included all papers and citations published in international journals between 1996 and 2006, though without checking the individual references for validity.

Patents are another relatively accessible indicator of innovation. We counted patents from the period 1996-2006, again checking only the titles or texts of the patents for relevant keywords.

The notes to this chapter give more details of the databases and search terms we used to gather our statistics. (See textbox page 72). Choosing the right search terms is a challenge when reviewing both bibliometric and patent data, and we enlisted the help of experts in particular scientific and technical fields to help with this.

*Private sector R&D budgets and venture capital*
Several studies have tried to assess private-sector expenditure on energy-related R&D, but the shortage of comparable data makes this very difficult. Venture capital is also an interesting indicator, but again, reliable figures are hard to come by.

In hydrogen and fuel cell technology, an international survey of R&D expenditure and company equity found that North American companies dominated the area. Out of a total of 23 publicly-traded companies, the 16 North American firms had raised $3.3 billion, or 93% of the total equity, whereas the six European firms had raised only $0.13 billion (3.6% of the total). The picture from R&D expenditure was similar. [11]. In general European firms' expenditures on energy-related R&D seem to have decreased during the recent years.

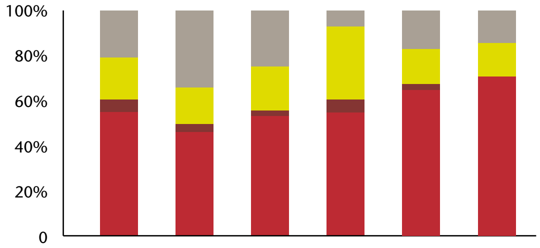
## *8.2.2 Actors and markets*

The literature on innovation measurement suggests several ways to measure the performance of actors and markets. Here we will concentrate on two indicators: market figures, and cooperation between the various actors in a particular technology.

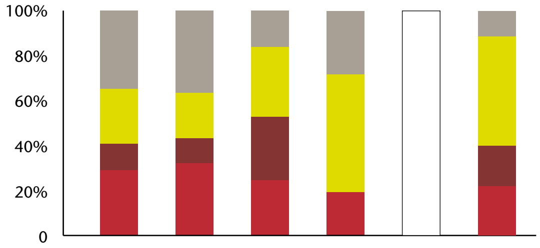
*Market size and growth*
For most commercial energy technologies, trade publications show cumulative installed capacity in MW, plus the number and size of new projects for the previous year. With suitable breakdown by country, region or technology type, these figures can be an excellent source of market data.

Markets can be broken down into two types: energy markets (such as bioethanol) and technology markets (such as equipment or plants to produce bioethanol). From an energy technology perspective the latter figures are of course the most important, provided that they are available. But energy market data is useful. As indicated by the European Environmental Technologies Action Plan (EU ETAP) there is a need for – and a large commercial potential in – developing new services and business models in the energy sector [12].

**Figur 45: Indicators for wind energy technology**



**Figur 46: Indicators for fuel cell technologies**



**Figur 47: Indicators for energy technologies related to hydrogen**

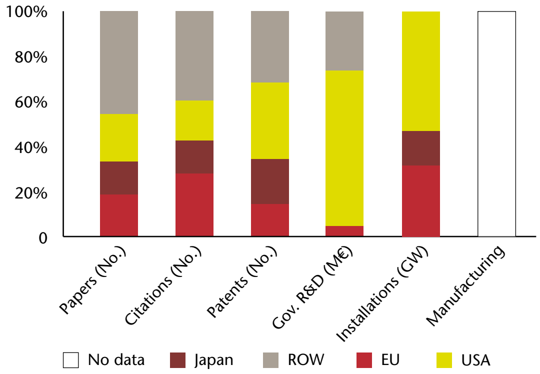
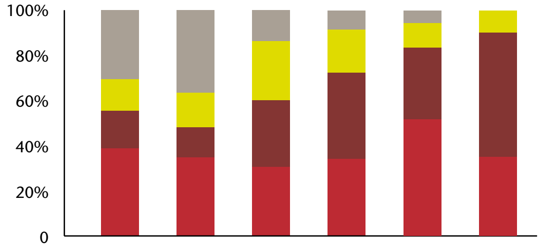


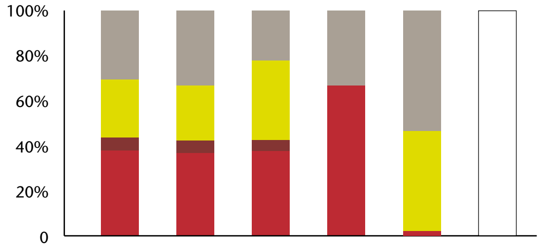
Figure 45: Indicators for wind energy technology [15].

Figure 46: Indicators for fuel cell technologies. Government expenditure on R&D is for 2004-5 only. Since portable applications account for most of the present fuel cell market, these are not included here. Manufacturing data is for 2005 only, and is taken from a recent market survey [16].

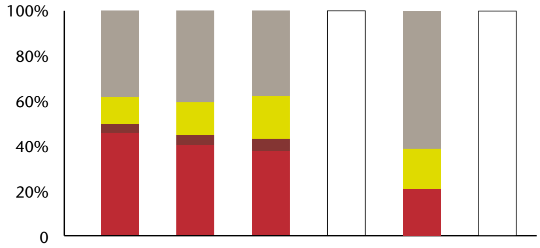
Figure 47: Indicators for energy technologies related to hydrogen. Government expenditure on R&D is for 2004-5 only. Data for hydrogen filling stations is for 1995-2006 [16] and figures for USA includes all of North America.



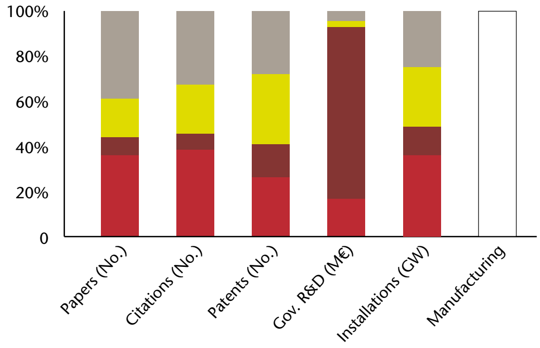
**Figur 48: Indicators for photovoltaic (PV) energy technologies**



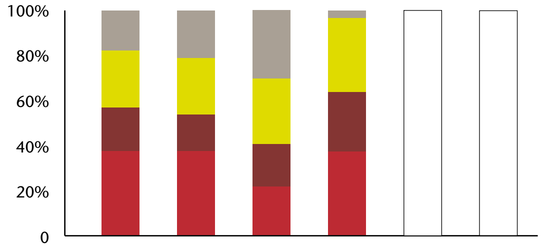
**Figur 49: Indicators for biofuel energy technologies**



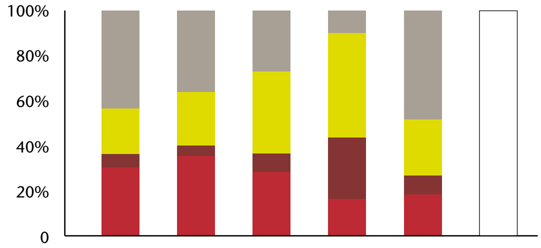
**Figur 50: Indicators for biomass technology**



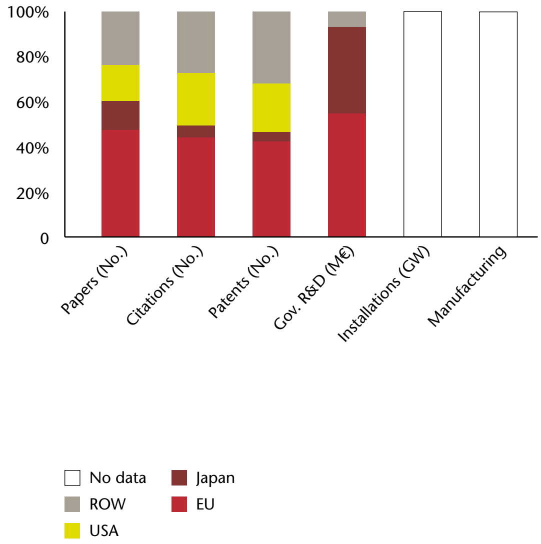
**Figur 51: Indicators for nuclear (fission) energy technology**



**Figur 52: Indicators for fusion energy**



**Figur 53: Indicators for geothermal energy**



**Figur 54: Indicators for ocean energy**

Figure 48: Indicators for photovoltaic (PV) energy technologies. "Installations" refer to cumulative installed capacity up to the end of 2006 [17]; as the market is developing rapidly, this is quite a good proxy for the annual PV technology market over recent years.

Figure 49: Indicators for biofuel energy technologies. The data for publications and patents cover all biofuels, but bioethanol predominates. Production data is for bioethanol only [4].

Figure 50: Indicators for biomass technology for heat and power production. The IEA figures for government R&D expenditure cover only 2004 and 2005, and lack data from important countries including the USA. Installed capacity refers to electricity, and is cumulative as of 2004 [18].

Figure 51: Indicators for nuclear (fission) energy technology. Installed power reflects operational reactors by May 2007 [19].

Figure 52: Indicators for fusion energy.

Figure 53: Indicators for geothermal energy. Installations refer to global direct use of geothermal energy in 2000, measured as cumulative installed thermal power (MWt) [20].

Figure 54: Indicators for ocean energy (tidal and wave).

A related indicator is the number and size of companies operating in a selected energy technology. Again, trade literature often lists the "top ten" firms in each technology, though the increasing internationalisation of industrial production can make it difficult to assign these firms to specific countries.

Several consultancies publish regularly-updated reports on markets and technology for individual energy technologies, often in considerable depth. BTM Consult, for instance, provides an annual market update for wind power [13], while Johnson Matthey plc publishes an annual survey of fuel cells [14]. The cost of these reports may put them beyond the reach of academic reviewers, however.

### *8.2.3 Interactions*

To assess the degree of cooperation between different actors in particular energy technologies, indicators such as co-authoring and co-patenting might become useful tools in the future. Useful information can also be gathered from databases of research projects involving both academia and industry, as this is generally the case with projects supported by the EU's Framework Programmes.

### *8.2.4 Indicators for individual technologies*

Figure 45 to Figure 54 show the indicators discussed above – publications, citations, patents, government R&D expenditure, installed capacity and annual manufactured capacity – for the various energy technologies examined in this report.

"Installations" refers to cumulative installed capacity. "Manufacturing" refers to the home countries of the leading manufacturers.

## 8.3 Timeframes for new energy technologies

Table 20 (see page 77) gives an overview of the timeframes for the energy technologies discussed in this report.

Associated with each energy technology are several statements or hypotheses, each of which is assigned a likely date range.

## 8.4 Conclusions

The previous sections have assessed regional strengths in research and development for each of the various new energy technologies, based on estimates of publications, citations and patents, government expenditure, installed capacity and market share. Together, these indicators give quite a good overview of Europe's relative position in each new technology.

### *8.4.1 Energy technologies*

As Figure 45, Figure 48 and Figure 51 show, the EU is very strong in wind energy and strong in both PV and nuclear technology. In each of these technologies, the EU has a significant share of market and knowledge production, as well as global industrial players.

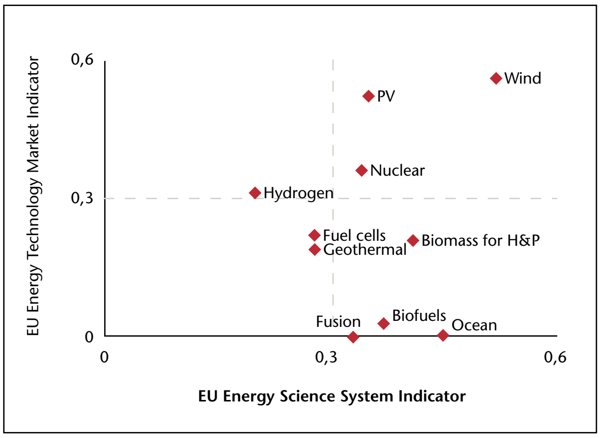


Figure 55: The EU's Energy Science System Indicator plotted against EU's Energy Technology Market Indicator for a range of energy technologies. Market figure for hydrogen are based only on filling stations. Market figures for fuel cells are based on manufacturing capacity, not on markets. No market data are available for ocean power, and no market exists for fusion.

For the established but still not mature technologies of geothermal energy and biomass for heat and power, Europe has a fair share of both installed capacity and knowledge production. Especially in biomass for heat and power, Europe is the home of several world-leading firms.

Brazil and the USA are world leaders in biofuel technology, but Europe seems to be quite well placed in biofuels research. Bioethanol dominates by large the global biofuel production but Europe has a strong position on the smaller market of biodiesel. Together, this is a good platform from which appropriate policy can be used to expand European biofuel activities.

The EU seems to be lagging behind Japan and the USA in two important emerging technology areas: hydrogen and fuel cells. As well as being short of R&D, Europe seems to lack global players in these areas. DaimlerChrysler is the only European firm among the leading vehicle manufacturers with advanced plans for fuel cell cars within ten years; the other manufacturers are American (Ford, GM) or Asian (Honda, Toyota and Hyundai) [16]. It is important to remember, however, that these technologies are still emerging and that commercial markets are in their formative phases.

Ocean energy is also still in the formative phase with respect to both technologies and markets. Here Europe seems quite well placed to benefit, as long as markets can be developed within Europe to test and develop the technology.

Figure 55 summarises the relationship between European science and markets for the energy technologies we have discussed. EU Energy Science Indicator is constructed as EU's average score in the three indicators: papers, citations and patents. EU Energy Technology Market Indicator is based on the installations indicator if nothing else is mentioned.

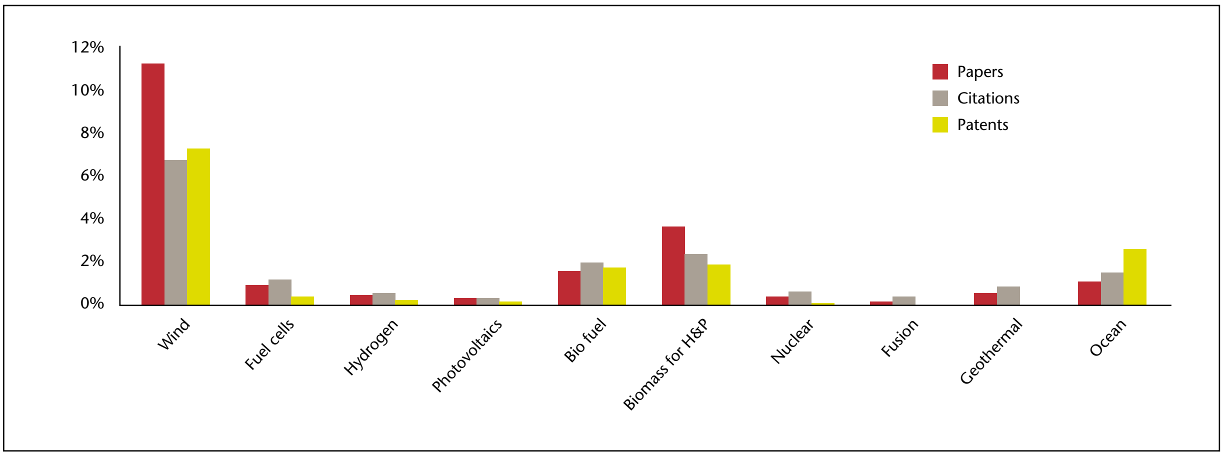


Figure 56: Energy science system indicators for Denmark. The bars show Denmark's percentage of the global total.

### *8.4.2 The Danish position*

Danish markets for energy technologies and services are important for demonstration purposes and as an advanced market for the user-driven aspects of modern industrial innovation. Apart from this, however, the Danish market for energy technologies is insignificant in a global context. Our focus is therefore on science system indicators (Figure 56).

It comes as no surprise that Denmark has a very strong position in wind energy. Denmark also seems to have a relatively strong position in bioenergy – both bioethanol and biomass for heat and electricity – and in fuel cells.

In ocean energy Denmark has a small but interesting position that is relatively strong in patents. This may reflect the fact that ocean energy depends on careful design and practical testing, rather than on scientific breakthroughs. Both tidal and wave energy are represented in the figures, but Danish wave technology surprisingly has the stronger position, with 8.3% of all patents. This area is, however, currently very small compared to PV or wind power – let alone established fossil based energy technologies.

| Technology | | Statement | Period in which the statement will first be true | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Before 2010 | 2010-2015 | 2016-2020 | 2021-2025 | 2026-2030 | 2031-2035 | 2036-2040 | After 2040 |
| Wind | 1 | Wind power delivers 12% of EU electricity demand | | | | ■ | | | | |
| | 2 | North Sea offshore wind turbines produce electricity at €0.04/kWh (tendering fixed price for Horns Reef 2 is €0.07/kWh) | | | | | ■ | | | |
| | 3 | First use of HVDC for long-distance (>2,000 km) transmission of wind power to EU population centres | | | | ■ | | | | |
| | 4 | Wind provides 12% of global electricity demand | | | ■ | ■ | | | | |
| Fuel cells | 5 | First commercial use of natural-gas-fuelled SOFC CHP systems | | ■ | | | | | | |
| | 6 | First commercial use of fuel cell APUs for trucks, cars and marine applications | | ■ | | | | | | |
| | 7 | Fuel cell stack price falls to $30/kW | | ■ | | | | | | |
| | 8 | Annual installations of fuel cells for power generation reach 1 GW | | | | | ■ | | | |
| Hydrogen | 9 | Hydrogen produced solely from renewables or nuclear constitutes a significant part of the energy system | | | | | | | ■ | ■ |
| | 10 | First nationwide network of hydrogen filling stations allows commercial rollout of hydrogen vehicles | | ■ | | | | | | |
| | 11 | Commercial use of SOEC electrolysis to produce hydrogen, methanol or methane | | | ■ | | | | | |
| | 12 | First mass production (>10,000 annually) of H2/FC cars | | ■ | | | | | | |
| Photo-voltaics | 13 | PV provides 3% of global electricity demand | | | | | ■ | | | |
| | 14 | Price of PV modules falls to $0.75-1.1/Wp (present price is $3.5/Wp) | | | ■ | | | | | |
| | 15 | Cost of electricity from PV below falls to €0.2/kWh in areas like Denmark | | | ■ | | | | | |
| | 16 | Second- and/or third-generation PV technology overtakes first-generation technology in the market | | | ■ | | | | | |
| Biofuels | 19 | Second-generation bioethanol plants reach commercial scale | | ■ | | | | | | |
| | 20 | 10% of EU transport fuel replaced by biofuels such as bioethanol and biodiesel by 2020 | | | ■ | | | | | |
| Biomass | 21 | Biomass is widely used throughout the EU for district heating and electricity production | | ■ | | | | | | |
| Nuclear | 22 | 15% increase in the use of nuclear power compared to current figures | | ■ | | | | | | |
| | 23 | Nuclear reactors with passive safety are in practical use | | | | ■ | | | | |
| | 24 | Fourth-generation reactor technology commercially available | | | | ■ | ■ | | | |
| Fusion | 25 | Plasma confinement technologies for nuclear fusion are in practical use | | | | | | | ■ | |
| | 26 | Operation of first commercial fusion power plant | | | | | | | | ■ |
| Geo-thermal | 27 | Installed capacity of geothermal energy in OECD Europe reaches 3 GW | | | | | ■ | | | |
| Ocean | 28 | Practical use of ocean energy technologies (tidal and wave) | | | | ■ | ■ | | | |

Table 20: Overview of timeframes for a number of energy-producing technologies.

# Index

# References

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# Risø Energy Report Series

## New and emerging technologies: options for the future

*Risø Energy Report 1*

EDITED BY HANS LARSEN AND LEIF SØNDERBERG PETERSEN

Risø National Laboratory, October 2002, 64 p.,
ISBN 87–550–3082–3
*Risø-R-1351(EN) (515 Kb)*

All over the world, increasing energy consumption, liberalisation of energy markets and the need to take action on climate change are producing new challenges for the energy sector. At the same time there is increasing pressure for research, new technology and industrial products to be socially acceptable and to generate prosperity. The result is a complex and dynamic set of conditions affecting decisions on investment in research and new energy technology. To meet these challenges in the decades ahead, industrialists and policymakers need appropriate analyses of energy systems, plus knowledge of trends for existing technologies and prospects for emerging technologies. This is the background for this first Risø Energy Report, which sets out the global, European and Danish energy scene together with trends in development and emerging technologies.

## New and emerging bioenergy technologies

*Risø Energy Report 2*

EDITED BY HANS LARSEN, JENS KOSSMANN AND LEIF SØNDERBERG PETERSEN

Risø National Laboratory, November 2003, 48 p.,
ISBN 87–550–3262–1
*Risø-R-1430(EN) (1 Mb)*

Three growing concerns – sustainability (particularly in the transport sector), security of energy supply and climate change – have combined to increase interest in bioenergy. This trend has been further encouraged by technological advances in biomass conversion and significant changes in energy markets. We even have a new term, “modern bioenergy”, to cover those areas of bioenergy technology – traditional as well as emerging – which could expand the role of bioenergy. Besides its potential to be carbon-neutral if produced sustainably, modern bioenergy shows the promise of meeting a considerable part of the world’s energy needs, increasing the security of energy supply through the use of indigenous resources, and improving local employment and land use. To make these promises a reality, however, requires further R&D.

## Hydrogen and its competitors

*Risø Energy Report 3*

EDITED BY HANS LARSEN, ROBERT FEIDENHANS’L AND LEIF SØNDERBERG PETERSEN

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*Risø-R-1469(EN) (643 Kb)*

Interest in the hydrogen economy has grown rapidly in recent years. Countries with long traditions of activity in hydrogen research and development have now been joined by a large number of newcomers. The main reason for this surge of interest is that the hydrogen economy may be an answer to the two main challenges facing the world in the years to come: climate change and the need for security of energy supplies. Both these challenges require the development of new, highly-efficient energy technologies that are either carbon-neutral or low-carbon. Alternative fuels could serve as links between the different energy sectors, especially between the power system and the transport sector, to facilitate the uptake of emerging technologies and increase the flexibility and robustness of the energy system as a whole.

## The future energy system: distributed production and use

*Risø Energy Report 4*

EDITED BY HANS LARSEN AND LEIF SØNDERBERG PETERSEN

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

- 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.

## Renewable energy for power and transport

*Risø Energy Report 5*

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Global energy policy today is dominated by three concerns: security of supply, climate change, and energy for development and poverty alleviation. This is the starting point for Risø Energy Report 5, which addresses trends in renewable energy and gives an overview of the global forces that will transform our energy systems in the light of security of supply, climate change and economic growth. The report discusses the status of, and trends in, renewable energy technologies for broader applications in off-grid power production (and heat). It also addresses the wider introduction of renewable energy in the transport sector, for example through renewable fuels and vehicles powered by batteries, fuel cells and hybrid propulsion systems.