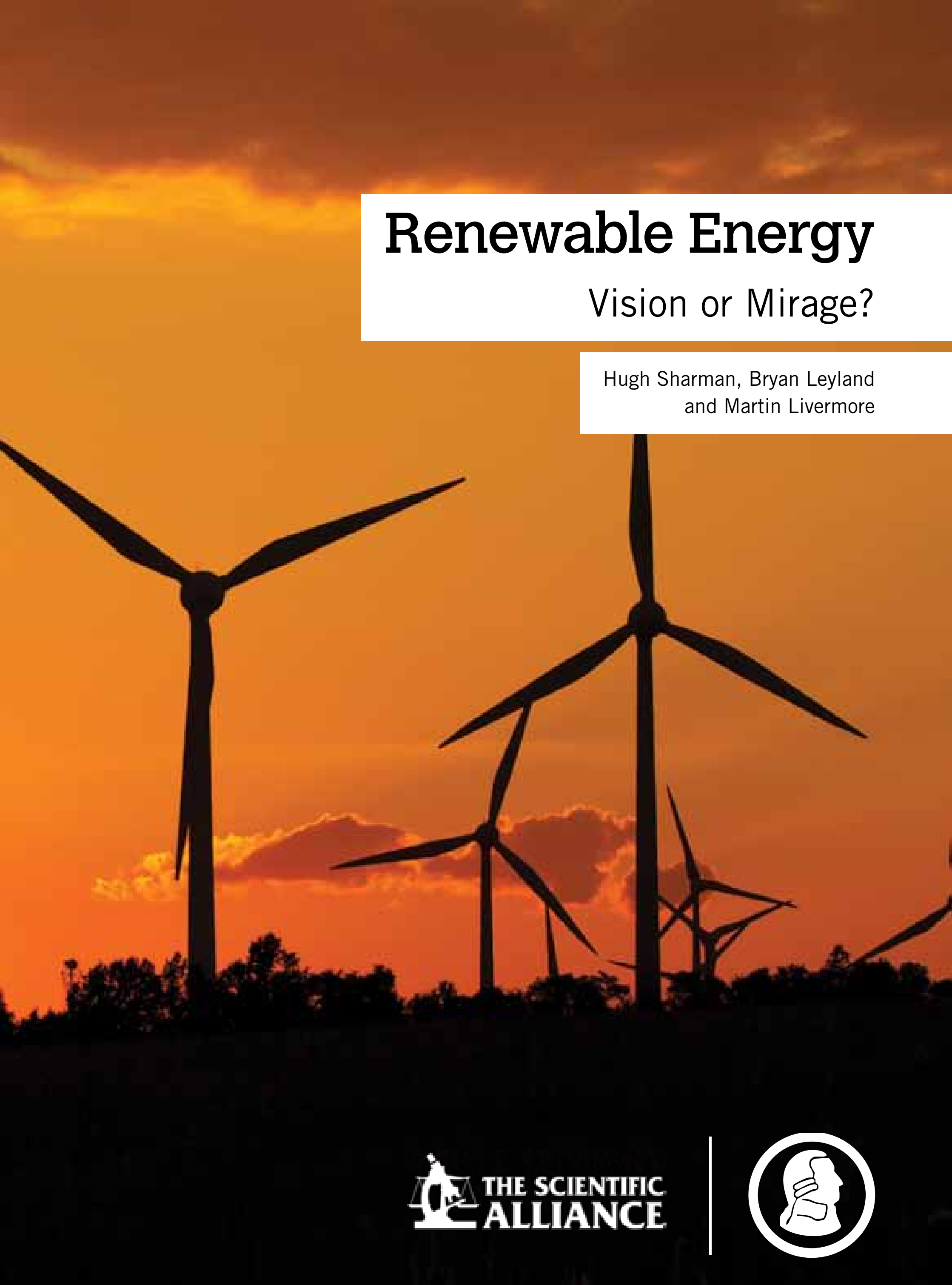

Renewable Energy

Vision or Mirage?

Hugh Sharman, Bryan Leyland
and Martin Livermore

THE SCIENTIFIC ALLIANCE

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Published in the UK by ASI (Research) Limited

ISBN 1 902737 81 4
Printed in England by Grosvenor Group (Print Services) Limited, London

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Foreword

There have been many studies on renewable energy technologies in recent years, both from a UK perspective and elsewhere. Some cover a rather narrow aspect, a number present a somewhat one-sided view, and most focus on a single source of energy, generally wind. We have attempted something broader: to review the information available on the range of current and emerging renewable energy technologies and summarise the present position and potential contribution of each one. In doing so, we have tried to be objective and make judgements solely on the information available.

The conclusions may not be very palatable given the current political enthusiasm for renewable energy. However, facts are facts and we believe strongly that policy should have a good chance of achieving its goals in a cost-effective way, and also be guided by evidence. Governments are elected to lead, but they also have a responsibility to spend taxpayers' money wisely. Moreover, they have an obligation to the electorate to provide a secure, affordable supply of energy, on which economic competitiveness and the safety and comfort of citizens depends. The evidence shows that continuing along the current path will not do this and certainly does not represent an efficient use of tax revenues.

The authors are grateful to all those who have provided material for this report and commented on drafts. We particularly appreciate the constructive reviewing of Colin Gibson and John Scott. The final report represents the views of the authors and we are wholly responsible for whatever errors and omissions remain.

Executive summary

1. EU and UK national government policy is driving a move towards progressive replacement of fossil fuels (coal, oil and gas) by renewable energy sources and nuclear power. However, with a few notable exceptions (hydro power in Norway, geothermal energy in Iceland, for example) available renewable power technologies are neither economically competitive nor easily capable of providing the degree of energy security demanded by a developed society.

2. This report reviews the options from a technical and economic standpoint and assesses the real contribution they can make to a future secure, affordable energy supply. At the same time, we consider the efficiency with which they can achieve one of their primary objectives: to reduce emissions of carbon dioxide.

3. We conclude that the renewable energy technologies which are commercially available or in development cannot form more than a minor part of the overall mix without putting the security of supply at jeopardy. The need for increasing amounts of conventional backup capacity as renewables form a larger part of the overall mix severely limits their contribution to emissions reduction.

4. On-shore wind is the lowest-cost option, but still requires financial incentives to encourage investment and has limited scope for expansion because of public opposition and lack of appropriate sites. Its viability would be reduced even further if developments had to carry the cost of the additional gas-fired generating capacity needed as backup. 28% of Ireland's installed electricity generating capacity is in the form of wind farms, but only 13% of power consumed was generated by wind in 2010/11. UK capacity factors are lower.

5. Experience from other countries with larger percentages of wind generation shows that only limited savings can be made in fossil fuel consumption and that security of supply can only be guaranteed by having a large-scale backup capability or a high degree of interconnectivity with neighbouring countries having surplus capacity. Wind farms supply only about 10% of Danish electricity consumed, despite generating more than double this.

6. Burning of biomass to generate electricity has some merit and may be economically competitive as fossil fuel prices rise. However, its relatively low energy density increases transport costs, and in practical terms it can never make more than a minor contribution to the overall energy supply. To meet DECC's targets for the UK, by far the greater part of the biomass would have to be imported. For example, UK-grown straw could generate less than 2% of the country's electricity needs.

7. Solar power – the most expensive of currently available technologies – has little contribution to make in northern Europe. Germany has become the world's leader in solar cell installations, paying billions of euros annually to provide just 2% of the country's electricity from photovoltaic panels with a capacity of 17GW but which operate at a capacity factor of only about 10%.

8. A high contribution from intrinsically intermittent renewable power generation without matching conventional capacity as backup – even if demand and supply were to be better balanced via a Europe-wide grid – would require affordable and reliable large-scale energy storage capacity capable of providing backup over a period of days or weeks. No technologies capable of providing this exist or are in development.

9. The economically extractable supply of fossil fuels is not infinite and our dependence on them must inevitably decrease as their real price increases and viable alternatives are developed. Some public support will be needed to bring these new technologies to market. However, governments are currently indulging in the dubious practice of providing guaranteed, long-term subsidies to technologies which have little hope of becoming truly competitive for the foreseeable future.

10. In the meantime, taxpayers' money would be far better spent on measures to increase energy efficiency, plus investment in proven nuclear and gas generating capacity to provide energy security as many of the UK's coal-fired stations – and nearly all existing nuclear reactors – are decommissioned over the coming decade.

11. Neither can we ignore the possibility of building new coal-fired stations, or commercialising underground gasification, to make use of the large reserves of coal in the UK and other European countries, which could contribute to energy security for many years to come.

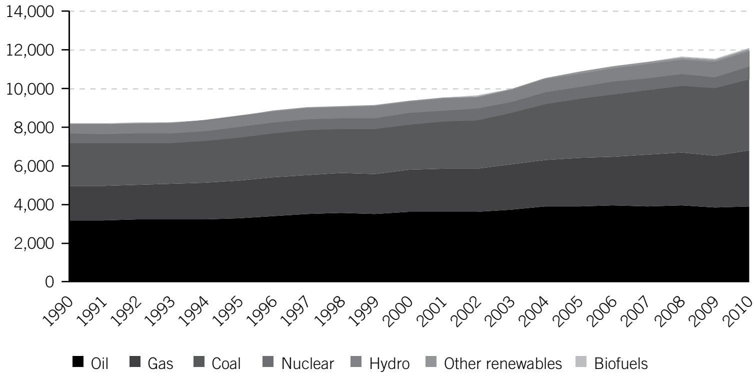
Introduction: energy supply and demand

A modern economy depends on a secure, affordable supply of energy. Although energy intensity – the amount of energy needed per unit of economic output – has decreased in the industrialised world over the years, economic growth has meant that overall energy use has continued to increase.

With the invention and development of the coal-powered steam engine during the 18th Century, the UK became the world's first industrial economy. The rest of the world followed and now energy use, mostly derived from fossil fuels, is the key to every aspect of modern life in every industrial economy in the world. Fossil energy use makes labour and agriculture vastly more productive, and has allowed the rapid growth of a human population which is overall very much more prosperous, better fed and long-lived than ever before.

In 2010, the world consumed roughly 12 billion tonnes of oil equivalent (toe) of primary energy, an average of about 2 toe for everybody on the planet (see Figure 1 for a breakdown of sources).

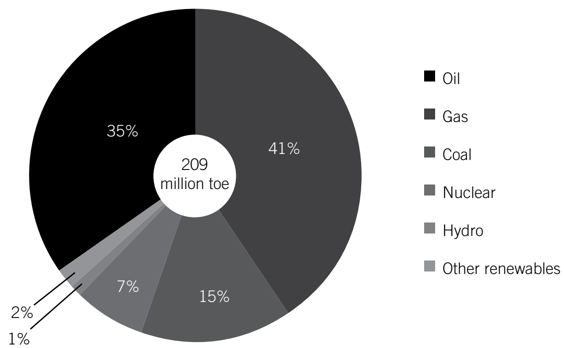
Figure 1: Global Fuel Production & Consumption



Source: BP Statistical Review 2011

In 2010, UK energy consumption was 209 million toe, roughly 1.7% of the global total and about 3.4 toe per capita. 97.5 % of all UK energy was provided from fossil (coal and gas) and nuclear resources. The combined contribution of all renewable resources to the UK's energy needs (including hydropower, wind, solar, landfill gas and biomass) amounted to 5.7 million toe, or just 2.5% of all energy consumed (see Figure 2).

Figure 2: UK Primary Energy Consumption 2010

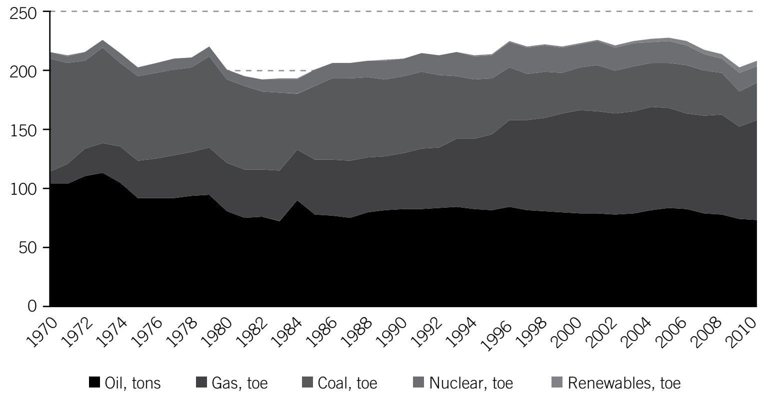


(toe = tonnes of oil equivalent)

Source: BP Statistical Review 2011

It is important to note that the largest fraction of UK primary energy now comes from gas, used for power generation, to produce chemicals and fertilizers and, above all, for heating. Although it is far down the list of the world's countries by population, the UK is one of the largest gas consumers, behind only the USA, Russia, Japan, China and Iran. This is the legacy of finding, developing and emptying a world-class hydrocarbon resource within a single generation (Figure 3 shows this development).

Figure 3: UK primary energy demand



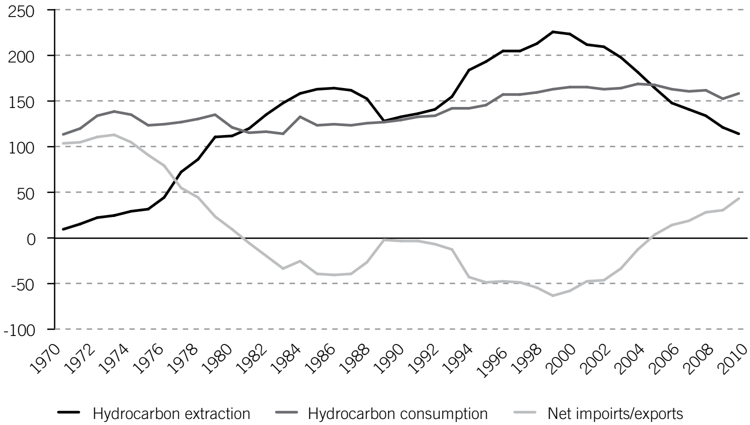
Total energy demand and the growing importance of gas

Source: BP Statistical Review 2011

Figure 3 shows that UK energy demand has stayed fairly constant over the last forty years. Over the same period, GDP has grown from £170bn to £370bn (at constant 2006 prices): energy intensity has declined dramatically, largely as a result of increasing energy efficiency and the decline in heavy industry. Nevertheless, within this overall trend, it is clear that precipitate drops in demand coincide with economic recessions such as those in the early 1980s and following 2008.

Until 2005, the UK had been self-sufficient in energy for a generation, but is now rapidly becoming import-dependent, despite having substantial reserves of coal. Figure 4 shows the trend.

Figure 4: UK Hydrocarbon Extraction & Consumption



An increasing dependence on imports
Source: BP Statistical Review 2011

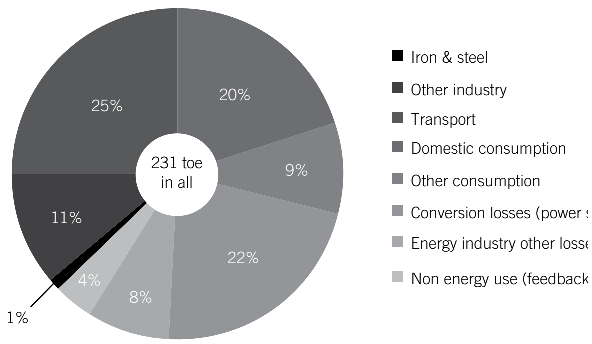
Global oil supplies, on which well over 95% of transport depends, are tight. There is a risk that supplies might even decline while demand, especially in the BRIC countries, is rising. Whether or not peak oil is an imminent reality, prices are high in historical terms and there is a high degree of volatility, strongly influenced by geo-politics. Fortunately, the global supply of gas is a fungible energy source that can be adapted quite cheaply and quickly as a transport fuel. If this happens to a significant extent, the present surplus of gas on the international market may prove to be a temporary blip, pushing prices higher and aggravating the difficulties faced by an increasingly import-dependent UK. To set against this, the emerging exploitation of shale gas may provide a large increase in supply if its proponents are proved correct.[1]

1 The recoverable gas reserves in the Marcellus shale deposits in the eastern USA were recently downgraded by 80% to 84 trillion cubic feet by the IEA following a survey by the US Geological Survey. However, in 2002, the USGS's estimate was only 2 tcf, since 'fracking' had not been fully proven at this stage.

Against such a background, it seems simple commonsense that – if technically and economically feasible – the UK should seek "non-fossil fuel" alternatives as fast as possible. A more diverse and affordable primary energy mix would certainly be a fine thing. But this cannot be done simply by legislating for change; both the technology and the economics must be right. Governments do not have a good record when trying to force change (or, in some cases, block it) by using taxpayers' money to provide long term subsidies for economically uncompetitive options. Some degree of subsidy can be justified to support the development of emerging technologies until they are economically viable, but it is irresponsible to back a development which has no foreseeable prospect of being competitive.

The current energy mix is a single point on the curve of continuous evolution since the start of the Industrial Revolution. Coal was once dominant for both heat and power, a position now occupied by gas. Oil soon became the obvious choice for motor transport as the internal combustion engine developed. Since the 1950s, nuclear power has developed as an additional option. The point is that energy can be delivered in a variety of ways, and, until recently, the mix has developed largely as the result of market forces.

Figure 5: How UK's primary energy ends up



Not all the fuel used produces useful energy

Generating electricity is by no means a 100% efficient process. Figure 5 shows that 31% of the total primary energy demand – a huge 69 million toe – is lost when coal and gas are burned to produce electricity. Reducing such losses in electricity generation by replacing fossil fuel generators with renewable energy generators that convert effectively inexhaustible resources like wind, sun and tides directly into electricity "without waste" looks like an easy hit. This is one of the main reasons why policymakers get so exercised by renewables. If all that electricity could be generated other than by burning fuels, then a massive reduction in fossil fuel dependency and CO_2 emissions could be achieved. Would that things were this simple!

The drive for efficiency is not new. Engineers have been delivering improvements since the Industrial Revolution began (for example, the first steam engines were about 1% efficient, but James Watt increased this five-fold with his introduction of the external condenser). Figure 3 illustrates how UK primary energy demand has been essentially flat in recent years, as the economy has continued to grow. This is partly due to increased energy efficiency, but the loss of energy-intensive industries to lower-cost economies has also made a significant contribution. As the price for raw energy increases, we can be quietly confident that power equipment and vehicle manufacturers will improve the efficiency of their machinery, although large, "step" improvements will require innovative new developments. For instance, Renault claims that the fuel consumption of petrol engines can be reduced by about 16% by changing to high-pressure injection[2], so approaching diesel engine efficiency. Another development, called Hyboost, combines a number of technologies to produce a low-cost, high-efficiency alternative to the current generation of hybrids[3].

Despite continuing efficiency increases, the transport sector keeps on expanding, and so increases demand for oil. Natural gas can partly fulfil the demand if enough drivers are willing to pay for the necessary conversion, but

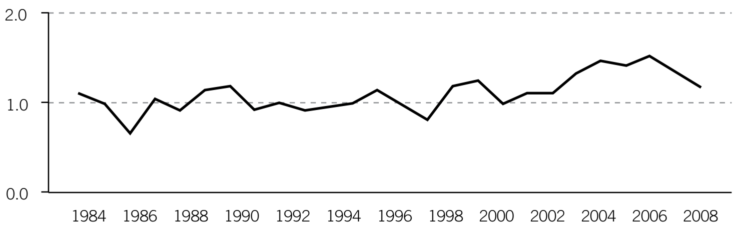
2 http://www.autozine.org/technical_school/engine/petrol1.htm

3 http://www.theengineer.co.uk/in-depth/analysis/hyboost-programme-promises-engine-efficiency/1010742.article

(despite the distinct lack of enthusiasm from the public) the government is also trying to develop the market for electric cars. If (and it's a big if) good solutions are found to the range, cost and battery recharging and replacement issues, then part of the primary energy demand will be shifted from petrol and diesel to the electricity grid. Security and affordability of supply then not only affects domestic and commercial electricity users, but also personal transport. Also, electric cars only make sense if the additional electricity demand is supplied from non-fossil generating plants; if gas is the primary energy source, it is much more efficient to burn it in an internal combustion engine than to use it to generate grid electricity and charge batteries.

Some commentators have suggested that exploitable reserves of unconventional gas (in particular, from shale) could increase proven reserves to the extent that gas and oil prices decouple. However, this is not likely in the immediate future. A dislocation between oil and gas prices in the USA, caused by the success of American shale gas developments, is considered by some observers as proof that the historical link illustrated in Figure 6 will finally be broken. However, unlike oil, gas markets are largely regional. For European prices to be similarly affected, additional major reserves would need to be proven and exploited in this region, which would take some time.

Figure 6: Historical Ratio crude oil:gas price



Will oil and gas prices decouple?

(Average LNG CIF Japan & EU piped gas CIF)

Source: BP Statistical Review 2011

But after sharp falls in global demand for gas during the economic crisis years of 2008 – 2009, creating a surplus of gas extraction capacity, demand recovered sharply in 2010. Global demand rose 7.4% in 2010[4]. China's gas consumption increased by 22%, and the nuclear tragedy at Fukushima led to Germany closing down a number of safe and reliable nuclear power plants. Accordingly, the surplus in global gas extraction capacity is likely to disappear by 2012. Once again, the large monopolistic suppliers, Russia, Qatar and Algeria, will gain the upper hand and can achieve their openly stated aim of price parity with oil. If large reserves of shale gas in consumer countries can be exploited efficiently, then this situation may well change, but we are some way from that happy situation. The UK, in particular, has left itself shockingly exposed to the vagaries of international gas supply.

The widely reported higher costs of electricity and gas that are working their way through the economy during the second half of 2011 will result in quite significant reductions in the amount of energy used by industry, homes and commercial premises and will affect the spending power of the population. Some of this reduction will come from more efficient use of energy, but there is a very real danger that some industries will relocate to regions with lower energy costs. At the same time, fuel poverty will increase, and there is a real risk that many British homes will not be able to afford even basic energy supplies. A recent report[5] estimated that currently 2,700 people die each winter as a direct result of fuel poverty. The problem is significantly compounded by the additional costs of wind and solar energy being paid directly by all consumers in the form of higher electricity charges.

4 BP Statistical Review 2011
5 http://www.bbc.co.uk/news/business-15359312

The optimistic assumptions that got us where we are today

All public expressions by the government about global energy price and supply security during the Labour years (1997 – 2010) were marked by extreme optimism. This optimism found economic expression in the annual *Updated Energy Price Assumptions* that underlie the energy (and now climate) policy and have formed the economic basis of investments in public energy infrastructure, including new power stations.

The International Energy Agency has a lamentable record of advising its OECD members (including the UK), on energy security and must accept a major part of the blame. It has been consistently over-optimistic in its projections for the availability and price of crude oil (as well as gas and coal). As an example, the following is a table from its *World Energy Outlook (WEO) 2000*.

Table 1: Fossil Fuel Price Assumptions (in year 2000 dollars)

	2000	2010	2020	2030
IEA crude oil imports ($/barrel)	28	21	25	29
Natural gas ($/MBtu):				
US imports	3.9	2.7	3.4	4.0
European imports	3.0	2.8	3.3	3.8
Japan LNG imports	4.7	3.9	4.4	4.8
OECD steam coal imports ($/tonne)	35	39	41	44

Note: Prices in the first column are actual data. Gas prices are expressed on a gross calorific value basis (MBtu)

Figure 41 shows the actual price of oil in 2010 to have been $80 or more. In 2004, the IEA confidently forecasted that, by 2030, global demand for hydrocarbon liquids would be 123 million barrels of oil per day (bopd) and that this would be delivered at an expected price of $55 per barrel (in 2004 dollars).

Fortunately, the IEA based *WEO 2009* on a fundamental reassessment of its basic data. Instead of accepting third-party (eg OPEC) assertions as fact, it examined the real data from over 800 of the world's largest oil fields during 2009. In the light of this, it saw fit to sharply reduce estimates for demand in 2030 to what it believed might be possible to supply, i.e. 106 million bopd. Just one year later, in November 2010, this assumption was further reduced to less than 100 million bopd, only ten million bopd more than what may be demanded in 2012, if supply can be met. However, the IEA now admits that even to achieve this requires the world's upstream hydrocarbon industry to find, develop and commission a "new Saudi Arabia" every five years. At present, this seems very unlikely, but a combination of new discoveries, improved extraction methods and exploitation of unconventional sources may assure continued security of supply.

Both the Blair and Brown governments rejected the notion that fossil fuel supplies were in any serious way at risk. Only in the spring of 2011 did UK Coalition government ministers begin to express any public concern. Energy security now features as a priority alongside the drive to reduce carbon dioxide emissions and, indeed, is used by policymakers as further justification for expanding the use of renewables and for having accepted the case for new nuclear generating capacity.

With all this in mind, the key question is whether greater investment in renewable energy generation can fulfil the hopes and expectations implicit in government policy.

Setting the scene I: the case for greater energy efficiency

The choices we make about future power generation systems will be influenced by total demand. As the population rises and the economy grows, energy use will tend to increase, albeit with a continual decline in energy intensity. But this is to ignore the very real potential impact of a range of energy-saving options.

Globally, lighting alone accounts for 25% of electricity used, and there are significant opportunities for cutting this figure.[6] The fact that compact fluorescent lamps (CFLs) use less energy than their incandescent equivalents now being phased out does not, of course, mean that energy consumption for lighting will drop in the same proportion. For example, they are not dimmable and may be left on more. Also, a degree of consumer resistance to CFLs (due largely to the quality of light and compounded by the difficulty of disposing of them safely to avoid mercury leakage) has meant that many people have stocked up with filament lamps and will continue to use them for some years to come. In developing countries, it is quite probable that cheap incandescent bulbs will be the norm for many years to come as distributed power becomes more available.

Nor will projected large price reductions for LED lighting (which is almost certain to replace compact fluorescent lamps in the medium term, perhaps

6 http://www.economist.com/node/21526373

even over the next five to ten years) necessarily produce a revolution over the coming decade: all alternative technologies have their strengths and weaknesses, and it is not always simply a case of swapping one light fitting for another. Nevertheless, it is reasonable to expect electricity used for lighting to decline somewhat from current levels, although the global situation will depend very much on the availability of affordable alternatives to incandescent bulbs in developing countries.

In the UK, domestic consumption forms the largest single sector of overall energy use, accounting for 32% of the total in 2010.[7] The great majority of this is used for heating. Modern condenser gas boilers now deliver significantly higher efficiencies than were available a generation ago and heat pumps, despite their high capital cost, can also make use of low-grade external heat to reduce other energy consumption. Not before time, the government is also encouraging higher standards of house insulation to reduce heating costs. With its (relatively) mild climate, the UK has for too long ignored this rather obvious way to save considerable amounts of energy.

Transport is another major energy user. According to the InterAcademy Council, it accounted for 22% of total world energy use in 2005, with cars being by far the dominant sector.[8] Car usage still continues to increase, albeit at a relatively modest rate, in many industrialised countries, but in China, India and other rapidly-developing economies, there is now an enormous and rapid expansion in ownership. In China alone, about 18 million new cars were sold in 2010.[9] But, to set against that, there have been remarkable increases in fuel efficiency over recent decades, and these seem set to continue. For many diesel-powered cars sold in Europe, 50mpg is perfectly achievable. Nevertheless, we cannot expect fuel efficiency to continue to improve at the same rate as over the last few decades, particularly given the greater weight added by safety features and the constraints imposed by tightening

7 http://www.decc.gov.uk/assets/decc/11/stats/publications/energy-consumption/2323-domestic-energy-consumption-factsheet.pdf

8 http://www.interacademycouncil.net/CMS/Reports/11840/11914/11924.aspx

9 http://www.ft.com/cms/s/0/319abfda-1813-11e0-9033-00144feab49a.html#axzz1XGFH8QQn

emissions standards. Meanwhile, new engine designs, such as the MUSIC (Merritt Unthrottled Spark Ignition Combustion) engine developed at Coventry University, offer the prospect of similar efficiency for petrol engines.[10] Similar fuel efficiency increases are also seen in aviation, with advances in engine design and greater use of lightweight composites in construction. The latest commercial airliner from Boeing – the 787 Dreamliner – uses this approach to achieve a 20% increase in fuel efficiency.[11] Overall, energy requirements for transport will continue to increase, but at a slower rate than might be predicted from increased amounts of travel alone.

Factors such as this can slow the overall rate of increase of energy consumption; there may even be a modest reduction in demand for both grid electricity and total energy. They are part of the overall trend to reduced energy intensity in rich societies. However, citizens and companies in all developed countries still expect a secure and affordable supply of energy, and total demand will remain very high, whatever the details may turn out to be. The question this report addresses is the extent to which current and emerging renewable energy technologies can contribute to this.

10 http://www.coventry.ac.uk/newsandeventsarchive/a/4588/$/selectedYearId/1269/selectedMonthId/1282/tab/news

11 http://www.boeing.com/commercial/787family/background.html

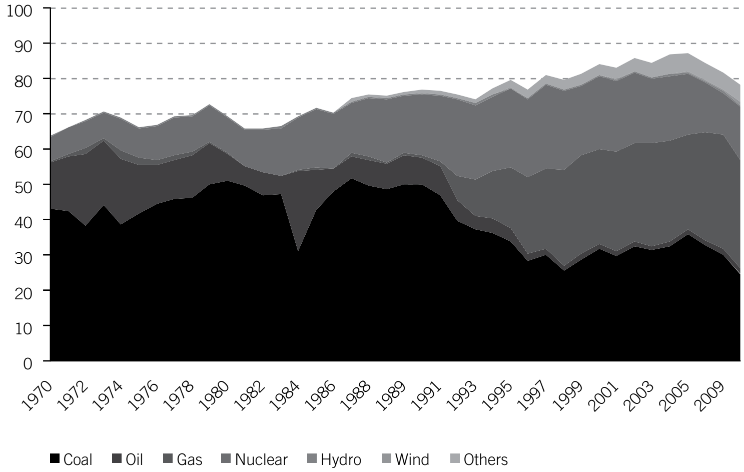
Setting the scene II: the decarbonisation agenda

Since Margaret Thatcher first raised the profile of the global warming issue,[12] reduction of greenhouse gas emissions has increasingly become an overriding concern for politicians, with energy security – whether intentionally or not – being given second priority.

In fact, any truly significant carbon emission reduction in the UK that has taken place until now has been largely driven by the construction of highly efficient but low cost combined cycle gas turbine (CCGT) power stations that were able to take commercial advantage of the low price of North Sea gas after restrictions in its use for power generation were lifted by the EU in 1989 (see Figure 7). CCGTs achieve their efficiency by using the waste heat from the first stage gas turbine generator to generate more electricity via a steam turbine. The better efficiency of the CCGT and the higher proportion of hydrogen in natural gas relative to coal made CO_2 reduction an inevitable by-product of the rapid exploitation of the North Sea resource.

12 http://www.heraldscotland.com/sport/spl/aberdeen/thatcher-sees-nuclear-power-solution-to-greenhouse-effect-1.630851

Figure 7: Fuel mix of UK power generation since 1970



Trends in generation capacity by fuel type
Source: DECC Dukes Table 5.1.1

Decarbonisation of the global energy system has been the main agenda of UNFCCC (the UN Framework Convention on Climate Change). The Kyoto protocol, covering the period up to 2012, commits industrialised countries (other than the USA, where ratification proved impossible) to quantitative targets, but the extent of adherence has varied among signatories, and targets after 2012 have been set nationally and regionally in a fairly ad hoc way. The EU as a whole committed to a 20% reduction in emissions by 2020, as well as a 20% share of total energy use to come from renewable sources (the20-20-20 targets).[13] The UK government, ever ready to gild the lily when it comes to EU matters, passed the Climate Change Act in 2008,[14] with a mere handful of MPs voting against it. This provides a framework for the radical restructuring of the UK's energy supply up to 2050. The Climate Change Committee, an independent body of government nominees, produces annual

13 http://ec.europa.eu/clima/policies/package/index_en.htm
14 http://www.decc.gov.uk/en/content/cms/legislation/cc_act_08/cc_act_08.aspx

‘carbon budgets’ which the government is expected to accept and adhere to. Although failing to meet the targets would be highly embarrassing, it is difficult to see how the “illegality” of this can be punished.

In fact, the 20-20-20 targets have now become 20-20-15, with the target for deriving 20% of primary energy from renewables being lowered to 15%, following negotiations with the Commission. This is still a hugely demanding target: in today’s terms, it requires the UK to displace fossil fuels with an annual output of renewable (or nuclear) energy equivalent to 30 million toe. This can be achieved, say the politicians, by a massive increase in the use of renewable energy to generate electricity. The historical precedents for such long-term, top-down directives are not encouraging, but this is what elected politicians have committed to. However, there seems to be some willingness to review this by some senior Conservative politicians, if Chancellor George Osborne’s comments at the 2011 party conference are to be taken at face value.[15]

The political aim of the Climate Change Act is, by saving ‘wasted’ expenditure on fossil fuels and further penalizing their use as an energy source, to create a ‘low carbon’ economy that will stimulate job-creating investment, ahead of the UK’s competitors. This is not just a radical energy policy, but a drastic re-engineering of the entire economy. Policy is wandering further and further away from market discipline by neglecting to incentivize the construction of plant needed to replace the coal-fired and nuclear capacity due to be retired over the next decade.

Electricity Market Reform (EMR)

Sensibly, if far too late, the energy regulator OFGEM recognised in 2009, through its “Discovery” study,[16] that the New Energy Trading Arrangements

15 http://www.guardian.co.uk/environment/damian-carrington-blog/2011/oct/03/george-osborne-carbon-emissions-conservatives

16 http://www.ofgem.gov.uk/markets/whlmkts/discovery/documents1/discovery_scenarios_condoc_final.pdf

(NETA) it had brought into being in 2002 were not fit for purpose in the second decade of this century. NETA was introduced in England and Wales on 27th March 2001 and replaced the "England and Wales pool trading system" introduced by the Conservatives, following electricity industry privatization.[17]

NETA replaced an electricity trading system that had rewarded both production capacity and actual energy production with a system that only allowed remuneration for pure energy trades, removing the reward for providing dispatchable[18] capacity in the Pool. The idea was to deliver electricity more efficiently and competitively. It did lead to a substantial, if short term, reduction in wholesale electricity prices and the concurrent forced sale of significant fractions of their capacity by the then dominant power generators, National Power and PowerGen. The short term electoral advantages were obvious.

At the time of its introduction, oil was still cheap (roughly $3/GJ, or $20 a barrel), and the UK's upstream industry was unconstrained in its hydrocarbon production, an extraction policy inherited from the previous Tory government. Given the low specific prices (themselves a consequence of political policy) the industry could only recover its high costs by maximizing extraction rates. This policy led directly to the almost complete evacuation of the nation's North Sea hydrocarbon resources within a generation. This is in contrast to the more conservation-driven policies of the Netherlands and Norway, whose policies have constrained extraction and will almost certainly ensure that terminal depletion will not take place as soon as is the case for the UK's reservoirs.

NETA certainly "constrained" electricity prices. British Energy and Drax Power Station, to name only two generating companies, were effectively bankrupted by the low price (gas-based) competition. Large US investors in the UK electricity generating sector, like Mission Energy, AES and AEP, lost many billions of pounds in consequent fire sales of premium coal-fired plants and

17 http://www.ofgem.gov.uk/Pages/MoreInformation.aspx?file=1098-factsheet0502_27feb.pdf&refer=Media/FactSheets

18 'Dispatchable' means immediately available and can be varied on demand. Wind and solar, by comparison, are intermittent, and nuclear provides base load capacity which cannot be ramped up or down very easily.

write-downs. To avoid premature closure and decommissioning, the Labour Government was forced to nationalize the whole of the nuclear power industry.

What NETA was specifically designed for – to cut short term prices – was achieved, providing fuel, especially gas, stayed cheap. What it could not do was to send any sort of appropriate pricing signal that would provide a suitable and diverse mix of generating capacity for the times to come when the UK would once more have to compete in the global market place for primary energy supplies. Those times have now come.

It is a huge paradox that the publication of *Discovery,* concluding that NETA (and its successor BETTA[19]) are not fit for purpose, and that radical electricity market reform is needed to incentivize the construction of a more diversified fleet of dispatchable power generators, has actually increased uncertainty in the investment community. Until the EMR has been concluded and a greater degree of certainty restored, generators are unlikely to start building new stations to fill the looming gap. Investors have not forgotten the many billions of pounds that were lost by the generators when NETA was introduced. They are determined not to be caught a second time.

19 British Energy Transport & Trading Arrangement, also covering Scotland

Paying for investment in renewables

The Renewable Energy Roadmap[20] is an attempt by the DECC to "plan" and incentivize the incorporation of massive amounts of renewable energy into the UK's infrastructure by 2020 (see Table 2). This is a hugely ambitious plan and, for the reasons explained shortly, is most unlikely to succeed in any case. This brings into question the feasibility of the road map – even under the most favourable circumstances – and therefore the wisdom of its forty year strategy.

Table 2: The planned contribution of renewables in 2020

Technology	Central range for 2020 (TWh)
Onshore wind	24-32
Offshore wind	33-58
Biomass electricity	32-50
Marine	1
Biomass heat (non-domestic)	36-50
Heat pumps (non-domestic)	16-22
Renewable transport	Up to 48
Others (including hydro, geothermal, solar and domestic heat)	14
Estimated 15% target	**234**

20 http://www.decc.gov.uk/en/content/cms/meeting_energy/renewable_ener/re_roadmap/re_roadmap.aspx

If 234 TWh (20 million toe) is to be 15% of all primary energy used in 2020 – the current government target – it is clear that the planned primary energy use in 2020 will be 133 million toe. In 2010, the UK's total primary energy use, including wastage, was just over 210 million toe. So by publishing this roadmap, the government is signalling its intention to drive down primary energy use by 77 million toe, or 37%, during the next eight years, largely by replacing fossil fuel used in electricity production with renewable resources.

As we saw in figure 6, roughly 31% of all primary energy use in the UK, totalling roughly 63 million toe during 2010, was lost due to the inefficiencies in the generation of electricity from coal and gas.[21] Wind and solar power produce electricity without any such "waste" of fossil fuels. If all the MWh of electricity produced from "sustainable" wood, photovoltaics and wind can replace MWh produced from fossil-powered equipment, then the savings in primary energy consumption and the consequent reduction in CO_2 emissions would be considerable. On the face of it, this is a very attractive proposition. However, it is seriously compromised by the need to supply electricity reliably when and where it is needed, not just when the wind blows or the sun shines. The other fly in the ointment is cost; the current generation of renewables technologies are not economically competitive with fossil fuels, even at current, relatively high, prices. But we should not forget that this is not just a question of economics; even a ten-fold increase in oil prices would still leave the intermittency problem to be solved.

A brief history of subsidised renewable energy in the UK

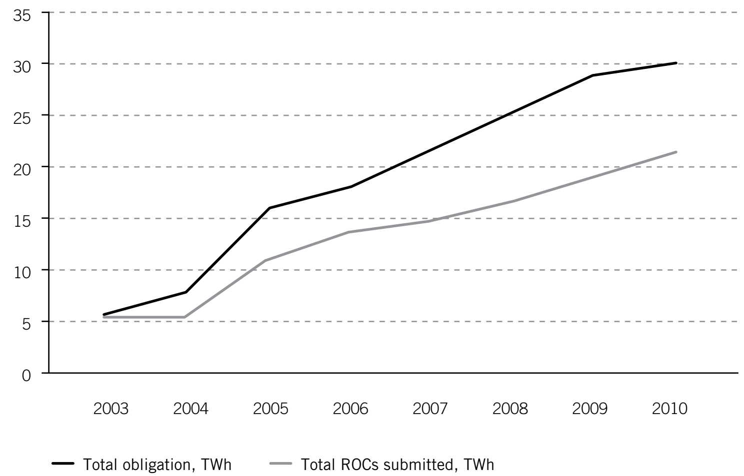
Incentives to encourage the use of renewables have been used for some time. The Non-Fossil Fuel Obligation (NOFO) was part of the Electricity Act of 1989. It got "renewables" started as a business, essentially by a levy on fossil fuels.

21 Such losses can be reduced hugely by capturing lost heat and delivering this to commercial and private customers in district heating systems. All thermal power stations in Denmark deliver both electricity and heat, during the winter with an efficiency exceeding 90%, averaging over 60% throughout the year. This compares with about 35% for UK thermal plant.

It was meant to encourage all types of non-fossil fuel generation, including nuclear. Its contribution to stimulating investment in the renewables sector was modest overall but, by the time it was replaced, it had driven down the cost of a "NOFO" kWh from 7p/kWh to 2.7 p.

The *Renewables Obligation* was introduced in 2002 mainly to distinguish Labour from Conservative policy and, significantly, it no longer included nuclear. It is complicated and subject to almost annual "tweaks", which means it is a nightmare to understand. It is a high cost option compared to the much simpler system of feed-in tariffs used elsewhere, and has signally failed to meet its objectives. Figure 8 shows the total "obligation" to generate renewable energy and the number of certificates (ROCs) submitted by generators to record their output. Over the entire period of the REO, the industry has been unable to generate the "obligated" renewable energy. Because the energy suppliers have an increasing commitment to buy (or make) the renewable energy, and are fined when they cannot supply the arbitrarily set quota, the consequent scarcity of ROCs drives up their value.

Figure 8: A Brief History of the Renewable Energy Obligation, TWh



Despite the high price of ROCs and the lowering of the original target for 2010, the delivery of renewable electricity is 28% below the reduced target and 35% below the originally intended 10.4% of electricity generated in 2003. This suits the renewable generators very well; the wider the gap between the obligation and the supply, the higher the value of the ROC and the greater their return. A cynical observer might even suggest that it is not in the interests of the renewable generators to see the obligation supplied at all. After all, it is consumers who underwrite and pay for the entire programme, whether successful or not. They have no choice.

Figure 9: ROCs charged to consumers (millions)

At the end of 2010, the cumulative cost of the ROCs programme has been over £5 billion and its cost to consumers in 2010 alone reached more than £1 billion. Banding of ROCs has now been introduced as a further tweak to speed up investments in more expensive technologies, such as offshore wind and domestic solar power generation.

The provisional new arrangements for banding are shown in Table 3.[22] By multiplying the target TWh (Table 2) by the new ROCs in Table 3, the annual cost of the ROCs programme looks set to rise to almost £6 billion per year before

22 Renewable Energy Foundation "*Renewables Output 2010*" (http://www.ref.org.uk/publications/229-renewables-output-in-2010)

2020. Of course, this will only happen if the current *Renewable Energy Roadmap is* adhered to and if the currently foreseen subsidies are more successful at stimulating investment than the ROC programme has been hitherto.[23]

Table 3: The latest proposed RO regime[24]

Generation type	Amount of electricity to be stated on an ROC
Electricity generated from landfill gas	4 megawatt hours
Electricity generated from sewage gas	2 MWh
Co-firing of biomass	
Co-firing of biomass	1 MWh
Onshore wind	
Hydroelectric	
Co-firing of energy crops	
Energy from waste with CHP	
Geo-pressure	
Co-firing of biomass with CHP	
Standard gasification	
Offshore wind	2/3 MWh
Dedicated biomass	
Wave	½ MWh
Tidal stream	
Advanced gasification	
Advanced pyrolysis	
Anaerobic digestion	
Dedicated energy crops	
Dedicated biomass with CHP	
Solar photovoltaic	
Geothermal	
Tidal impoundment – tidal barrage	
Tidal impoundment – tidal lagoon	

23 Renewable Energy Foundation, http://www.ref.org.uk/publications/238-the-probable-cost-of-uk-renewable-electricity-subsidies-2002-2030

24 http://www.decc.gov.uk/en/content/cms/meeting_energy/renewable_ener/renew_obs/renew_obs.aspx

As an aside, it is worth noting that this money would be enough to fund a very large nuclear programme. Under the present regime, funding for the first new nuclear plant, which could be commissioned by 2018-19, will have to compete with the massive renewables build-out that will precede it.

Renewable energy technologies: the competition

Before looking at specific technologies, we need to consider briefly what the alternatives are. For the UK, the previous reliance on coal has been transformed into dependency on gas, while the significant contribution of nuclear (peaking at about a quarter of total supply) will decline rapidly over the coming decade as existing stations are closed. This capacity has to be replaced, but the big question is with what. The following remain proven, viable technologies:

- Combined Cycle Gas Turbines, which are efficient, cheap and quick to build. However, the 'dash for gas' towards the end of last century has already resulted in a strong reliance on gas. The declining supplies from the North Sea fields leaves the country increasingly dependent on gas from geo-politically sensitive areas, particularly Russia, the Middle East and North Africa. The big unknown is the future impact of exploitation of shale gas deposits. Enthusiasts argue that there are enormous reserves which can be opened up to greatly extend the future security of supply and decouple oil and gas prices. Others believe the talk of vast new reserves to have been greatly exaggerated and suggest that little fundamental will change in the gas market over the coming generation. Whichever school of thought is proved to be right, gas will be a major part of the energy mix for the foreseeable future, but at an unknown cost.

- Pressurised Water nuclear reactors. Despite continued controversy, the recent reversal by the German government of its previous decision to maintain output from its existing nuclear plants, and fierce arguments over the costs and handling of radioactive waste, nuclear fission has been shown to be a reliable, safe and secure power source. In addition, there are good reasons to believe that the stringent limits on exposure to radiation – which may be significantly lower than background levels in some areas – are unnecessarily low and add considerably to construction and operational costs.[25] Nuclear power is also the only generation technology capable of providing a reliable base load with essentially zero carbon dioxide emissions. Further developments of fast breeder technology could make the fuel cycle more efficient and eliminate plutonium as an undesirable component of fuel rods at the end of their life. Beyond that, use of the much more abundant element thorium as a fuel for nuclear fission has a number of conceptual advantages, although there are many hurdles still to be overcome before it becomes a commercial reality.

- Modern coal-fired power plants also remain a reliable and cost-effective option, although their high levels of carbon dioxide emissions makes them unattractive based on current policy directions (this is not a constraint for countries not in Annex 1 of the Kyoto protocol, including South Africa and China). The EU response has been to encourage Carbon Capture and Storage technology, by means of which coal- (and gas-) fired stations could have their emitted CO_2 removed from the flue gases, compressed and injected into, for example, depleted oil fields or onto the deep sea floor. Although superficially attractive, this is an expensive option, has many serious practical problems which need to be overcome if it is to be used on a large scale, and is itself energy-intensive (the IPCC estimates an additional fuel usage of 25-40%; if widely deployed, it would put great pressure on productive capacity and tend to push up fuel prices). Despite some small-scale plants being built, the availability of EU funding has still

25 For example, see http://www.radiationandreason.com/uploads/RnR_AIreduced.pdf

not resulted in a full-scale demonstration plant being built.[26] Nevertheless, all new coal-fired plants planned for EU Member States must now be built with the capacity to be retro-fitted with CCS equipment.

26 http://www.bbc.co.uk/news/uk-scotland-north-east-orkney-shetland-15371258

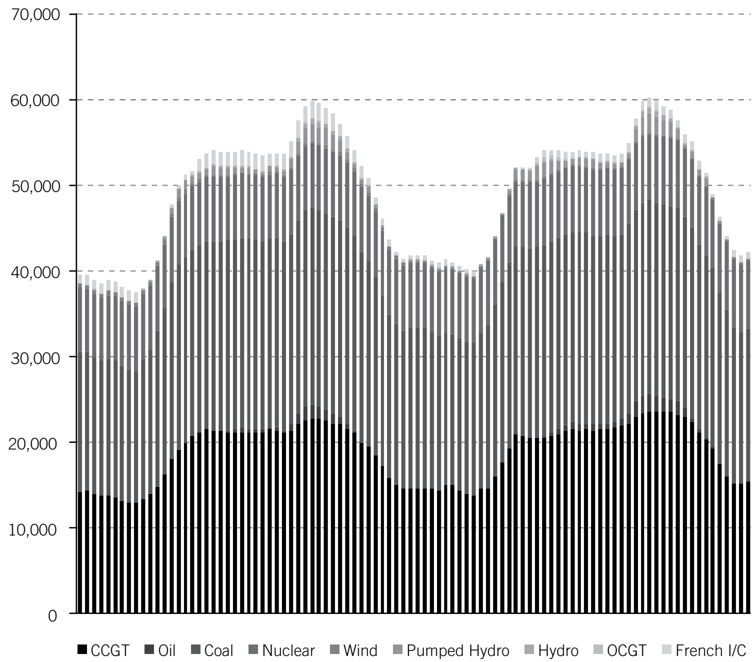
Renewables technologies commercialised or in development

Wind power

The need for backup

The focus of the government on CO_2 emission reduction by the introduction of renewable energy has resulted in all the large generators taking large stakes in the highly subsidised wind industry, where their returns on sites with good wind characteristics can be spectacular. However, the amount of wind power available will always be dependent on the weather. Back-up, dispatchable power plants must always be available to supply demand and balance the grid for the demand for power that the wind is not producing. On the 6th and 7th of December 2010, two cold days, during which mainland UK demand reached 60,000MW, wind output from a nominal national wind capacity of over 5,000MW was between 200 and 300MW (see figure 10). Power supply on these days relied almost entirely on gas, nuclear, oil- and coal-fired plants, together with some imported power from France.

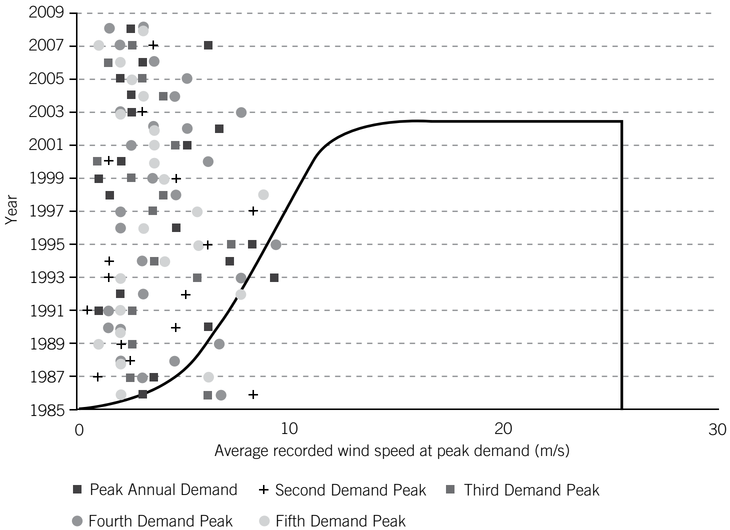
Figure 10: UK Electricity Supply, MW



Wind cannot always offer much at times of high demand
6 & 7 December 2010
(BM Reports)

It so happens that this situation is quite typical for NW Europe. Winter peak power often coincides with very large, slow-moving anti-cyclones, which bring extremely cold weather and almost no wind; therefore little or no wind power output is possible. On these days, the anticyclone covered the whole of NW Europe. Further south, similar events during summer coincide with peak air-conditioning loads.

Figure 11: GB Wind Overview



The wind tends to blow at the wrong time
(The curve shows the output of a wind turbine as wind increases)

The more general point is well illustrated in Figure 11 from the National Grid[27] which illustrates that generally, peak load occurs when wind power is low.

Total "firm" (that is to say, dispatchable) generating capacity stands today at around 74GW (a figure that excludes Northern Ireland and all wind power).[28] The chart illustrates that no matter how much wind capacity is built, to ensure that the lights stay on and that the grid remains strong, there can be very little reliance on it.[29] Its only useful role in the system is to save fossil fuel – and therefore CO_2 emissions – and this in itself is limited because of the need to have conventional capacity on standby.

27 Future System Operations, Sam Matthews, National Grid
28 DECC – Dukes Table 5.11
29 National Grid assumes that 5% of wind power capacity can be relied upon at peak demand (source: author's private correspondence with National Grid)

Of the plant that supplied the back-up power on those days in December 2010, 11GW of old, polluting but reliable coal- and oil-fired capacity is scheduled to close by 31st December 2015[30] (although it is not inconceivable that the UK government would request a derogation if energy security was threatened). Over the same period, about 3.4GW of nuclear will also close unless the life of these power plants can be extended further. This is almost 15GW in all; about one-fifth of the current total. So unless that can be replaced, there is a high risk of a capacity crisis by the middle of this decade. Not only will consumers be paying more for their electricity, but they may not even get a secure supply.

But because the government's plans for wind power are so ambitious, the hours of full-load operation of the replacement dispatchable equipment, brought in to "back up" wind, will be reduced by an unknown amount, as wind power will always have priority for access to the system. Under the present trading arrangements, the revenue of the back-up plants will be reduced. This "lost" revenue can only be replaced by having another stream of income to compensate for the unknown (and still unknowable) loss of sales and the extra cost of operating plants that will start and stop more frequently and must also ramp up and down, which reduces efficiency, increases wear and reduces life. We should also mention the problem of more wind power being generated than the grid can cope with at windy times. Not only does wind power need under-utilised backup generators for continuity of supply, but their operators also receive constraint payments to switch them off when their output is not needed.

As this report is being written, the EMR proposals have been published. But the important issue of how to reward dispatchable capacity remains "under consultation", at least until the end of 2011. It is therefore most unlikely that any of the many proposed CCGTs that have been licensed, have planning permission and have agreements to connect to the system, will be built before the terms of such capacity payments have been agreed. The investors will then re-assess the risk, negotiate a gas supply contract and put in train the purchase and construction of the power plant.

30 The closure of these plants, that did not fit sulphur dioxide reduction equipment on time, is mandated by agreement with the EU.

Given the lack of time, it is most unlikely that any coal-based power plants, with provision for carbon capture and storage, can be built and commissioned by the end of 2015. New nuclear is unlikely to be licensed, built and commissioned until at least 2018/19. So to keep the lights on from 2016 until this comes on stream, the country will be relying on large numbers of new open cycle gas turbines being built between 2012 and 2015. Our dependency on imported gas will be further increased.

The Story so far

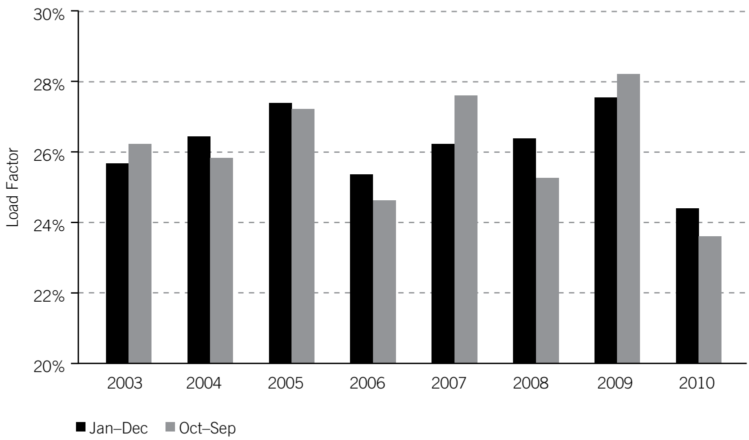
Given that the UK government is relying heavily on wind power to reduce the carbon intensity of the electricity system, we need to look at the experience to date.

At the end of 2010, the nominal wind power capacity was 5GW, of which just over 1.5GW was offshore. The report by ILEX Energy (*Quantifying the Cost of Additional Renewables in 2020*, commonly called "*SCAR*") was published in October 2002.[31] It confidently foresaw an average capacity factor[32] for onshore wind power of 30% and for offshore wind of 35%. These assumptions were accepted by the then DTI and to the best of our knowledge have never been re-visited.

The year on year capacity factor for UK wind is shown in the following chart.[33] Averaged out, this comes to 25.8%, or approximately one quarter of the rated output.

31 http://www.ilexenergy.com/pages/Documents/Reports/Renewables/SCAR.pdf
32 Capacity factor equals (total energy produced)/(8760*rated capacity)
33 Low wind power output in 2010, Renewable Energy Foundation, February 2011

Figure 12: UK Windfarm Fleet load Factors by Year



Oct-Dec 2010 are REF estimates

The average capacity factor for offshore wind is 28% and for onshore, 24%. However, better may be achieved with more development: the capacity factor for Danish offshore wind farms is over 40%[34] while the best performing UK offshore wind farm so far is Inner Dowsing which has achieved 34%. Nevertheless, at present the average capacity factor for onshore wind is 25% lower than foreseen upon publication of the ROCs legislation and even the target capacity factor of 35% for offshore wind in the UK may be unrealistic. The misplaced optimism of DECC (and its predecessors) over the future price of fossil fuel seems to be matched by its expectations of what renewable energy could deliver.

To achieve its targets for 2020, the government hopes that onshore wind power can be expanded from 4GW to something between 11 and 14GW, while offshore wind expands from 1.5GW to between 11 and 19GW (assuming

34 http://www.pfbach.dk/firma_pfb/statistical_survey_2010.pdf

a 35% capacity factor). The target for installed wind power is thus something between 22 and 33GW, with Ministers appearing to favour the higher end of this range.

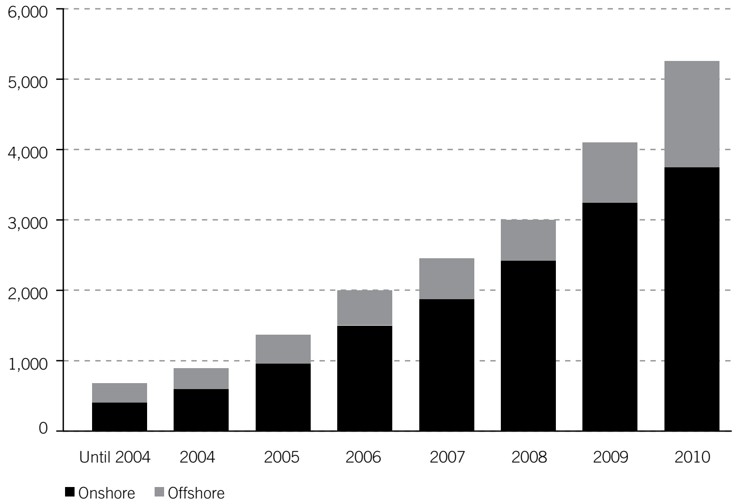
Physical feasibility queried

Few experts outside DECC and RenewableUK, the trade body representing wind and marine power companies, believe that such ambitious targets are physically or financially achievable. As an example, to deliver 18GW of offshore turbines, each, say, with a capacity of 3.6MW,[35] will require the construction of 5,000 turbines during the roughly 3000 days left until 2020. Optimistically, there will be roughly 120 days per year, 1080 days in total, that will be suitable for offshore construction. So with nine years remaining to 2020, almost 5 turbines must be installed each working day, starting now, and then all the way through to 2020, in order to achieve the target.

At 630MW, the London Array[36] will be the largest offshore wind farm ever constructed. The project started in 2001 and aims for commissioning in 2013. It stretches credulity to believe that between 2011 and 2020, 28 more projects equivalent to the now ten year-old London Array, can be conceived, planned, financed and constructed. (More information on offshore wind farm construction can be found on the BBC website).[37]

35 This is the turbine size used in the London Array, http://www.londonarray.com/the-project/
36 http://www.londonarray.com/the-project/
37 http://www.bbc.co.uk/news/science-environment-14412189

Figure 13: Cumulative UK Wind Capacity MW



The growth of wind power in the UK

The average rate of wind capacity construction since 2005 has been an impressive 937MW per year on-shore and 440MW per year off-shore.[38] At a similar rate of build, the commissioned capacity by 2020 could therefore be 18GW total. In order for the target of between 22GW and the preferred 33GW to be reached, the rate of construction must more or less double. This seems unlikely, even if popular resistance to new, large, on-shore wind farms were not a factor. The even greater ramping up of construction of offshore wind farms, which are less likely to be objected to, is subject to much greater practical constraints, as we have already seen.

The other practical factors which must be taken into account are reliability, maintenance and service life. Not only do gearboxes fail and need to be replaced, but blades also break from time to time. Repairing turbines is not a

38 http://www.bwea.com/ukwed/index.asp

simple task on-shore, but the problems off-shore are much greater. This not only adds to operating costs, but reduces the number of turbines which can operate an any time. The ultimate factor limiting life is likely to be the condition of the supporting column. In any case, service life of wind turbines is normally expected to be 20 years – much shorter than for coal, gas or nuclear stations – and refurbishment would not be an option at end of life, in contrast to much conventional generating plant.

Popular resistance to onshore wind developments

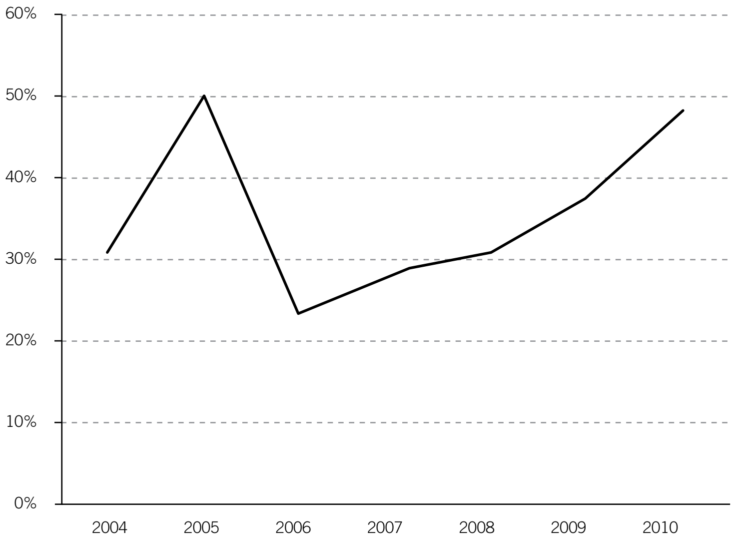
Danish wind developers have more or less given up trying to install large, modern turbines on land,[39] as Danes do not want them to intrude on their small-scale landscape. Denmark's ambitious plans for further increases in wind capacity will be fulfilled with very large offshore wind turbines, which will be built "over the horizon".

Figure 14: Wind turbines in the Danish landscape[40]

39 http://stilhed.eu/
40 http://stilhed.eu/wp/wp-content/uploads/2011/03/taasinge01.jpg

Those wishing to drive the construction of more wind capacity in the UK should take note that such opposition is widespread, with the great majority of proposals spawning local groups objecting on grounds of visual intrusion, noise,[41] flicker, reduced house value and wildlife destruction. Despite wind power only delivering 3% of UK electricity in 2010, there is already a high and rising rate of local resistance, as illustrated by refusals of local (democratically elected) councils to provide building permits for new, mostly very large, onshore wind turbines.[42]

Figure 15: % Applications onshore refused



Rising popular resistance to large on-shore turbines

However, because onshore wind power is so much cheaper than offshore, the present government, like its predecessor, would dearly like to override local

41 See, for example, Shepherd et al; Evaluating the impact of wind turbine noise on health-related quality of life; Noise and Health; 2011, Vol 13 (54); pp 333-9

42 http://www.bwea.com/ukwed/index.asp

concerns in its drive to achieve the 20-20-15 targets. Any Government doing so against wide-scale opposition can expect to be punished by its electorate.

Deteriorating "wind quality" of remaining building locations

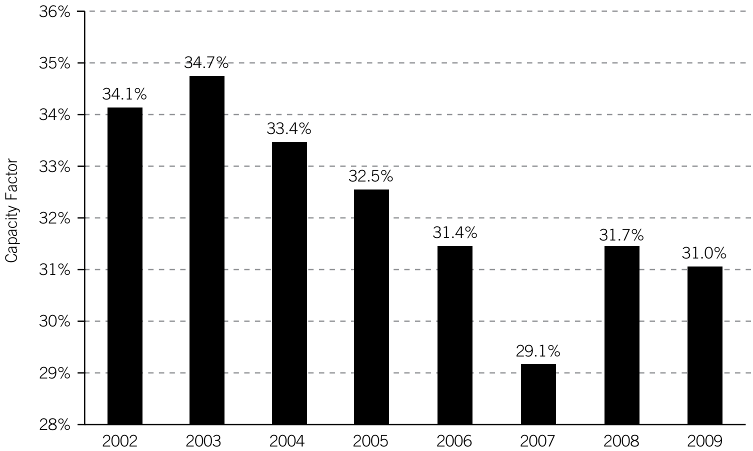
Despite the hype, the UK is not a particularly windy country. It compares poorly with other wind energy hotspots, such as the Great Plains in the USA where the average load factor can be 40%. A very high proportion of wind farms in England, particularly in the east, have a load factor under 20%. That the national average load factor is higher is mainly because it is boosted by very large, utility-owned wind farms at prime, windy locations, mostly in Scotland and North Ireland. But even so, investment in wind farms is not a commercial proposition without subsidies.

Ireland has built on-shore wind power much more aggressively than the UK. Currently, roughly 13% of electricity generated and sold on the Irish system is from (mostly on-shore) wind power.[43] This gives another point of reference for a future UK system with a higher penetration of wind. The first thing to note is that, as Irish wind capacity has risen, its overall load factor has declined. Figure 16, which illustrates this, was part of a presentation by Eirgrid's Dr Jonathan O'Sullivan at the *Irish Renewable Energy Summit in Dundalk*, 20th January 2011.[44]

43 http://www.eirgrid.com/operations/

44 Reference supplied by the Renewable Energy Foundation

Figure 16:The declining wind capacity factor in Ireland[45]



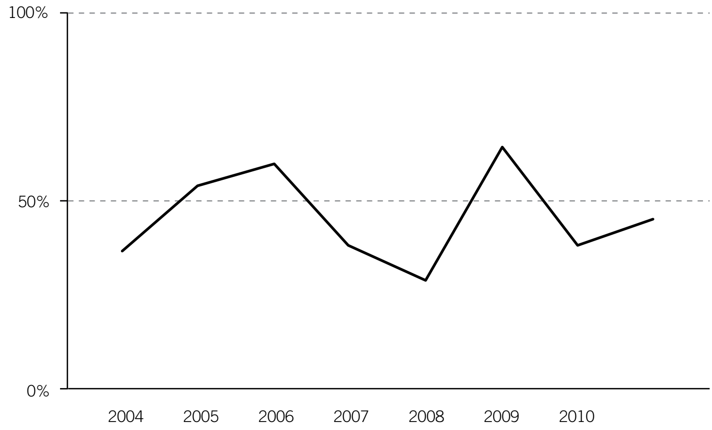
Currently, the share of wind-generated electricity in the UK is roughly 3%, similar to Ireland's in 2002. If Ireland is a good proxy for its eastern neighbour, then politicians and policymakers should take note that, as the UK on-shore wind fleet expands, and the number of prime wind locations diminishes, its already modest national capacity factor is also likely to decline even further. If it declines at a similar rate to Ireland's, wind power, already 25% less productive than Government models assume, will become progressively less economic. Overriding local objections surely requires a stronger rationale than that.

Low take-up of approved applications

Between 2004 and 2010, planning permission was sought for 17GW of wind, on- and off-shore. Of this, 11.8GW was approved, with not a single offshore scheme being turned down. Yet at the end of 2010, the total installed capacity was just 5,259MW. In other words, a high proportion of approved wind farms have not been built at all.

45 http://www.eirgrid.com/media/GCS 2011-2020 as published 22 Dec.pdf

Figure 17: % onshore capacity built vs applications approved[46]



One reason for this failure could be the difficulty of receiving a connection to the Grid: windy sites are often far from existing infrastructure. Some operators also argue that the financial reward is not commensurate with the risk. But wind power operators in the UK receive a higher subsidy per MWh than in other countries in the EU. This includes those like Denmark and Germany which have incentivised a high penetration of wind power, and yet appear to get much more value out of their public support programmes.

Why is the UK's renewable energy programme so expensive?

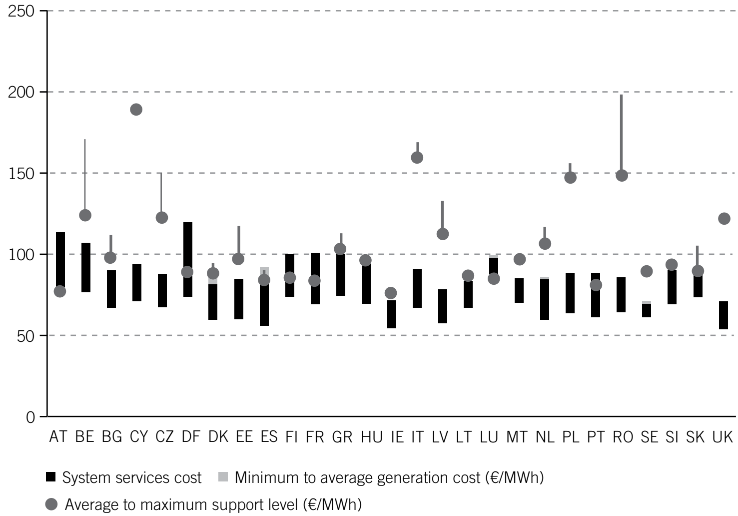
Figure 18 compares the cost of wind generation and levels of subsidy for EU Member States (from a study by the *Fraunhofer Institute* of Germany published in an internet article by the *Alliance for Renewable Energy*[47] promoting the use of feed-in tariffs for incentivizing wind energy). Promoters of renewable energy often claim that the UK's wind conditions are "the best in Europe". However, its subsidies are among the highest of those that are aiming for a high penetration of wind power. Subsidies are contractually guaranteed for up

46 Renewable UK: http://www.bwea.com/statistics/year.asp

47 http://www.allianceforrenewableenergy.org/2011/02/status-of-feed-in-tariffs-in-europe-2010-.html

to 20 years (longer in some instances), while payback periods may be as short as five years. In particular, note how subsidies in Ireland, Germany, Denmark, Spain and Portugal are so much lower than in the UK, while their average generation costs appear to be at least as high.

Figure 18: Current level of support and costs per Member State



Generation costs and levels of support for wind power

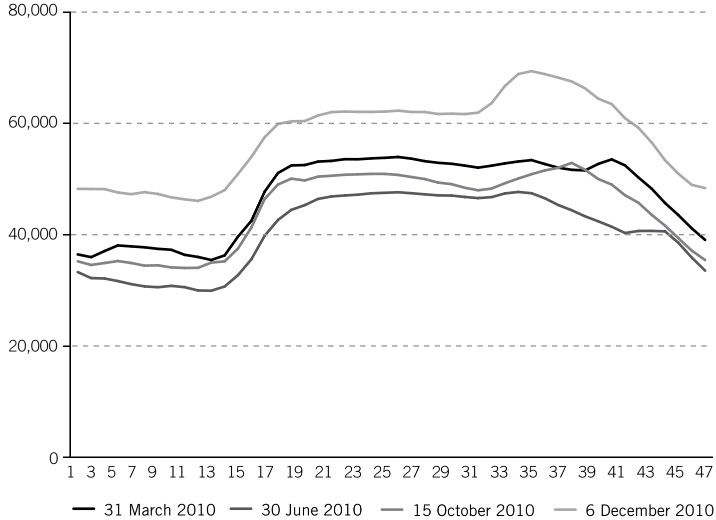
Example of wind onshore – Dec. 2009

Wind overflow may preclude the construction of dispatchable balancing capacity

While the contribution of wind power to overall demand at peak times will be unpredictable, as installed capacity grows there may be a problem of *excess* generation at night. Figure 19 shows that the night time system load is usually below 30GW in the summer and hardly more than 40GW in the winter. So with the amount of wind capacity proposed (33GW), there will be many occasions when unconstrained wind power will be a high fraction of total demand or may exceed all demand.

The recent Eirgrid/SONI report[48] recognises additional problems of voltage control and synchronous inertia that will further increase constraints beyond those imposed by transmission, ramping capability and response plant. A practical upper limit on the contribution of wind power to the grid at any one time could be about 50%; excess power would have to be spilled.

Figure 19: Half Hour UK Electricity Demand 4 working days, 2010, MW[49]



Seasonal electricity demand

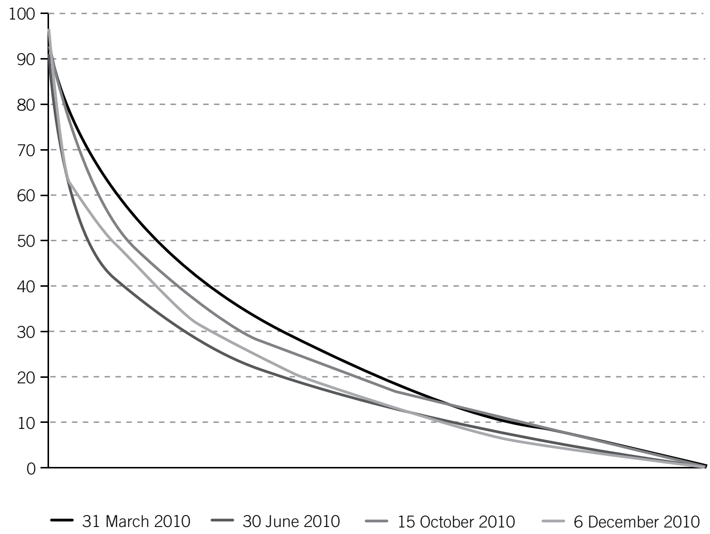
Source: National Grid

48 http://www.eirgrid.com/media/GCS 2011-2020 as published 22 Dec.pdf

49 http://www.decc.gov.uk/assets/decc/11/about-us/Science/3150-final-report-changing-energy-use.pdf

The load duration curves[50] in Figure 20 indicate that the total installed wind capacity in most European systems never delivers 100% output (most of the time, it actually delivers significantly less than half its potential output). But if the UK's "road map" plan is delivered, there will be a high coincidence of high wind with low demand, which would increase the uncertainty for the investors in dispatchable balancing capacity.

Figure 20: Wind Power Duration Curves % 2010



Load duration curves
(The y axis shows output as a percentage of installed wind capacity while the x-axis is the period over the year)

For so much wind power to work in a way that does not call for frequent and expensive curtailment, the rest of the system should be balanced in an altogether different way compared with today. The new nuclear fleet which (hopefully) will be coming on stream in the 2020s can provide most of the base load (and do so more cheaply than wind power). Although it can and

50 *Enlarged wind power statistics 2010* by Paul-Frederik Bach (www.pfbach.dk)

does follow load, nuclear is capital intensive and its fuel cost is low, so it is best that it should not be cycled. Should new coal-fuelled power plants (complete with as-yet-unproven Carbon Capture and Storage systems) also be built, similar considerations will apply.[51]

Therefore there is a high risk that the commitment of the UK to such a large expansion of wind power before 2020 will almost certainly preclude the possibility of investment in diversified and efficient generating capacity which cannot be rapidly ramped up and down to balance the output of the wind farms. Given this, it would surely be sensible to aim for a level of wind penetration that allows for a fully diversified generating portfolio, which must include nuclear. The case for a lower and more pragmatic wind capacity target was argued by one of the authors in two papers published by the *Institution of Civil Engineers* in 2006.[52] At the time, the author hazarded a guess that the UK should aim to build no more than 10GW of wind power so as to optimize its effect. There is more on this subject later in the report.

Solar

There are only modest ambitions for the use of solar power in the UK, which seems appropriate given its high cost and low efficiency at such a high latitude. Nevertheless, it is something we have become familiar with as solar panels increasingly appear on roofs and in fields. Given this, readers should be familiar with the principles and limitations of technologies under this heading. It may surprise them to know how little value is extracted from an approach being actively promoted by the government, albeit at a lower level than wind.

There are two types of solar power. The first, and more familiar, is photovoltaic, using arrays of cells that convert sunlight directly into direct current electricity.

51 The authors believes that the odds against CCS ever being successfully upscaled are widening rapidly and this technology will never become commercial. However, this is outside the scope of this report.

52 http://www.icevirtuallibrary.com/content/article/10.1680/cien.2005.158.2.66 and http://www.icevirtuallibrary.com/content/article/10.1680/cien.2005.158.4.161

Most solar power schemes are based on these cells. The second uses sunlight to heat a liquid that boils and drives a turbine. Some observers believe that there is great potential in this technology but it is losing out to PV where the costs are falling more rapidly. This technology is also quite unsuited for northern Europe, but it could be a component of the supply if a (technically feasible but hugely expensive) Europe-wide grid was to be constructed.

One financial disincentive to solar power is the large land area required. A 1000MW Concentrated Solar Power facility requires 6000 acres of land, enough for about ten coal-fired plants with the same rated output. Producing 1000MW from photovoltaics requires over 12,000 acres of land. Nuclear power stations need much less land than even coal-fired ones; their land use is minuscule compared with renewables.

The current worldwide installed solar capacity is about 40,000MW of photovoltaic power and about 1,170MW of concentrated solar power.

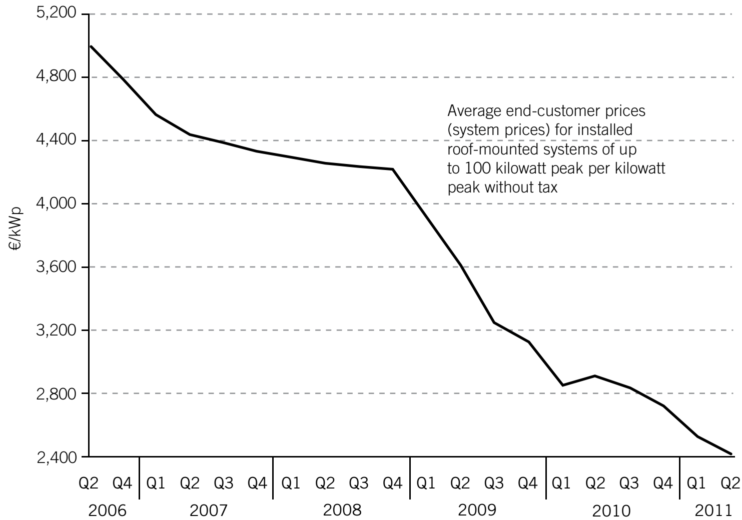
The development of solar power is driven entirely by subsidies, since the costs are significantly higher than those for conventional sources. These can be in the form of direct grants, tax breaks, "Renewable Portfolio Standards", "net metering" and others. Net metering, for example, offers a consumer with a domestic solar panel the same price for imported and exported electricity. To give an example, if the import and export are equal, the consumer pays nothing. The consumer exports electricity to the grid when, to a large extent, it is not needed, such as on summer afternoons. In return, the consumer takes electricity from the grid every night and, in particular, on cold cloudy winter days and nights. But because he pays nothing for the electricity, he makes no contribution to the cost of the transmission and distribution system and the cost of the generation and fuel to provide his electricity when the sun is not shining. Because the costs imposed by net metering are left with the electricity distributor rather than being paid by taxpayers, the metering finishes up being a subsidy from poor consumers who cannot afford solar panels to rich consumers who can. In the UK, the chosen method is to pay a (high and guaranteed) "feed-in tariff" for every unit of electricity generated, whether it is sent to the grid or used at source. Germany takes a similar approach.

Without these subsidies, it is safe to say that the grid-connected solar energy industry would not exist. As a result of them, solar power is being developed in countries in northern latitudes where the sunshine is less intense and skies are often cloudy. Typical capacity factors in desert areas are about 21%, but in high latitudes they can be 10% or less. This leads to the absurd situation where Germany is the world's leading market for photovoltaic systems, with a total installed capacity of 17GW at the end of 2010. Over 7GW of that was installed in 2010 alone, and the German government is now reducing the very generous feed-in tariffs to slow the boom in the industry and control the €13bn paid out annually in incentives.[53] The UK government is taking similar action.[54]

However, despite the current high cost of PV cells and their low output at times of high demand at high latitudes, greater manufacturing efficiencies and economies of scale have brought prices down significantly. For example, data from Germany shows that the installation cost per kW has halved in the last five years (see figure 21).

53 http://www.reuters.com/article/2011/02/24/germany-solar-idUSLDE71N2KG20110224
54 http://www.decc.gov.uk/en/content/cms/news/gb_fits/gb_fits.aspx

Figure 21: PV system prices decrease steadily



PV installation costs in Germany 2006-2011

Source: BSW-Solar PV Price Index 5/2011

A major disadvantage of solar power in high latitudes is that system peak demands nearly always occur in winter evenings. This is when solar power output is very low or, more often, zero. As a result, solar power generates most energy when it is not needed and virtually none when it is. The only way of mitigating this problem would be to come up with a technology that can provide low-cost, efficient long-term storage for electricity. No such technology yet exists and none is on the horizon.

To use the example of Germany again, in 2010 the total amount of energy generated by photovoltaics was just 12TWh, or 2% of the total output of 603TWh.[55] If we assume an average PV system capacity of 13GW over the whole year, the theoretical output would have been 114TWh, giving a capacity factor of just 10.5%. A less efficient use of taxpayers' money would be hard to

55 http://www.renewableenergyworld.com/rea/news/article/2011/03/new-record-for-german-renewable-energy-in-2010

find. The situation is exacerbated by concerns over the ability of the electricity grid to cope with such an intermittent source of power.[56] Although the capacity factor is rather small, peak output on a sunny summer's day could approach the total rated capacity, which would be the equivalent of turning on several major conventional power stations at once, at a time of low demand.

Dust can be a major problem with solar power systems. A relatively small amount of dust can cause a large reduction in solar output.[57] Cleaning solar cells and solar reflectors can lead to considerable expenditure. According to one source, it costs about $15,000 to clean 1MW of solar panels 3 times per year.[58] If the solar cells are in a desert the problem can be much greater because, in many cases, dust storms happen more frequently and cause a dramatic loss of output. One factor that does not seem to have received much attention in the literature is that of "sandblasting" in the deserts of the Middle East (and presumably in others). A severe dust storm can sandblast car paintwork and damage windows and, presumably it will damage the surfaces of solar cells. It can also erode cable terminal boxes and other electrical equipment. Clearly, there is a risk of losing all the solar panels in an installation during one severe sandstorm. Cleaning panels usually also requires water, which is scarce and expensive in the desert. Such factors further reduce the attractiveness of the concept of supplying Europe from PV farms in North Africa.

Concentrated Solar Power (CSP)

With this technology, mirrors are used to concentrate sunlight and generate electricity indirectly. In most cases the sunlight boils a liquid in a tube which, in turn, drives a heat engine and generator. A few use mirrors to boost the performance of photovoltaic cells. Figure 22 shows a typical system[59] with reflectors and a tower.

56 http://www.upi.com/Business_News/Energy-Resources/2010/10/19/German-grid-aching-under-solar-power/UPI-13471287518368/

57 http://www.thenational.ae/news/uae-news/environment/dust-clouds-sap-uaes-solar-panels-power

58 http://www.procleansolar.de/en/solar-farm-cleaning/costs-benefits-.html

59 http://www.trec-uk.org.uk/csp.htm

Figure 22: A concentrated solar power array

This technology is not directly relevant to the situation in the UK (or, indeed, in any other country this far north). However, one of the key elements of a new European electricity system is the installation of a long-distance, direct current grid to balance power generation and demand over much greater areas than is currently the case. With this enormously expensive system in place, large concentrated solar power plants could be built in North Africa, where they would operate more efficiently, to supply European customers. The Desertec Industrial Initiative, a consortium of energy, construction and investment firms based largely in Germany, has announced that it plans to start construction of a 150MW capacity solar thermal plant in Morocco before the end of 2011.[60]

There is considerable debate as to whether CSP is cheaper or more expensive than photovoltaic. It would appear that not enough concentrated solar projects have been commissioned and costs published for any reliable assessment to be made. There are a number of large farms of this type in the United States

60 http://www.businessgreen.com/bg/news/2121579/report-desertec-start-african-solar-plant

and in Spain, but it seems that they are not going ahead at anything like the rate of photovoltaics.

It is said that solar thermal plants can store energy for short periods and this makes them less vulnerable to passing clouds and enables them to generate some power in the evening. Presumably this involves extra cost. But this is still a long way from the days and weeks of storage which are needed to make them comparable with conventional power generation.

Photovoltaics

Outside the UK and Germany there are many large photovoltaic installations. The biggest are just under 100MW. As a scale effect applies, larger schemes are more economic, but in many countries subsidies have tilted the field heavily towards smaller installations. For example, in the UK, the government introduced the following feed-in tariffs in April 2010:[61]

- Less than 4kW – 43.3p/kWh in first year, declining to 18.8p over 10 years
- 4-10kW – 37.8p/kWh, reducing to 16.4p
- 10-50kW – 32.9p/kWh, reducing to 14.3p
- 50-100kW – 32.9p/kWh, reducing to 8.5p
- Greater than 100kW – 30.7p/kWh, reducing to 8.5p (but with different rates of decline depending on size and when installed)

The policy specifically favours small-scale, often domestic, installations which are intrinsically less cost-effective. Many householders, not surprisingly, are putting their money into such schemes, which offer payback periods of less than ten years, and a considerably higher rate of return (government guaranteed) than offered by bank savings accounts. However, this boom is likely to be short-lived: the government has already announced cuts in the subsidies available for installations registered after 11 December 2011.[62]

61 http://www.ofgem.gov.uk/Sustainability/Environment/fits/Documents1/Feed-in%20Tariff%20Table%201%20August%202011.pdf

62 http://www.decc.gov.uk/en/content/cms/consultations/fits_comp_rev1/fits_comp_rev1.aspx

It is difficult to understand this discriminatory policy. If the objective is to reduce emissions of carbon dioxide, and if (against all the evidence) it is decided that massive subsidies for solar power are an effective way of doing it, then all the subsidies should be the same.

House mounted solar cells have their own set of problems. If one of a bank of solar cells is shaded, the output of the whole bank is reduced. Also, because their angle and direction is dictated by the roof, not by the need to align it accurately with the Sun, the output of most house mounted solar cells will be less than optimum. Finally, all solar cells need regular cleaning. If the householder does it, it will be dangerous and if a contractor is brought in, it will be expensive. So the end result will be that most won't be cleaned and will soon be producing much less power.

According to the database established by the Renewable Energy Foundation,[63] in mid-2011 there were 42,400 solar photovoltaic installations with a total capacity of 116MW in the UK. The average size of these installations was 2.75kW. By contrast, there were 153 installations above 15kW with a total output of 4.3MW and an average size of 28kW. Clearly the subsidies have led to a proliferation of small, seriously uneconomic installations, in a political move to encourage micro-generation, presumably to increase public support for renewables. Of course, the power generated and used directly at the installation site does not suffer from transmission losses, but the power which flows into the grid does.

The minimum cost of solar power can be estimated for a 1000 kW installation as follows:

Cost of solar cells[64]	$1,000,000
Cost of inverter[65]	$700,000
Cost of installation etc	$200,000
Total	**$1,900,000 ($1900/kW)**

63 http://www.ref.org.uk/energy-data
64 http://solarbuzz.com/facts-and-figures/retail-price-environment/module-prices
65 http://solarbuzz.com/facts-and-figures/retail-price-environment/inverter-prices

In the UK, the capacity factor would not be above 9%,[66] and could be significantly less. To generate the same amount of energy as a nuclear station with a capacity factor of 90%, 10,000MW of solar power would be needed to be equivalent to 1000MW of nuclear power.[67] Based on these figures, the equivalent installation cost of a large PV farm is $19,000/kW. This is more than three times the cost of nuclear power, and even more when an allowance is made for backup generation. In contrast to the price calculated above, home installers typically offer to install a 2.5 kW unit for £12,500.[68] This works out at £5,000/kW of nominal capacity ($8000/kW). The price is then more than $50,000/kW of actual output, or more than eight times the cost of nuclear!

Huge installations are being proposed in the North African desert (in particular, the Desertec Foundation[69] promotes the use of deserts around the world to generate power) in spite of the fact that there appears to be no prospect that they will be competitive with conventional generation or nuclear power at the current stage of technology development. The concept is that power would be distributed Europe-wide using a proposed direct current grid, so even something as far away as this could conceivably contribute to the UK's energy supply. However, there is still the unsolved problem of providing the longer term energy storage needed before solar power can supply most of the load of a typical power system. If the solar cells are in a desert the dust problem mentioned above can be much greater because, in many cases, dust storms happen more frequently and cause a dramatic loss of output.

66 According to http://re.jrc.ec.europa.eu/pvgis/download/download.htm the capacity factor of UK solar cells at an optimum angle is 9.5%. Cells in Cyprus would have a capacity factor of 16.3%

67 But even then, it is not equivalent because the solar units generate no power at night and during winter evenings when the system load is highest. At the very least, 1000 MW of backup generation is needed. This will be inefficient open cycle gas turbines as they are the only ones that are able to react sufficiently rapidly.

68 http://www.solarcentury.co.uk/homes/how-to-buy/buy-outright/

69 http://www.desertec.org/?gclid=COaq3O-SjasCFUUNfAodhUVkvw

Figure 23: A large photovoltaic array in Spain

To give another example, the huge Olmedilla photovoltaic farm in Spain has a rated capacity of 60MW for a cost of €530 million. This works out at $8800/kW of nominal output. Given that the capacity factor is 16.5%, it is a very poor investment indeed. The Spanish government appears to have recognised this and has recently reduced the subsidies considerably.[70] Previously, they were ten times the price of wholesale power. The subsidy was so high that some solar farms found it profitable to exploit the system by installing diesel generators to boost the output.

Biomass

UK government plans for biomass as an energy source are ambitious. The renewables roadmap has mid-range estimates of 41TWh of electricity and 43TWh of non-domestic heat to be generated from biomass by 2020. In addition, the roadmap expects up to 48TWh of energy in the form of transport

70 http://online.wsj.com/article/SB125193815050081615.html

biofuels. The grand total – 122TWh – is considerably larger than the 73TWh of electricity planned to be contributed by wind power. DECC estimate biofuels in 2010 to have supplied about 14TWh of transport energy. The major part of this in the UK (and the EU generally) is biodiesel, plus a smaller amount of bioethanol. Biodiesel is produced from European oilseed rape or imported palm oil, depending on market prices. Ultimately, producing crops for either biodiesel or bioethanol (currently made from cereal starch or sugar cane) competes with food production and puts more pressure on available arable land. Neither biofuel is a direct replacement for conventional fuels. Bioethanol tends to pick up moisture, which precludes its transport in pipelines and can cause engine corrosion if used at high levels, while the physical properties of biodiesel make it unsuitable for use above about 20% in many engines. Both fuels have a lower energy density than their conventional equivalents.

Biomass for electricity generation or heating is superficially more attractive, since the feedstock is agricultural by-products or forestry waste (but also dedicated energy crops such as miscanthus). A purpose-built straw-fired power station was built as long ago as 2000 near Ely in Cambridgeshire (operated by Energy Power Resources).[71] But biomass may also be used to co-fire existing stations. Drax, the largest coal-fired generator in the UK, has expanded its use of biomass over time (averaging 7% of its output in the first half of 2011, and capable of increasing that to 12.5%) and now plans to become mainly a renewable electricity plant.[72]

While it makes sense to use short-rotation coppice, other energy crops or agricultural by-products if they are economically competitive, in practice biomass suffers from two key drawbacks: it has a low energy density[73] (and is therefore expensive to transport and handle) and there simply is not enough of it. Thus, the Ely station already mentioned is quite small (rated at 38MW and generating 270GWh annually) because it relies on a

71 http://www.eprl.co.uk/assets/ely/overview.html

72 http://www.draxpower.com/

73 4166kw per tonne for straw, compared to 7583kw per tonne of coal; http://www.nef.org.uk/logpile/faqs.htm#_Toc120012284

comparatively small hinterland from which to source straw (its primary fuel) economically. Nevertheless, it is the largest straw-burning power station in the world, and requires 200,000 tonnes of straw a year, supplied by a sister company.

A study by the Central Science Laboratory[74] gives a figure of 2.75-4 tonnes/ha of recoverable cereal straw at 85% dry matter (typically about 60% of total straw, with the rest being ploughed in and helping to maintain the level of organic matter in the soil). The authors estimated a potential total straw yield of 11.9 million tonnes for the UK in 2007, with over half coming from wheat. After subtracting the quantity used for animal bedding, mushroom growing and similar added-value uses in the farming sector, the net availability is 5.7 million tonnes. Assuming that all of this could be supplied to generating stations operating at the same efficiency as the one at Ely, straw could generate about 7.7TWh annually (nearly 30 Elys), compared to total UK energy use of 400TWh. Although it could make only a limited contribution to energy supply, burning straw would tend to push up its price for existing uses. For comparison, the total output of wind turbines in the UK was over 10TWh in 2010, according to DECC figures (although, of course, this is not all provided at the time when it is needed, and is impossible to predict with any degree of certainty from year to year).

Drax, on a vastly bigger scale, has sourced biomass from farmers in its East Yorkshire neighbourhood, but is now planning to import the majority of its supply. The motivation for such a large generator is to reduce its carbon dioxide emissions and fulfil its Renewables Obligation. The company has reported plans to build three 300MW biomass-fired stations on separate sites and to increase co-firing of its existing huge coal plant to 500MW out of its total capacity of 4,000MW. These plans are enormous compared with the size of the Ely station. For comparison, the total renewables capacity owned by Drax would be the equivalent of 37 stations the size of Ely and (if straw was the fuel) would use more than the total available UK production. Realisation

74 http://www.northwoods.org.uk/files/northwoods/StrawAvailabilityinGreatBritain.pdf

of the plans depends on a sufficiently attractive long-term subsidy regime; if and when investment plans are completed, Drax will generate about 15% of the country's renewable electricity.

At present, the company is sourcing various energy crops, such as miscanthus and short rotation coppice, plus forestry waste and straw. Managing the supply chain to meet its future demand will be crucial and the company is not giving any details about how it will source its fuel, but it seems clear that a large quantity will have to be imported.

Although it is difficult to get clear figures, use of biomass is not generally cost-effective compared to fossil fuels at current prices. Generators receive benefits under the Renewables Obligation and, for heating schemes, will soon be subsidised under the Renewable Heat Incentives system. To fulfil the government's expectations, these incentives will have to be sufficiently generous to pay the transport costs for biomass imports.

If Drax's plans are fulfilled, it will have a renewables generation capacity of 1.4GW, with the potential to deliver around 11TWh annually. But that's still only about a quarter of the projected total for 2020. Based on the consumption at the Ely power plant, Drax would take about 7.5 million tonnes of biomass. To meet DECC's projected figures would require 30 million tonnes, and a similar amount would be needed to meet the expected demand for renewable heating. This is an order of magnitude greater than UK farmers are likely to be able to supply as straw and other agricultural by-products; in the case of straw, it will also compete with other value-added uses.

Biofuels are currently made from cereal starch, sugar or vegetable oil, all of which could be part of the food supply. Successful commercialisation of second generation fuels, using biomass as a feedstock, would in principle therefore be an excellent idea. However, the need for an additional 15+ million tonnes to supply the transport sector can only come from imports without turning large areas of woodland and pastureland over to energy crops.

We have to conclude that use of biomass as an energy source, despite its attractions, is likely to be severely limited. The energy road map figure could be achieved using mainly imports, but only if other countries did not follow the UK's lead and compete for available biomass supplies.

Hydro power

At the end of May, 2010, the UK had 78 hydropower plants (excluding microhydro), mostly located in Scotland, delivering 1,420MW[75] in total. Further large scale power developments in the UK will be limited by a lack of suitable sites. The most recent "large-scale" hydropower plant in the UK, built by SSE at Glendoe[76] is just 100MW and reportedly the first "large" scale hydropower plant to be built in the UK for 50 years (at a reported cost of £150 million). A rockfall in the tunnel in 2009 caused it to close down.

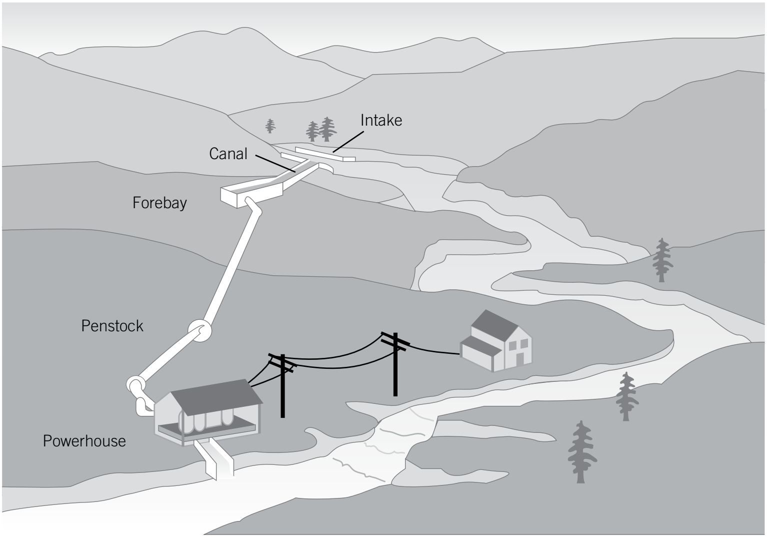
A hydro scheme, whatever its size, requires water flowing downhill or backed up behind a weir or a dam. In the case of some very large-scale schemes, huge artificial lakes are created. However, these are not relevant to the UK situation and so this discussion deals with small and micro systems only. For these, two important factors are the total volume of water available and the head (difference in levels between the intake and the turbine). In practical terms, heads of less than two or three metres are uneconomic to develop. Figure 24 shows the main elements of a typical small hydro scheme.

Flows can range from a few litres per second in micro-hydro schemes to thousands of cubic metres per second (m3/s) in large schemes. The majority of hydro schemes have heads ranging from about five metres up to several hundred metres. Very roughly, hydro schemes can be divided into micro-hydropower with outputs of less than 100kW, small hydropower between 100kW and about 10MW, with large hydropower covering the remainder of the range. The world's biggest hydro schemes have installed capacities in

75 DUKES table 5.1.1 DECC
76 http://www.scotland.gov.uk/News/Releases/2008/09/01081143

excess of 20,000MW with individual turbines and generators with outputs greater than 600MW.

Figure 24: A typical small hydropower scheme[77]



Hydropower technology as we know it has been around since the 1850s; in fact, it could be said that it has been around since before Roman times in the form of water wheels and water mills. The technology is well established and advances tend to consist of refinements to designs. These refinements usually lead to small increases in efficiency and, quite often, to a decrease in cost. Given that a large hydro turbine is something like 95% efficient and even smaller ones are usually in excess of 85%, there is not a big margin for further improvements.

Small and micro hydropower schemes are usually relatively expensive in terms of the energy generated compared with large hydropower and conventional power generation. One of many reasons is that each scheme, including

77 http://greenharmonyhome.com/wordpress/?p=1868

generating plant, has to be individually designed, in contrast to the use of standard modules for most conventional technologies. There are very few engineers with the wide range of knowledge and experience needed to design economic and reliable small schemes. Many designs are unnecessarily expensive because practices appropriate to large schemes have been used. In many cases, the high cost comes from unnecessary complexity and this does not always lead to reliable operation. Simpler is often better! On the other hand, many schemes that have targeted low cost as a major priority have often turned out to be seriously inefficient and unreliable.

Another reason for the high price tag is that design and approval costs are not scalable; the cost of getting environmental approvals and then designing and building a scheme of say 50kW is little different from the cost of building a scheme of 200 or 300kW. It would be safe to say that, in the UK at least, unless there is existing infrastructure that can be adapted easily, it is virtually impossible to build a scheme of less than 200kW or so that is truly economic.

Another problem with the economics of small hydro is that, although the flows and outputs are much more predictable than with wind or solar power, very few schemes carry sufficient storage to be able to guarantee to provide a substantial output during peak demand periods. This means that the system must carry sufficient reserve generation to cover the possibility of a low flow period during a system peak demand. Most micro-hydro plants will deliver between 15% and 40% of rated power in a dry period. The few that have a reasonable amount of storage will be able provide between 40 and 80% of full power during a peak demand period.

In the UK and some other EU Member States, governments have incentivised smaller installations. Quite a few years ago the UK government decided to subsidise schemes rated at less than 20MW. This included existing schemes provided that they had been fitted with new runners and guide vanes. This led many existing hydro operators to “refurbish” perfectly good hydropower schemes of more than 20MW while taking the opportunity to restrict the output of the refurbished station to 19.9MW. So the net result of the policy was a reduction in hydropower output at a net cost to the taxpayer. The recent decision to pay 20.9p/kWh to schemes below 15kW,[78] 18.7p for schemes between 15 and 100kW, 11.5p for schemes between 100kW and 2MW and 4.7p for schemes between 2 and 5MW means that some sites that are suitable for developments of 20kW or greater capacity will only be developed to 15 kW.

If hydropower is deemed to be a benefit to the electricity system it would be logical and sensible – although still not economic – to subsidise all hydropower capacity to the same degree. It would be even more sensible to provide all renewable energy schemes with a subsidy depending on exactly how much carbon dioxide emission is avoided, since that is ostensibly their primary purpose. The calculation should also include the carbon dioxide emissions from any backup plant that is needed.

Hydro power unfortunately represents a clear example of the dangers of top-down setting of targets and picking winners. If the aim is to reduce emissions (or indeed anything else), then the role of government should be to define the objective and, if necessary, provide incentives to encourage this to be achieved in the most efficient and lowest cost way. Such an approach would allow winners to emerge in a competitive marketplace.

Wave power

There are no commercially operating wave power stations in the UK, although the country hosts the European Marine Energy Centre in Orkney.[79] The potential energy in waves is enormous, so it is not surprising that there have been many attempts to use them to generate electricity. The wave energy around the United Kingdom has been estimated as equivalent to three times the country's total electricity consumption, with 50-90TWh/year economically recoverable.[80] But while the potential is there, harnessing it is neither easy nor cheap.

78 http://www.fitariffs.co.uk/eligible/levels/
79 http://www.emec.org.uk/scale_sites.asp
80 http://www.pelamiswave.com/wave-energy/the-resource

A fundamental problem with wave power is that any device that recovers energy from the waves needs to be able to survive a very large storm (and do so repeatedly). This means that it must be designed for the most extreme conditions likely to be encountered, while generating a useful amount of electricity over the year when operating at much lower levels of wave power. It is extremely difficult to design something that will survive a storm and, at the same time, generate electricity efficiently during average wave conditions.

Wave power is not new. Wave machines were developed and trialled in California in the 1890s.[81] Wave power became the focus of research in the 1970s during the oil price spike caused by OPEC. During this period devices like “Salter’s Duck” and the “Oscillating Water Column” were examples of the many approaches that were developed and tested. Salter’s Duck proved to be unreliable and extremely difficult to maintain. It generated about one third as much power as expected.[82] The Ducks (for the idea was to install arrays of them) worked by absorbing wave energy and using this to operate pistons driving a hydraulic motor which produced electricity. Claims were made of very high potential efficiencies but, as often happens, the reality was somewhat different. For more information, see an article in The Engineer (Stephen Salter: pioneer of wave power).[83]

Many other devices that were tested also gave unexpectedly poor results. The Oscillating Water Column, originally invented by Yoshio Masuda, has a deceptive simplicity. It is essentially a closed upright tube, fixed to the seabed, with an opening near the base to admit waves. The water level in the tube rises, compressing air trapped at the top and driving a turbine generating electricity. The design of this so-called Wells turbine means that it also rotates in the same direction when the air flow is reversed as the water column drops.

81 http://www.outsidelands.org/wave-tidal3.php
82 Personal communication, Prof Norman Bellamy
83 http://www.theengineer.co.uk/in-depth/stephen-salter-pioneer-of-wave-power/299034.article

A wave power station was constructed off the coast near Bergen in Norway in 1985 using an OWC that was carefully tuned for resonance.[84] This generated electricity reasonably successfully, but a storm broke off the upper part of the column, so that experiment was abandoned. At the same time the Norwegians installed a very ingenious system of their own design using a tapered channel to amplify the wave height and spill it into a basin. At the other side of the basin, a conventional water turbine generated electricity from the water that had been lifted into the basin. This had the enormous advantage that the equipment harvesting the wave power was quite separate from the power plant. Sadly, they found that, during a storm, rocks and boulders became lodged in the tapered channel and could not be removed.

An installation which has had a degree of success is known as LIMPET 500, on the island of Islay. This uses the OWC principle in a concrete structure built directly on the coastal rock face.[85] However, this is a small-scale development, having a single turbine generating a few hundred kilowatts. After an extended development and construction phase, it first generated power in 2000.[86] [87]

Recently, a number of other developers have adopted the oscillating water column. A very good appraisal of the prospects for the technology was provided by Arup in 2005. It concluded that the cost could be 17.5 p/kWh with an ultimate target of around 5 p/kWh.[88] This is comparable to wind power. However, Arup suggested that a 22.5MW demonstration project would have a target generation cost of about 10p/kWh and that this would only be reduced to 5p/kWh after 250 units had been installed, at a capital cost of £1bn. Many problems remain to be solved and, inevitably, costs will rise.

84 http://www.renewables-map.co.uk/details.asp?pageid=1715&pagename=Islay Wave Power
85 BBC How it works: wave power station
86 http://www.renewables-map.co.uk/details.asp?pageid=1715&pagename=Islay%20Wave%20Power
87 http://www.wavegen.co.uk/pdf/Consruction,commission%20&%20operation%20of%20LIMPET.pdf
88 http://www.carbontrust.co.uk/SiteCollectionDocuments/Various/Emerging%20technologies/Technology%20Directory/Marine/Other%20topics/OWC%20report.pdf

The report considered on-shore facilities such as the Islay one to be suitable only for local supply, but its survey suggested that 141 km of coastline was suitable for installation of prefabricated, concrete wave power devices in water 9-11 metres deep. These would have the potential to supply 7.8TWh of electricity annually (not much more than 3% of the projected total renewables output in 2020, itself only 15% of estimated total primary energy needs). However, lack of real progress suggests this is extremely optimistic.

Figure 25: A prototype Pelamis unit

Recently, many of the devices originally developed in the 1980s have been revived and a large amount of money has been put into them. One example is "Pelamis" which was originally developed by Prof Norman Bellamy at Coventry University. After initial testing, he abandoned it, but it was revived a few years ago and three prototypes were moored off the coast of Portugal for a few months.[89] Figure 25 shows a prototype unit in action.[90] Maintenance turned out to be a problem and, in the end, it was abandoned due to "economic and technical problems".

89 http://www.pelamiswave.com/our-technology/development-history#Agucadoura
90 Credit: Pelamis Wave Power

About a year later it was revived with a new design of energy converter. The new unit is heavier and stronger than the previous one and weighs 1300 tonnes total and 650 tonnes unballasted, for an output of about 750kW, at a capacity factor of 25 to 40%.[91] If one assumes that with mass production the unballasted cost is $10,000/tonne then it would cost $8,700/kW.[92] At this price, and with a relatively low capacity factor, there is no way that the device can produce an economic supply of electricity. Such a design does, however, have the advantage over the anchored OWC device considered in the Arup report of being capable (in principle) of working in a range of water depths. It could therefore be deployed to generate a much larger total amount of power, if the economic problems could ever be overcome.

Many other wave power devices have been designed and some prototypes have been built. Apart from the Pelamis and LIMPET, no one appears to be near to building a commercial production version of any wave power device.

The “Sea Clam”, originally developed by Prof Bellamy and now revived by others, is an interesting concept that avoids many of the problems inherent in most wave energy devices. It uses wave action on a flexible membrane (airbag) to pump air through a turbine driving a generator. During a storm, the airbags can be deflated. In this way, it avoids the major problem of other wave powered devices of all components having to withstand violent storms. When the original development was suspended in 1992, it was reckoned to be the most attractive of all the wave power devices available at that time. A company has recently been formed for further development.[93]

In mid-2011 Professor Bellamy patented a new concept for wave power. The device lies on the surface of the ocean. It consists of a tube with an internal diaphragm that flips from one side of the tube to the other. Wave action

91 http://www.pelamiswave.com/contact-us/frequently-asked-questions

92 Note that, in 2005, a ship weighing 3500 tonnes cost about $26 million. This equates to $7,500/tonne. (Page 224 of “Maritime economics” by Martin Stopford)

93 Sea Energy Associates Ltd http://www.sealtd.co.uk/contacts.html

causes the diaphragm to pump air along the tube. The pressure increases along the tube and the discharged air has sufficient energy to drive an air turbine generating 1MW or more. If the remaining technological challenges can be overcome, it may make all the other wave power devices obsolete. The next step is to build prototype tubes and establish air flows and pressures. The final step is to connect it to a turbine generator and work out how to get the power ashore.

Unless someone comes up with a brilliant new idea (and Prof Bellamy's latest proposal may prove to be one), it is difficult to be optimistic about wave power as a large scale alternative to conventional power stations. It is hard to escape the feeling that much of the research is driven by the availability of funds, rather than by a conviction that truly economic wave power is within reach. The UK plans for 2020 only include a nominal 1TWh of wave power, which reflects the government's degree of commitment. Waves are an energy source which, although superficially very attractive, look extremely unlikely to be exploited on any scale for at least the next generation. Although likely to operate to some degree for a large part of the year (unlike wind and solar), wave power still has to be seen as an unreliable and intermittent source of electricity. To compound that, even a relatively steady output is subject to rapid fluctuation because, even under steady conditions, all waves are not the same height.

But, to give a sense of the enthusiasm some people have for wave power, consider this quote from an article by David Ross for the United Nations Environment Programme website:[94]

> *"The big hurdle is financial. Wave energy was not devised to save money but to save the world. Early researchers used to say optimistically that the energy was free because the gods provided the waves. Others swung to the opposite extreme by using high discount rates, which hit wave energy unfairly because it is a capital-intensive technology, where most*

94 http://www.unep.org/ourplanet/imgversn/123/ross.html

of the expenditure is during construction. The simple way to change the costing is to change the discount rate."

Many things would be more attractive at a lower discount rate, but then we would all be broke if that's where we invested our money.

Tidal power

Another apparently attractive source of power is tides. Vast quantities of water are moved in a regular and predictable way, and particular geographies can concentrate the flows into regions of high potential. Tidal power comes in two forms: schemes that use a barrage and those that rely on tidal currents.

Tidal barrage

Barrage type schemes were first developed more than 1000 years ago. In Roman times there was a tidal mill in London and about 800 years ago there were 76 of them in London including two on London Bridge. These mills were superseded by the advent of steam engines.

In the 1960s, Electricité de France EDF) developed a scheme at La Rance in Brittany. It is rated at 240MW and was commissioned in 1966. No costings were made available so it was assumed that the price was embarrassingly high. Nevertheless, it has been technically quite successful and, because the costs have now been fully depreciated, it generates electricity at a cost of about 1.8 c/kWh. No other tidal power schemes have been developed by EDF. There is also a small tidal power scheme in Russia and another in the Bay of Fundy in Canada. All of these suffer from the same limitations which apply to the proposed Severn barrage, discussed below.

The other current example of such a project is in Korea. A few years ago, construction commenced on a tidal power scheme, which should be completed before the end of 2011. At 250MW, it is slightly larger than La Rance. The scheme is based on an existing barrage which was originally built to form a freshwater lake. However, the lake became polluted, making it unsuitable for its original purpose of farmland irrigation. The barrage was breached to flush the lake with seawater and then it was decided to build a tidal power scheme. Because it did not carry the cost of the barrage and other works, its cost of $300 million ($1,200/kW) appears to be reasonable. However, because the capacity factor is about 25%, the like-for-like comparison with a nuclear power station operating at 90% capacity factor is a cost of $4,300/kW. Given that backup plant is also needed, there is no way that the scheme would have been economic if it had also needed to finance the barrage (although overall economics depend heavily on credits for such benefits as flood control and transport links).

Figure 26: The Sihwa tidal power scheme, Korea[95]

95 http://www.advancedtechnologykorea.com/?p=7299

In the UK, over the last 70 years, an enormous amount of effort has been put into a tidal scheme on the Bristol Channel: the Severn barrage. Many different designs have been proposed. Unfortunately, the cost appears to be high: much higher than nuclear power. One of the problems is that the station would generate for only about eight hours out of 24, operating only when the tide is ebbing, twice a day. At varying times it would generate a very large amount of power and shortly after it would shut down. This means that, like all intermittent technologies, equivalent conventional generating capacity has to be held in reserve and used to replace the barrage station output at times of peak demand (such as a winter evening peak when the tide is flowing in). The main advantages of such a tidal system over wind is its predictability and lack of short-term random variability during the generation period, but the scheme adds little firm capacity to the system and would require a large amount of expensive backup generation.

The scheme involves drowning huge areas of tidal mudflats. The environmental impact could be very high and is largely unknown, but has led to significant opposition from some quarters. Those in favour suggest that there would be a significant benefit from the avoidance of annual flooding by the river Severn, together with the core benefit of carbon dioxide emissions saving (although given the intermittency of operation, the extent to which nominal savings would have to be offset by emissions from backup generators is unclear). The economic benefits of flood control, in particular, might make the scheme more attractive than it first seems.

The most recent study proposed a number of schemes at about £3,000/kW, without any allowance for backup. None of them were competitive with conventional generation. Indeed, an article in the New Civil Engineer in 2008[96] reports on independent research which showed the cost of a 16km barrage from Cardiff to Weston-super-Mare to have risen from £15bn to £23bn. The output of this scheme (the largest being considered) was put at 17TWh per annum. By October 2010, when Energy Secretary Chris Huhne announced

96 http://www.nce.co.uk/severn-barrage-cost-hits-23bn/1340287.article

that the government no longer saw a strategic case for the barrage, its estimated cost had risen to £30bn (although it is fair to point out that this included a large contingency cost).

To sum up: barrage type schemes suffer from the high cost of low head generating plant, high civil costs for the barrage, the powerhouse and the various control gates, combined with a fluctuating power output. It is not easy to see how these problems can be overcome to the extent that tidal power generation would compete with conventional generation. There are also relatively few suitable sites, and each project would be unique. Nevertheless, the Severn barrage project cannot be dismissed out of hand and it will certainly be revisited before too long.

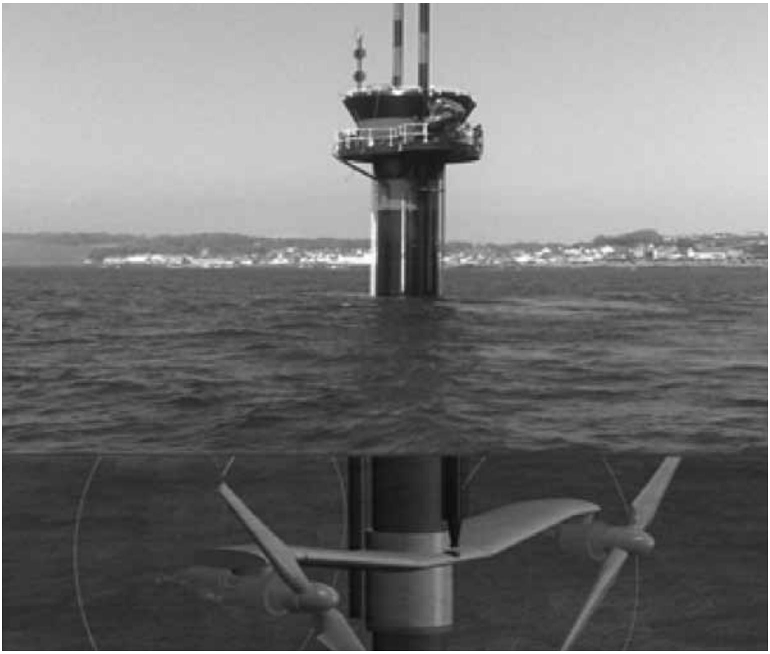
Tidal Stream Generation

Tidal stream generation uses tidal currents to generate electricity in the same way as a wind turbine does. Because water is denser, the turbines do not need to be as big as wind turbines to deliver the same power (although the water also flows more slowly, so the blades are still substantial). But against that, they generate power intermittently and they must survive in an aggressive environment with strong currents in two directions. As a result, they tend to be quite heavy and this means that they are inherently expensive.

The availability of subsidies and grants has spawned many interesting concepts for tidal stream generation. Most of them use propellers, but one turbine design has an outer casing with a hole in the middle surrounded by blades with the generator and magnetic bearings around the periphery. It is hard to avoid the conclusion that this machine will be extremely heavy. Magnetic bearings of that size are largely unknown technology and it is notable that the conventional hydro turbine industry has not yet adopted magnetic bearings. Other tidal current devices use flapping wing type arrangements that would appear to have major mechanical challenges.

Some prototypes have been tested and have a capacity factor of around 25%. As with conventional tidal power, they operate for only a few hours a day and generate much less during neap tides because the turbine power follows a cube law.

Figure 27: SeaGen at Strangford Lough



The most advanced development is that of SeaGen at Strangford Lough in Northern Ireland, shown in Figure 27. According to a report from the Northern Ireland Assembly, the unit cost £12 million.[97] The project received £5.2 million as a grant from the UK government and a further £0.5 million from the regional assembly. The installation is produced by Marine Current Turbines Ltd[98] and has been in operation since 2008. According to the company website, it feeds 10MWh per tide into the Grid or about 6,000MWh per annum. This output is about what is expected of a wind turbine rated at 2.4MW, which suggests that tidal power of this sort is twice as efficient. Even at its modest size, it is by far the largest tidal turbine in use (the diameter of each turbine is 16 metres).

97 http://www.niassembly.gov.uk/io/research/2009/1409.pdf
98 http://www.marineturbines.com/

An estimate of the cost in serial production can be made based on the fact that the unit weighs about 1000 tonnes and generates 1200kW at a capacity factor of 60%. Assuming, as before, that such machinery costs $10,000/tonne, the total cost would be $10 million or $8300/kW. If these costs could be halved, and the maintenance cost is not excessive, it might become competitive with conventional generation,[99] although intermittency remains an intrinsic problem.

It is probable that all tidal stream turbines will suffer from marine fouling. The best marine antifouling treatment lasts about five years, so they will have to be removed from the water, thoroughly cleaned and repainted at intervals of less than this. The intervals may be much less because even a small number of barnacles can have a large effect on the efficiency of a propeller. According to one paper, fouling by barnacles could cause an efficiency drop of between 20 and 70%. This is seriously large.[100] One advantage of the Seagen unit is that the turbine assembly can be lifted out of the water for maintenance and cleaning.

There are a number of other schemes mooted. The Pentland Forth, between Orkney and the Scottish mainland, is often put forward as a possible site for a tidal power array, since it has very high tidal flows. The government of Alderney, in the Channel Islands, has granted a licence to Alderney Renewable Energy[101] to develop a tidal flow scheme, which could produce between 1 and 3GW of power, to be supplied locally and via interconnectors to France and the UK mainland.

In some countries, such as Sweden and Canada, hydro power is generated by turbines placed in flowing rivers ("run of the river" hydro) where the environment is much less aggressive, the water always flows in the same

99 It is estimated that a modern nuclear power station would cost less than $5000/kW (http://www.world-nuclear.org/info/inf02.html) once a number have been produced. A nuclear station operates at a capacity factor of about 90% and has a life of about 60 years. A tidal current scheme of 3.5 times the capacity would be needed to give the same energy output. So the comparable cost of the tidal power scheme would be about $25,000/kW for a scheme with a probable life 20 years. The gap is huge.

100 http://en4.swan.ac.uk/egmastersi/images/biofouling2.pdf

101 http://www.are.gb.com/index.php

direction and continuous power is generated. The UK's rivers are, however, unsuitable for this technology.

In conclusion, tidal power schemes based on barrages use a well-developed technology that cannot compete directly with conventional generation, although some schemes in favoured sites may be justified on the basis of environmental benefits. By contrast, tidal current turbines are a developing technology with many potential problems and, because they have to be very heavy, they will have problems competing with conventional generation. They also suffer from the problems of intermittency.

Heat pumps

Heat pumps are not used to generate electricity, but can provide heating for domestic or commercial property. Nevertheless, we include them here because they could make a contribution to overall primary energy consumption.

Heat pumps work like a refrigerator in reverse. They take low-temperature heat energy from the atmosphere or from the ground and, by using a compressor, convert it into higher temperature heat. The ratio between the heat delivered and the energy required is called the Coefficient of Performance (COP). Many heat pumps can also operate in a reverse cycle where the heating element inside the house is reconnected as the cooling element. They can thus warm or cool a building.

The COP varies according to the internal and external temperatures. For an air source heat pump with the external air at 2°C, and delivering air at about 35°C, the coefficient of performance of a modern heat pump is about 3.2. However, if the outside temperature is minus 15°C, it drops to slightly over 2. As the technology improves, the ability to operate at lower temperatures will also continue to improve.

In the UK, ground source heat pumps are also used. These requires long lengths of tubing to be buried in the ground and, on a very cold day, they are in a warmer environment then they would be if an air source was being used. However there is a risk of the ground freezing, in which case the performance drops off dramatically. Ground source heat pumps are also a lot more expensive. As air source technology improves, it would be reasonable to expect that more air source heat pumps will be used in the UK, particularly if people are prepared to move from radiator-based systems to warm air heating.

Air source heat pumps are a development of room air conditioners made for the tropics. In the smaller sizes they are mass produced on a huge scale, and the result is that the small units tend to more efficient than the larger ones. Also, it turns out to be more economic to have several small compressor-distributor units rather than a single large compressor driving a number of heat distribution units. These mass produced units cannot be used for heating water in place of an existing gas boiler for a radiator-based home heating system, which makes them less attractive in a UK context.

From the point of view of overall efficiency, it is better to burn gas in a combined cycle power station than it is to burn gas in the home, if the electricity is used to power a heat pump. If the gas is burned in the home, then 1kW of gas will provide roughly 800W of useful heat. If the gas is burned in a combined cycle gas turbine station with an efficiency of 55%, then 1 kW of gas delivers approximately 500W to the home. If used to power a heat pump with a coefficient of performance of 3, this equates to 1.5kW of final heat output; an improvement of approximately 90%. Whether or not it is economic, depends entirely on the relative price of gas and electricity and the cost of installation. Recent electricity price increases, driven partly by the high subsidies paid to renewable energy generators, may have upset the normal balance between gas and electricity prices considerably. This aside, the high capital costs of current heat pump installations makes them unattractive to many householders, even if the long-term economics are favourable.

Electricity grid requirements and the intermittency problem

Renewable energy can clearly make some contribution to electricity supplies, albeit at a cost. However, as we have already seen, the problem is not just one of installing sufficient capacity, but also of how to cope with a high degree of intermittency, which is only predictable to a certain degree. This section deals specifically with how wind power can be accommodated in a secure and stable electricity supply, but the arguments hold equally for solar and, if they ever become commercial, wave and tidal power generation systems.

Balancing wind & system stability – what is the optimum wind penetration without storage?

The "traditional" electricity system consists of power stations feeding a high voltage transmission grid, which in turn feeds lower voltage distribution grids delivering the power to consumers at the required voltage and frequency.

For an electricity grid to function properly, the electricity entering it from generators must at all times be balanced by the electricity leaving it to consumers. If this balance is disturbed by an over-supply of electricity, the frequency rises. The converse occurs when demand exceeds supply. If the imbalance swings outside the safe operational limits of the generation system, then protection mechanisms close down the local system, causing a local power failure. From time to time, such failures, if they occur suddenly, can cascade through the whole system, triggering nation-wide black-outs. These are hugely disruptive, dangerous and costly.

All grids have evolved over time, growing to meet demand, fed by generators that can be turned on and off and ramped up and down with great accuracy. The operators of power grids have also learned how to predict demand. To protect the grid from an unexpected, large-scale failure, all grid operators have reserve power plants available that can be ramped up (or down) for unusual events like the emergency shut-down of a large power station or the (more predictable) simultaneous boiling of millions of kettles at some key break in a popular television programme. Grid operators often enter into "interruptible" contracts with large consumers who agree, for a significant fee, to be turned off at short notice. Some appliances like storage heaters, water heaters, fridges and freezers can be designed to be switched off automatically when the frequency of the alternating current drops too far.

Wind is stochastic, that is random, both in its strength and with time, so wind power presents a novel challenge to grid operators. Small fluctuations can be dealt with, but as the amount of wind power increases, operators have to be able to anticipate changes in output and manage them by rapidly ramping reserve plant up and down, or stopping and starting it.

It is important for the UK to learn lessons from other countries. For example, the US consultant, Bentek,[102] recently published some studies for US utilities, which show that for states having a high fraction of wind power, such as Texas and Colorado, the energy used in balancing the grid is actually greater than the energy produced by the wind power plants themselves, pushing CO_2 emissions up and more than negating the apparent benefits. There are numerous other studies, which show that the fossil-fuel saving benefits of

102 http://www.bentekenergy.com/InTheNews.aspx

wind energy are a fraction of what is claimed by the renewable industry's trade bodies.[103]

Ireland – a good proxy for predicting that wind power penetration in UK may be optimized at around 15GW

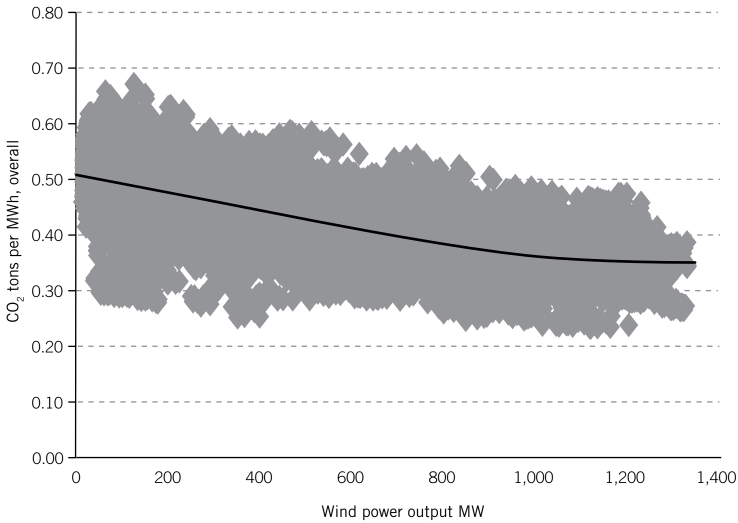
More direct lessons can be learnt from the experience in Ireland, which suggests that wind power can indeed save fuel and therefore CO_2, but only up to a point. Ireland's head-long pursuit of wind power does give some useful lessons about a "crash" wind construction programme on a similarly windy island system.

Ireland has a 5GW peak capacity[104] with most of the modern generation plant consisting of high efficiency CCGTs. Most of the gas is imported from the UK. There is a 900MW, 30-year old, coal-fired power station, small amounts of hydro and a 270MW pumped hydro storage plant. Its inter-connection with Northern Ireland is 500MW and with the UK mainland is at present limited to 250MW between Northern Ireland and Scotland (although a 500MW inter-connector between Dublin and North Wales will be commissioned in 2012).

Ireland has developed wind power faster, more aggressively, and more cheaply than the UK. Its installed capacity today is 1.4GW (28% of total capacity). During the nine months between November 2010 and June 2011, 13% of all power generated and consumed originated from wind turbines (a significantly higher capacity factor than the UK). Eirgrid, the Irish system operator, publishes its system demand, wind power output and CO_2 emissions (a reliable proxy for the system's specific fuel consumption) every fifteen minutes in real time[105] and so the results can easily be analysed (in unfortunate contrast to the situation in the UK).

103 http://www.clepair.net/windsecret.html
104 Republic only. Whole-island system has a probably peak of 7GW
105 http://www.eirgrid.com/operations/

Figure 28: Irish wind power & CO_2 emissions

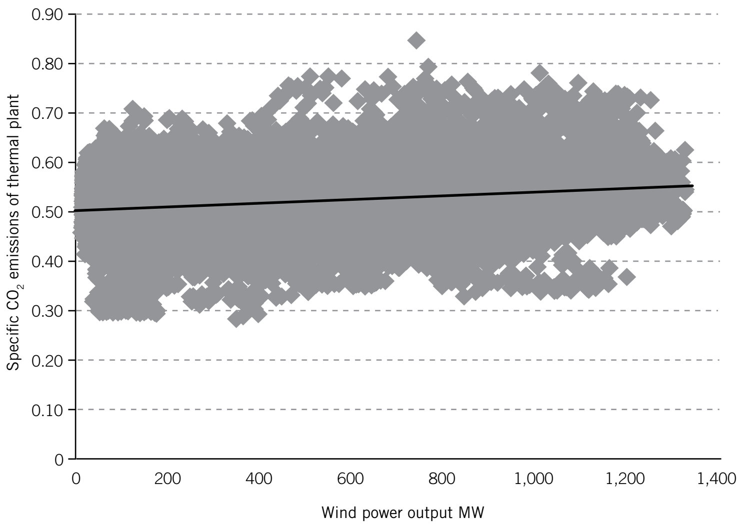


The data plotted in figure 28 clearly show that generating fuel is being saved when the wind is blowing in Ireland. What is also clear from the trend line (a 3rd power polynomial) is that, as wind power increases, fuel savings per MW *decrease*, levelling off at around 330 kg of CO_2 per system MWh, indicating that as wind power output rises past (say) 1400MW, there will be little if any further fossil fuel savings.

This can be confirmed by looking at the specific CO_2 emissions of the non-wind (mainly thermal) output. There is a huge scatter of results across a wide range, but there is undoubtedly a trend of rising specific fuel consumption as the output from the roughly 1400MW of installed wind capacity increases (see Figure 29).

1400MW in Ireland is equivalent to what will be (very roughly) 14-15GW of wind power in the UK, which it is reasonable to assume would be the level beyond which no more fossil fuel savings would be made.

Figure 29: CO_2 emissions per MWh(e) thermal plant



Unlike the UK, Ireland has ample, dispatchable, generating reserves. These were aggressively expanded until the economic melt-down because the government anticipated further high energy demand growth, as it experienced during the boom years.

The Dutch engineer and wind power analyst, Fred Udo, in a higher resolution examination of the same period, found many specific cases of high wind output coinciding with high CO_2 emissions.[106]

Rising levels of wind curtailment in Ireland

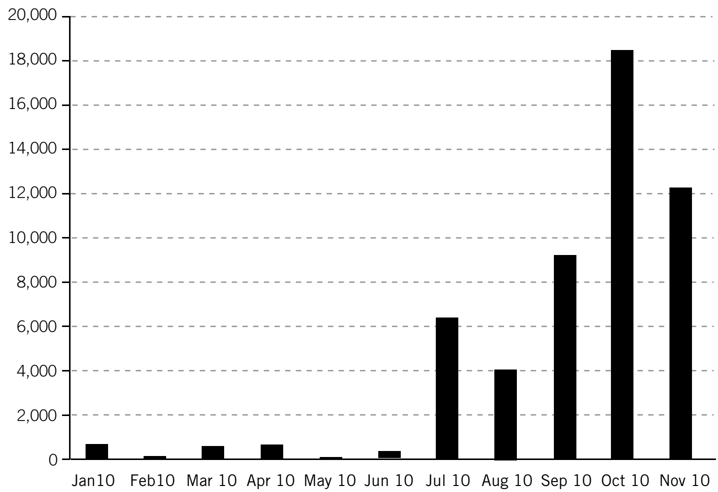
Wind power is often the most expensive electricity in the system, despite which it is given priority on the grid (although the marginal cost may be low

106 http://www.clepair.net/IerlandUdo.html

under central scheduling systems). If it did not enjoy such priority, it would be even more expensive, as not all the power generated would be needed. As elsewhere, Irish wind power enjoys priority on the system and is only turned off when system stability is threatened or transmission lines get overloaded.

Yet even at a penetration level of 13% by energy consumed, figure 30 illustrates that a high level of curtailment is required to maintain system stability and avoid transmission line congestion. In Ireland, the terms on which the wind generators operate mean that the wind generators must accept the loss[107] due to curtailment. In the UK (and Germany) forced wind curtailment is compensated. Thus consumers must pay for this expensive electricity not to be generated at the same rate as they pay for it to be generated!

Figure 30: Unused wind generation (VPTGs)[108]



Source: EirGrid, 2011

107 Personal communication with an Irish wind developer
108 Eirgrid 2011 – *Ensuring a secure, reliable and efficient power system*

Northern Germany, in particular Schleswig Holstein and Lower Saxony, is the centre of German wind generation. Roughly 15% – 20% of all the wind power that could be generated in this region is currently being curtailed. This has reached such a level and is so costly for German consumers that the arrangement whereby curtailed wind for new turbines is compensated will be phased out during 2012. Owners of new wind power plants constructed from 2012 must accept the loss of income forced upon them by curtailment.[109]

A rising level of wind curtailment is being ordered during 2011 by National Grid in Scotland, where the level of wind penetration per capita is the highest in the UK. This has been the subject of a report by the Renewable Energy Foundation.[110] The following table details the current level of constraint payments. The bid price quoted is as at 26 June 2011, with the total volumes and costs being for the period May 2010 to this date.

This demonstrates that wind capacity in Scotland has grown faster than the network's ability to get the generated electricity to the consumer and is yet another signal that a rush to fulfil arbitrary targets by 2020 will be expensive and will not achieve projected savings in emissions.

109 http://www.eon-netz.com/pages/ehn_de/EEG__KWK-G/Erneuerbare-_Energien-Gesetz/Einspeisemanagement/Einspeisemanagement_Einsaetze/index.htm

110 http://www.ref.org.uk/publications/239-scottish-wind-power-constraint-payments-update

Table 4

Owner	Bid Price (£/MWh)	Wind Farm	Volume Constrained Off (MWh)	Cost ('000 £)
Falck Renewables	£300	Kilbraur Millennium	355 786	107 205
RWE nPower	£200	An Suidhe Farr	324 3,213	66 847
Scottish Power	£180	Beinn Tharsuinn	952	170
		Black Law	1,860	332
		Dun Law,	–	–
		Mark Hill	–	–
		Whitelee	7,268	1,298
SSE Renewables	£150	Hadyard Hill	8,990	1338
		Toddleburn	–	–
Total			**23,747**	**4,364**

Thermal plant is not well suited to providing balancing capacity for wind power

Figure 9 illustrates that the UK's current coal-fired capacity, originally built for base load, is the most economic balancing capacity in today's UK system, ramping up and down to meet varying supply. Coal is usually cheaper than gas and retains an acceptable efficiency across a wide range of outputs. But the loss of so much of this capacity in the middle of this decade and the loss of all the remaining coal capacity early in the 2020s (if current intentions come to pass) means that already the system planners should be anticipating the need to balance the system if wind capacity is expanded as drastically as planned.

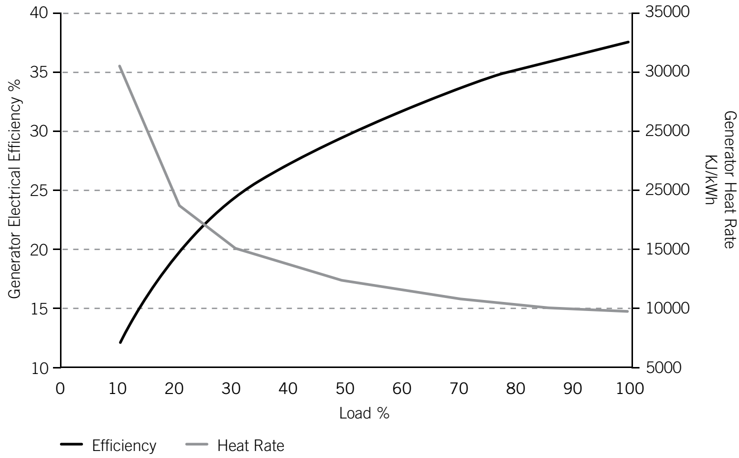
Nearly all the UK's newest gas-fired capacity, as in Ireland, is composed of CCGTs, which are highly efficient (over 50%) at full load. But this efficiency is lower at part load and cycling shortens the life of the power plant, especially the small, tight, heat recovery boilers that generate the steam for the steam turbine.[111] Because of the adverse effects cycling has on CCGTs, there is much focus on the open-cycle gas turbine (OCGT) for providing the balancing capacity should wind power expand much further.

Figure 31: General Electric LMS 100 Open Cycle Gas Turbine

These are usually industrial versions of aircraft jet engines and indeed can be quite efficient at full load, as high as 40%. Of course, this still means that 60% of the fuel's heating value is discharged into the environment as hot exhaust gas! But the physics of gas turbines means that high efficiency only occurs under particular conditions, like low temperature, low altitude and full load. When these parameters are changed, the efficiency falls very quickly.

111 There is a large literature on this subject

Figure 32: Siemens SGT-800, OCGT (53MW at full load)

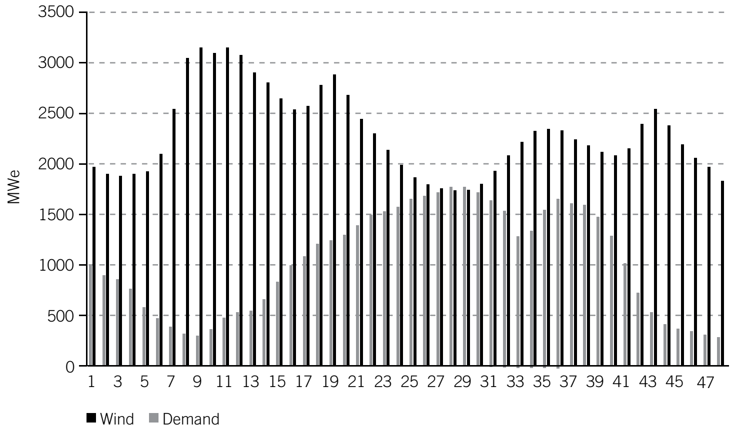


This Siemens turbine, the Rolls-Royce Trent and its GE-made equivalents are often cited as "ideal" OCGTs for balancing wind power. But their thermal efficiency, even at full load, is only 37%, no better than the UK's 40-year old coal-fired plants (The newest, super-critical coal plants are over 45% efficient). Figure 32 shows that at 50% load the efficiency drops to 30%. Gas is more expensive than coal, so the only "benefit" from using a gas turbine instead of coal to balance changes in wind output might be from the slightly reduced CO_2 emissions (compared with coal). But as the Irish case shows so well, at around 15% of total MWh supplied by wind, an island system with little hydro can only host so much wind power before the benefits (in saved fuel) diminish to nothing.

Denmark, a more successful example of high wind penetration?

Wind has become a major component of the Danish generating mix, comprising more than 20% of all power generated. The following is a fairly typical situation in West Denmark that could apply to the UK if the ambitions of the road map were ever realised.

Figure 33: March 8 & 9, 2002

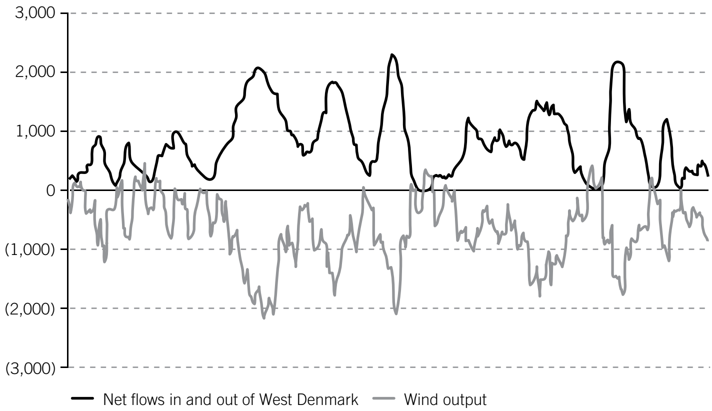


As so often happens with wind power, output was rising during the Friday night while demand was falling. Without curtailment, this situation would be impossible to balance on an "electrical island" system like the UK with large nuclear and coal-fired power stations that take many hours to turn on and off. In the case of nuclear, starting and stopping a power plant takes days.

But Denmark is actually an "electrical transit corridor" between its much larger neighbours, Sweden and Norway, to the north and Germany to the south, for all of which the "large" Danish wind output is fairly inconsequential. The chart for the month of January 2010 (figure 34) illustrates that whenever the wind power exceeds roughly 500MW in West Denmark, the spot price falls and there are net flows outwards towards Scandinavia and Germany. Conversely, very often during summer (especially) and winter when there is little wind power, the electricity price in Denmark rises and there are net power flows inwards, mostly from Norwegian and Swedish hydropower.

Norway, where more than 99% of the generation capacity is hydro-electric, and to which West Denmark is connected with over 1000MW of high voltage direct current (HVDC) capacity, acts effectively as a storage battery for Danish wind power, while Germany to the south acts more or less as an "infinite sink", limited only by the transmission capacity of the two interconnectors.

Figure 34: West Denmark Wind Output & Net Flows MWh per hour



January 2010

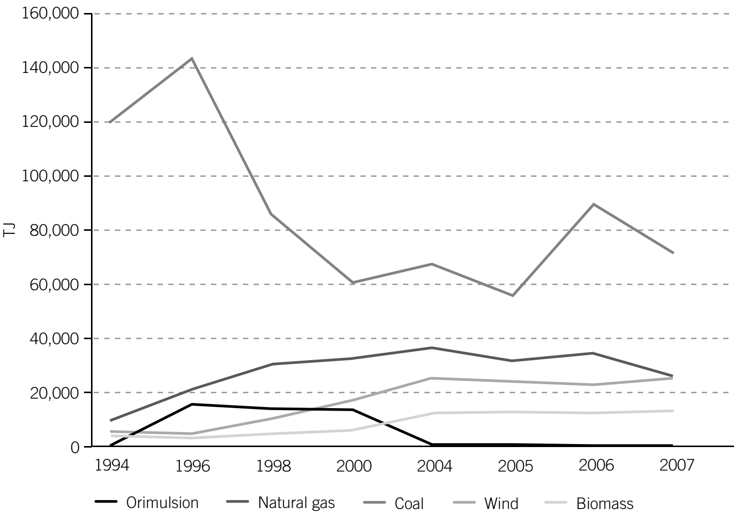
There is an unarguable correlation between wind power and net electricity exports in Denmark, which in any case generates more electricity than it consumes. A 2009 study showed that, while Denmark certainly *generates* more than 20% of its electricity from wind, only about 10% of the electricity it *consumes* comes from this source.[112] [113] The excess electricity is exported to neighbouring countries at very low prices, but when wind output is low, the same countries supply electricity to Denmark at much higher prices.

112 http://www.cepos.dk/fileadmin/user_upload/Arkiv/PDF/Wind_energy_-_the_case_of_Denmark.pdf

113 This case was disputed by the wind industry, some academics and wind energy enthusiasts who wrote a widely publicized report having the opposite opinion, which was that "coal energy" was exported, not wind energy! This can be downloaded at www.energyplanning.aau.dk/Publications/DanishWindPower.pdf

Whatever the case, Denmark's use of gas and coal was not been much impacted by its huge construction of wind power capacity between 2000 and 2009 (see figure 35). However, the significant variations in annual coal use are certainly weather related. There is a strong negative correlation between the quantity of water in the Norwegian hydro-electric lakes and the Swedish rivers and coal use in Denmark. During a wet year in Scandinavia, coal use goes down in Denmark and during drought years, more coal is used in Finland and Denmark to deliver the shortages of power to Norway, Europe's largest electricity consumer on a per capita basis.

Figure 35: Electricity production by fuel in Denmark[114]



During the winter of 2010 – 2011, every fossil plant that could generate electricity was working round the clock to deliver Norway's shortage of hydro-power of 24TWh.[115] Coal and gas used for power generation in Denmark's thermal power stations during the winter 2010 – 2011 is likely to be the highest during the last ten years.

114 Data from Denmark's National Statistics

115 http://www.pfbach.dk/firma_pfb/statistical_survey_2010.pdf

Energy storage options

So if their systems are so different, can any useful questions in the UK be answered from the Danish experience?[116] The answer lies to large extent in options for storage.

Storage is the (partial) answer to wind energy management[117]

The wind regime in the UK and Denmark is similar, with national wind fleets having broadly similar load factors. Figure 32 illustrates graphically that for a system with a wind capacity capable of delivering the equivalent of 25% of Denmark's demand, local thermal generators frequently cannot balance demand and wind output. In order not to curtail the wind power, a massive amount of storage is needed. Figure 33 illustrates why storage is the key to Denmark's ability to host a level of wind capacity to which the UK aspires.

In the case of Denmark, this is provided by the neighbouring systems of Norway and Sweden and its interconnections with Germany. Denmark's interconnection with its neighbours, a proxy for storage capacity, would

116 This matter was explored by HS in two peer-reviewed, medal-winning papers published in the *Proceedings of the Institution of Civil Engineers in 2005.* http://www.icevirtuallibrary.com/content/article/10.1680/cien.2005.158.2.66 and http://www.icevirtuallibrary.com/content/article/10.1680/cien.2005.158.4.161

117 It is important to declare that one of the authors (HS) is involved in the commercial development of electricity storage, being the EU Director for Sales and Marketing at Prudent Energy (www.pdenergy.com)

be equivalent to roughly 45GW if extrapolated to the UK. But it is entirely serendipitous that tiny, flat, Denmark is geographically so close to giant, mountainous Norway, having 27GW of hydro capacity and Sweden with 25GW of hydro, while also being inter-connected with the ‘infinite’ 600GW European grid to the south.

Hydropower can be turned up and down very fast and without shortening its life, so it is an ideal partner for wind power. Figure 34 illustrates very well how wind power (red) output varies rapidly and how rapidly balancing power is varied on the inter-connectors. Pumped hydro, which has a round-trip efficiency of 70 – 80%, and therefore entails significant loss, is unnecessary for balancing Denmark’s wind power.

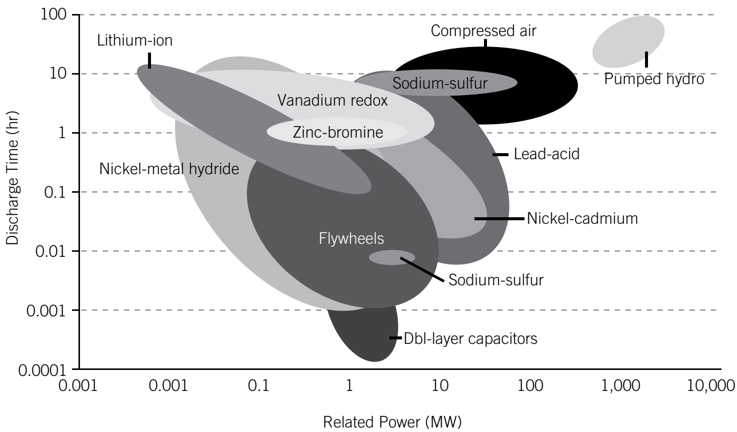
Both Spain and Portugal have significant wind power capacity but also host important amounts of hydropower, which can be turned up and down to balance supply and demand. In the case of Spain, there is more hydro capacity, 23GW, than wind power, 18GW. But both countries are having problems balancing the wind power and are currently building a number of new pumped hydropower stations to help with this. However, these only generate for a few hours (perhaps up to ten) at a time; they are not a solution to the need for long-term, seasonal energy storage.

The UK, on the other hand, is relatively poor in water resources and has little scope for adding more hydroelectric or pumped-storage schemes. But, if the country is to achieve its objectives for wind energy beyond 15GW, it must have in place a combination of distributed electricity storage and the capacity for surplus wind power to be stored (for example as heat or hydrogen).

Contrary to the traditional view, that “electricity cannot be stored”, one of the fastest growth areas associated with the renewable energy industry is short-term storage. Numerous studies point toward the inevitable growth of the electricity storage industry as the cost of intermittent renewable energy resources falls and their capacity rises. Some recent studies worth mentioning are:

- "Electricity Storage – making large scale adoption of wind and solar energies a reality" Boston Consulting Group, March, 2010,
- "Revisiting Energy storage, there **IS** a business case", Boston Consulting Group, February, 2011,
- "Bottling Electricity: Storage as a strategic tool for managing variability and capacity concerns in the modern grid" by the US Electricity Advisory Committee (2008).[118]

Figure 36: Electricity storage technologies represented by the Electricity Storage Association



Installed systems as of November 2008

Unfortunately, the UK government has focused on subsidising the expansion of (intrinsically intermittent) renewables capacity rather than trying to integrate it into a robust overall system. It seems that the renewable energy industry has successfully persuaded politicians that variable wind output can be painlessly and cheaply balanced with existing thermal plant without cost or efficiency penalty. A recent extreme example of the fallacy of this was the award of a

118 http://www.electricitystorage.org/images/uploads/static_content/technology/technology_resources/ratings_large.gif

long term electricity balancing contract by National Grid to a UK company that will deliver short term operating reserve using hundreds of diesel engines!

Whether the UK can rationally build out wind power past 15GW will depend on how quickly it can develop new ways of storing electricity. The technologies exist. They are not cheap but they do work. The various types of commercially available storage technologies are described below. But none of these currently offers an option for flexible, long-term storage; they can only cover relatively short periods and do not guarantee complete security of an extensive system.

When renewable energy becomes more than a relatively small part of total energy generation, the need for long-term energy storage arises. It is needed because wind and solar power are seasonal and they can drop to very low levels for periods of several days or weeks due to prolonged calm spells or periods of heavy cloud. Solar output is least in the winter when the peak demands occur and is at a maximum during the summer time when people go on holiday and relatively little lighting is used.

For fluctuations lasting for a few minutes or a few hours, batteries and pumped hydropower storage are satisfactory solutions. But when the time period gets into days, weeks and even months, there is no technology available that can store large amounts of energy at an acceptable cost. In fact, there is no technology that can do it at any price.

Because the capacity factor of wind and solar power is low, the installed capacity needed to meet the energy demand is very high. As a result, on occasions when the wind and solar generation is at a maximum, the system is likely to have large amounts of surplus energy. As already mentioned, this can happen long before the renewable energy output is equal to the system demand. The need to maintain system stability and voltage control means that renewable energy cannot supply much over 50% of the load, if that. In countries where it exceeds this, there are always interconnections with other systems, which maintain system stability.

So, as the energy cannot be stored, it must be dumped, its production curtailed or, most usefully, turned into heat as is planned in Denmark. This will further reduce the effective output of the already low capacity factor generating plant.

The main available or developing energy storage systems are discussed below.

Pumped hydro storage

This is the most common method of “storing” electricity. The UK has four such power plants, at Dinorwig and Ffestiniog in Wales and at Cruachan and Foyers in Scotland. Together, they contribute 2,800MW of pumped storage.

Normally, two artificial lakes are created, one at a high level and another usually more than 100 metres lower. Cheap base load power is used to pump the water from the lower lake to the higher one. The system then produces power by allowing the water in the higher lake to flow to the lower one through a water turbine.

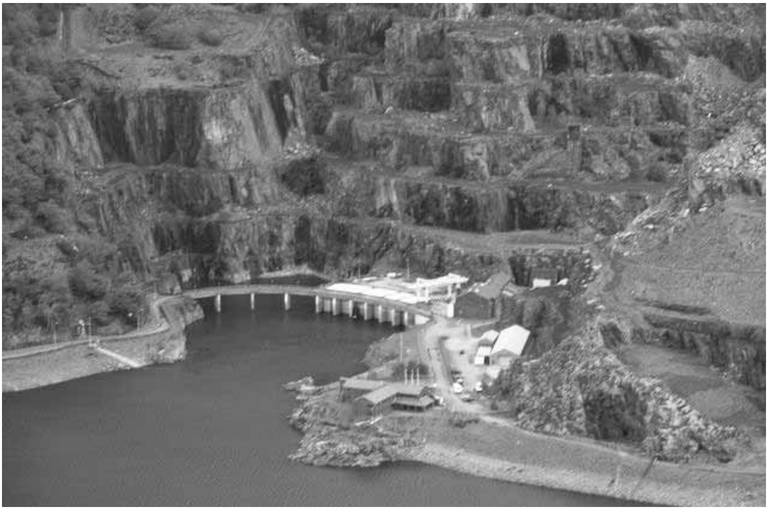
Pumped hydro, like any large-scale engineering project, can be very disruptive to the landscape. Normally, these schemes are built in areas of great natural beauty and involve the excavation and removal of enormous amounts of rock and soil. For reasons of security and public safety, the significant area devoted to a pumped hydro scheme cannot be readily accessed by the public. The lakes, which must be emptied and filled frequently, cannot host much wildlife, let alone be stocked with fish. Applications for new pumped hydro power stations will always be fraught with delay, public opposition and high cost.

Figure 37: Llyn Marchlyn Mawr, upper lake, Dinorwig, Pumped Hydro, North Wales[119]

For these reasons, in Europe, new pumped hydro is currently being constructed only in Portugal and Spain (by Iberdrola) while existing stations are being extended in Germany and Switzerland. Nevertheless, it is against the standards and parameters of pumped hydro storage that all other electricity storage systems are judged, since this is a reliable, proven technology. Typically, the energy stored is in the range 4 – 8 hours of the rated output of the turbine-generator. The round-trip efficiency is normally 75 – 80%.

119 http://www.geograph.org.uk/photo/428061

Figure 38: Outlet and inlet of the Dinorwig pumped hydro power station (and lower lake)[120]



It is impossible to guess what a new power station, on the scale of Dinorwig (1,728MW) would cost if built from scratch today. There is a completely new, 136MW, pumped hydro scheme currently being built in Portugal at Alvito[121] where the budget cost is €268 million. However, such projects rarely come in under budget, so it is wise to assume a "new" price of well over £2,000 per kW. For longer term storage as would be necessary to cope with seasonal variation in wind and solar output, pumped storage is a theoretical option. However, there are few sites anywhere in the world where such a large-scale system with sufficient head of water could be built. Much higher costs per kWh because of a lower level of water cycling, and high evaporation losses in some circumstances, make this even less likely.

120 http://www.geograph.org.uk/photo/287738

121 http://www.renewableenergyworld.com/rea/news/article/2011/08/balancing-the-grid-with-pumped-storage?cmpid=WNL-Friday-August12-2011

Compressed Air Energy Storage (CAES)

CAES technology[122] has been in use for 30 years. Electrical energy stored by compressed air is recovered by using it to supply compressed air to an otherwise conventional gas turbine generating plant. CAES plants are made using the following proven components:

1. Power system: gas turbine expander(s), generator
2. Compression system: complete with coolers
3. Containment vessel (or cavern) with airflow piping
4. Control equipment: switchgear, substation, cooling system etc.

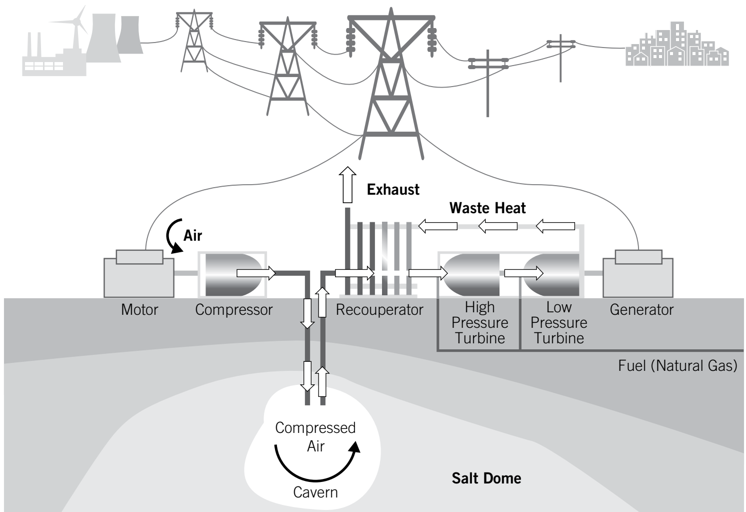
Only two CAES plants have ever been built, at Huntdorf, Germany, a 290MW installation built in 1978 and operated by EON, and the 110MW plant in Macintosh, Alabama operated by Power South.[123]

There is enormous interest in the idea of building more CAES to meet the growth of intermittent energy sources, especially in Germany and the USA. But there are environmental and geological issues with this technology, as there are with pumped hydro. Firstly, it is necessary to create a large underground cavern which can receive compressed air and allow the continuous, safe, cycling of compression and decompression. Caverns excavated from salt domes are favoured because of their stability. But these are also widely valued for gas storage and there are obviously a limited number that can be developed for this application.

The largest problem with this technology is its low overall efficiency. As anyone who has ever pumped up a bicycle tyre with a hand pump knows, compressing air creates heat, while releasing the pressure results in cooling. So there are intractable inefficiencies involved both in compressing and expanding the air in the cavern.

122 Simon Pockley: http://www.docstoc.com/docs/33810310/Compressed-Air-Energy-Storage-_CAES_
123 http://www.powersouth.com/mcintosh_power_plant/compressed_air_energy

Figure 39: How compressed air energy storage works[124]



The combination of these inefficiencies results in a round-trip efficiency (electricity in/electricity out) of around 42% for the two existing CAES plants. This means that the larger part of the power to be stored is actually lost, which is unacceptable in a world where the cost of primary energy is growing so strongly, so it is little wonder that no new CAES plants are actually being developed as this report is being written (autumn 2011). 57 upper Midwest municipal utilities participating in the Iowa Stored Energy Park (a “flagship” CAES development), cancelled the project in early August, 2011 after detailed geological investigation revealed fatal flaws.[125]

Research is underway to find solutions to these issues and raise the overall efficiency to the same level achieved by pumped hydro and electro-chemical batteries. But there is nothing commercially available yet. Unfortunately,

124 From a paper by Simon Pockley http://www.docstoc.com/docs/33810310/Compressed-Air-Energy-Storage-_CAES_

125 http://www.theenergydaily.com/ced/energy_efficiency/Geology-Studies-Sink-Iowa-CAES-Project-But-Developers-Gain-Valuable-Information_6514.html

because the idea of using compressed air to store energy seems so attractively simple, it is a technology that attracts many hare-brained eccentrics. The internet is full of “clever” ideas that cannot come to fruition because of the realities quantified by the English scientist Robert Boyle in 1662!

Distributed storage – electro-chemical solutions (batteries)[126]

If large-scale storage schemes have their problems, then perhaps storing energy in a decentralised way, using various types of battery, could be a solution.

Figure 40: Detroit Electric vintage car (1917)[127]

The lead acid battery is the work-horse of the battery industry and is in common daily use under the bonnet of hundreds of millions of trucks and cars, world-wide. Electric cars powered with lead acid batteries were running around the roads of the USA and UK before the First World War.

126 HS must declare his commercial interest in the use and commercial development of the vanadium redox battery
127 http://www.paenergyfest.com/photos07/

Lead-acid battery technology sets standards against which all other chemistry-based, electricity storage technologies are measured. Beside its affordable cost, the main strength of the lead acid battery is that it can deliver a short pulse of high power that can turn a vehicle's engine and get it started. These characteristics make it attractive in the supply of the large and growing Uninterruptible Power Supply (UPS) market which allows sensitive, high value processes to ride through interruptions and disturbances in grid-supplied power.

Its weakness, as anyone who has ever forgotten to turn the lights off after parking their car knows only too well, is that the lifetime of the battery is severely affected by "emptying" the charge. As long as the lead-acid battery is used within 75% of its full charge, it can provide a decent service life of around five years. But it cannot withstand repeated deep cycling.

For this reason, there is huge commercial interest in batteries that are robust and long-lived, both for use in electric vehicles (EVs) and the new "smart grids" that are needed to cope with stochastically intermittent power supplies, like wind and photovoltaics (PV). The storage technologies summarised in Figure 35 include a large number of new battery types. All of these are either commercially available or approaching commercialisation. More details of the various technologies can be found in the Appendix.

Is the electric vehicle (EV) a useful means of storing electricity?

If, as is predicted by some, global oil supply fails to keep pace with growing demand, the price and supply of oil will be subject to more of the wild gyrations seen since 2008 and oil will cease to become a reliable transport fuel. Gas may help to fill the gap and stabilise transport fuel costs, but its supply may also come under pressure. The present heavy investment in the manufacture of electric and hybrid cars might in such circumstances prove to have been a godsend (assuming, of course, that electricity generating capacity can be increased without use of additional coal or gas).

Manufacturers project that electric vehicles (EVs) could become a significant fraction of all vehicles on the roads by 2020. However, this cannot happen until battery costs fall, their limited range (reduced further when lights, heating or air conditioning are turned on), is extended and systems for fast re-charging or swapping batteries are widely available. These are major challenges, particularly as the fuel efficiency of internal combustion engines continues to improve steadily. A major increase in the numbers of EVs on the road will also make greater demands on the electricity supply. However, the Renewable Energy Roadmap foresees a considerable *reduction* in overall electricity use, which indicates a distinct lack of joined-up thinking having taken place at the Department for Energy and Climate Change.

There is much "blue sky" chatter about the use of mass fleets of EVs to provide reserve services to the grid operators, the so-called V2G (or vehicle to grid) solution. This will require the EV fleet to deliver power to the grid. This will have the effect of further shortening the lives of the already prohibitively expensive batteries. Such speculation seems highly premature. The battery cost per charge and discharge cycle is greater than the cost of conventional power generation. Another real, practical problem is that if an electric vehicle battery is depleted by the system during an evening peak demand and renewable energy fails to deliver through the early hours of the morning, the owner of the vehicle will be faced with a discharged battery in the morning. To most people, this would be a very unpleasant shock. So one can only conclude that this proposal would be very expensive and has an enormous number of real problems, even if electric vehicles become mainstream.

Heat as a way to store excess wind and solar power

A less costly, though not necessarily economic, way to store renewable energy as generation capacity exceeds the tipping point where wind energy would endanger the rest of the system, is to turn that electricity into heat through smart meters and remote switching in the UK's millions of hot water tanks, many of which are electrically heated already. This would clearly be more rational than turning wind power off just when the national fleet of such turbines is producing most power. The use of over-flow electricity can also be cheaply adapted to the small number of existing premises where electricity and storage heaters are already in common use.

The use of over-flow electricity in this way can be regarded as a stabilising service to the grid operator and will allow the operators of the necessary balancing thermal plant to avoid the higher fuel costs and increased wear and tear involved in starting and stopping or ramping up and down.

The wholesale cost of wind power has been estimated as £94 (onshore) and £110-125 (offshore) per MWh in the study “UK Electricity Generation Costs Update”, written in June 2010 for DECC by the UK consultants Mott MacDonald. However, this takes into account generator costs only. Once costs of transmission, backup and generator ramping are included, the costs as seen by the consumer rise to an estimated median figure of £190/MWh for onshore and £265/MWh for offshore wind. Even taking the lower figures from the Mott MacDonald study, for this solution to be fully economic compared to gas requires that the wholesale gas price (for heating) rises from today’s (summer 2011) price of about 4p/kWh to at least 10p/kWh (which could be the case if oil and gas supplies are as constrained as some commentators believe).

Hydrogen as a way to store excess wind and solar power

It is difficult to understand why there are still so many advocates for using hydrogen made by the electrolysis of water as a way to store overflow electricity. A more expensive way of storing electricity could hardly be imagined. The efficiency of electrolysing water to manufacture hydrogen is roughly 70%. It must then be compressed and stored, with an efficiency of 90% at best. To turn hydrogen back into electricity requires a rotating device (best efficiency 60% using a CCGT or the still highly theoretical fuel cell). So the round-trip efficiency will at best be 70%*90%*60% = 38%. Almost all other storage solutions can offer a higher round-trip efficiency with a lower capital cost.

A truly economic PEM-type (proton exchange membrane) hydrogen fuel cell remains highly elusive. Many billions of dollars (literally) have been spent trying to find an economic and durable product but disappointment is the only consistent outcome. In addition to the economic issue, secure containment of hydrogen, the lightest element, is extremely difficult, and losses from storage tanks can be significant.

However, there may be some merit in spiking the gas grid with hydrogen to deliver “waste” energy from over-flow wind energy. A whole literature exists on “hythane”.[128] However, doing this safely will require the most stringent planning and coordination with suppliers of natural gas who must ensure the safety and commercial integrity of the gas supply system.

128 Just type ”hythane” into Google!

The practical limits to use of renewables

The practical contribution renewable generating technologies can make to energy security is constrained by the following key issues:

Cost

Conventional, fossil-fuel based generating technologies have been developed and optimised to give today's rather efficient power stations. Biomass is simply an alternative, lower energy density fuel to fire conventional generators, and there is too little available to replace coal, gas or oil to a major extent. Hydro power is a mature technology which represents the best modern way to harness power from water, but which has little scope for further expansion. Tidal and wave power systems are attempts to exploit the power of water in other ways and are, in effect, the latest generation of waterwheels. Wind turbines are the modern incarnation of windmills, used for centuries to provide localised power when possible. But despite their higher efficiency, they are not well suited to integrate into a modern energy grid. Solar power installations are the only truly new renewable energy technology, with photovoltaic cells only having been available in significant quantities for the last few decades.

Both wind turbines and photovoltaic cells are commercially available on a large scale. The cost of turbines has decreased to some extent as manufacturing techniques have improved, but installation – particularly for the more efficient and more publicly-acceptable offshore wind farms – is expensive. The price of solar cell arrays has declined quite significantly (by 50% in five years in Germany), largely because manufacturing has moved to lower-cost economies. However, even with current fuel prices ($100+ for Brent crude futures as this report is being written) neither technology is yet economically competitive, a fact emphasised by industry concerns over the lowering of feed-in tariffs. It is difficult not to conclude that the official enthusiasm for renewables has more to do with the power of the green lobby than economics and energy security.

Hydro power is a proven technology which can be deployed relatively cost-effectively only in suitable geographies. Biomass burning can be economic if fuel is sourced locally, but implementation on any significant scale certainly requires price support at present. On-shore wind is the lowest cost of the newer options, but still requires significant financial incentives. Off-shore wind, although more efficient in terms of capacity factor, is significantly more expensive, mainly because of the added costs and complexity of installing turbines in water and making them sufficiently resilient to survive the more extreme conditions. We also have to factor in the need for scarce rare earth metals such as neodymium as essential components of the magnets used in wind generators. There is also a relatively high failure rate of gear boxes, which are particularly difficult and expensive to service in offshore installations.

Solar power is considerably more expensive than other available technologies, although it is fair to say that the capital cost has come down considerably in recent years, as a consequence of evolutionary improvements, economies of scale and production increasingly moving to lower-cost manufacturing countries (which do not always meet European standards of environmental protection). Nevertheless, very large reductions in the cost of solar cells and their installation would be needed to make them truly economic; even then, nothing can eliminate the intermittency problem.

Some tidal barrage schemes – particularly in the Severn estuary – could be cost-effective if additional transport and flood-prevention benefits are allowed for, but each scheme is a one-off, having to bear its own specific design and building costs. There are some indications that tidal stream generation could be close to commercial viability, but installations so far are essentially only demonstration projects and it would be many years before the technology might be mature enough to be a practical option. Wave power is even further away from becoming a reality, and may never be commercialised on any scale. Any estimate of costs in the long term would be pure conjecture at this stage.

Heat pumps are an efficient and proven technology. However, they can contribute only to space- and water-heating and their high capital cost makes them an unattractive option to many potential users.

Capability

No country can rely on a single energy source to generate power, although high dependency can be achieved in certain circumstances (e.g., geothermal power in Iceland, hydropower in Norway, with backup via interconnectors with neighbouring countries). In practical terms, the reliance of France on nuclear power for more than three quarters of its needs probably represents a practical upper limit on a single source. This means that we should not expect any one renewable technology necessarily to be a dominant source of grid electricity. On the other hand, decarbonisation policy requires the phasing out of all coal and gas capacity. The void has to be filled by a combination of existing renewables (and backup capacity) and nuclear fission, as things currently stand (assuming that no disruptive new technologies such as nuclear fusion reach the market).

In the UK, the renewables contribution has to come essentially from wind power, with a minor contribution from biomass (constrained by supply) and a more significant one from a Severn barrage, should it ever be built. Solar power, although inefficient in such high latitudes, could be deployed to a greater extent, but the cost would be prohibitive and there is likely to be public opposition to the use of large areas of otherwise productive land for this purpose. Even if these barriers could be overcome, the fact remains that the peak output from solar installations does not coincide with times of high demand in northern Europe. Wind power could make some contribution, but this report has shown that there is little point in installing the capacity envisaged in the road map. To do so would be expensive and give little saving in fossil fuel use.

Intermittency

With the exception of biomass burning – constrained by supply – all renewables technologies can provide only an intermittent supply of power. In the case of wind, which is the only one in principle capable of making a significant contribution to the overall supply, this intermittency is especially marked: stationary areas of high pressure in winter can lead to several days of essential zero contribution from wind power across the UK at a time of maximum demand. At other times, high wind speed will force wind farms to be shut down and, at all times, the inherent gustiness of wind will cause frequent short-term fluctuations in output.

The supply grid can cope with intermittency – and even then at a significant cost – only when wind (or tidal, or solar) power capacity is a minor part of the energy mix. However, as the Irish experience shows, above a certain level, we reach a point of seriously diminishing returns. To utilise all the output of wind power, greater use of interconnectors to neighbouring countries is needed, although the case of Denmark shows that this very often means dumping power at low cost at times of high output. Supporters of renewable energy propose a regional DC grid to match supply and demand across Europe, but this would take many years and many billions of euros to complete. Even if this was successful, it would still not guarantee a secure, year-round energy supply; stationary anti-cyclones can cover very large areas at times of peak winter demand, for example.

Unreliability

A final significant problem with wind power is its unreliability, a consequence of the intermittency problem. Although renewables are generally intermittent, some are predictably so. A Severn barrage would produce power at known times and solar panels will generate some electricity during daylight hours, albeit to a very variable degree. But wind is less predictably variable over all time scales. For calm, cold winter days, when demand is at a maximum, the country has to have conventional generating capacity available (either nationally or via interconnectors) to replace the entire potential contribution of wind .

What would be needed to make renewables a major contributor to the grid?

Technical

The case against the widespread deployment of current renewables technologies at present is quite clear. But it is only fair to consider what developments could occur which might change this picture. On the technical side, the two key issues are intermittency and energy storage. Intermittency is intrinsic – we cannot control the wind, sun, waves or tides – but if any technologies which use them to generate power could be made sufficiently low-cost and efficient, a very large nominal capacity could be installed affordably. However, this in itself would not be sufficient to guarantee energy security; if the wind doesn't blow, it doesn't matter how many turbines there are. Even a very large reduction in cost would have to be accompanied by a massive step-change in energy storage capacity to cover many days demand. This seems a remote possibility with the current state of knowledge.

The best that can reasonably be hoped for is that battery technology advances to the extent that large-scale but short-term storage becomes an affordable reality. However, this cannot guarantee energy security during periods of winter peak demand. It is argued that creation of a regional electricity grid would enable supply and demand to be balanced much better, but even if this became a reality – at enormous cost and over a considerable period of time – in cannot provide the guaranteed continuity of supply which modern societies have a right to expect. Possibly this would reduce the timescale over which stored energy was needed, but 100% security would be difficult to provide at any cost.

Wind turbines are a rather mature technology; manufacturing costs should still continue to fall, but there are unlikely to be any real quantum leaps in performance. Photovoltaic cells, on the other hand, are different. Currently a very expensive option, research on radical new approaches to converting sunlight to electricity could reduce their cost by a factor of ten or more. However, even at such a hypothetical price, PV cells require large amounts of space, are intrinsically intermittent in operation and – most importantly – produce their lowest daily output at times of maximum demand in high latitudes.

For now, the UK's 15% renewable energy target by 2020 might be possible with sufficient investment in both wind turbines and gas generating capacity, but progress beyond that seems very unlikely without the projected regional energy grid. Since this is still only a concept, this calls into question the very feasibility of meeting the increasingly stringent targets being considered beyond that.

Oil and gas price

The primary drawback of renewable energy is its intermittency, which no amount of money can solve. However, rising prices of fossil fuels would at least make investment in more renewables capacity a more realistic option. More generally, if advocates of peak oil are right in the short- to medium-term, and exploitable shale gas reserves turn out to be towards the lower end of expectations, fossil fuel supply will fail to meet demand adequately, and prices will rise considerably. This economic signal would focus minds very clearly on developing alternative energy supplies.

Figure 41: Recent oil prices[129]

Source: TradingEconomics.com; NYMEX

On the face of it, this should give a real boost to the expansion of renewable energy. However, when the wind doesn't blow or the Sun doesn't shine, a back-up source of power is needed which, for now, essentially means relatively inefficient open-cycle gas turbines. This would keep demand for gas at a higher level than the level of installed renewables capacity would initially suggest.

129 http://www.tradingeconomics.com/commodity/crude-oil

Main conclusions

This review has shown that the renewable energy technologies which are commercially available or in development cannot form more than a minor part of the overall power supply without putting the security of supply at jeopardy. On-shore wind is the lowest-cost option, but still requires significant financial incentives to encourage investment and has limited scope for expansion because of public opposition and lack of appropriate sites. Its viability would be reduced even further if wind farms had to carry the cost of the additional gas-fired generating capacity as backup. Experience from other countries with larger percentages of wind generation shows that only limited savings can be made in fossil fuel consumption and that security of supply can only be guaranteed by having a large-scale backup capability or a high degree of interconnectivity with neighbouring countries having surplus capacity.

Our more detailed conclusions are:

- Given that there is very little scope for development of new hydroelectric schemes, the only technologies which are sufficiently developed for large-scale deployment in the UK are wind and solar power (both photovoltaics and concentrated solar thermal), together with burning available biomass.

- Use of biomass is relatively attractive, having none of the drawbacks of wind or solar power, but the contribution it can make is constrained by the need to grow food and provide raw materials for transport biofuels and industrial processing. It can only be a minor part of the overall energy mix.

- On-shore wind is the least expensive of the other options, but is still uncompetitive without continuing subsidies. It is also both intermittent and unpredictable, requiring conventional capacity to be on standby to balance the supply, and is subject to increasing public opposition. Service life, at 20 years, is short compared with conventional generating technologies.

- Off-shore wind is considerably more expensive, although more acceptable to the public.

- Despite the cost of cells having come down recently, photovoltaic systems are far more expensive than wind and require large subsidies. Their use in such high latitudes is not to be recommended, and the willingness of the government to provide large subsidies, particularly for small-scale installations, is difficult to understand.

- Solar thermal systems are also only suitable for much sunnier environments than northern Europe.

- Heat pumps are suitable as a source of heating in some circumstances, but only on a local basis. They are efficient at producing low-cost heat, but are costly to install.

- Tidal barrage schemes, such as the proposed Severn estuary project, have limited potential. There are relatively few appropriate sites, they have a large environmental impact, and they are intermittent (although predictably so). Nevertheless, they cannot be ignored.

- Neither wave nor tidal stream technology is close to commercialisation. The need to harvest energy during normal conditions while withstanding storms presents enormous engineering difficulties. However, tidal power currently seems to offer greater practical possibilities and neither can be completely ruled out as long-term options. That said, there is no foreseeable prospect of them becoming competitive with gas or nuclear power generation.

- Wind and solar power generation schemes operate at a fraction of their installed capacity.

- Because – with the exception of biomass – renewable energy supply is intermittent, conventional generating capacity, particularly gas, has to be kept running on standby to balance the grid. This means that actual reductions in carbon dioxide emissions are lower than theoretically possible and that the cost per tonne is relatively high.

- Intermittency also causes significant problems with balancing the grid to maintain energy security. While not insurmountable for modest levels of renewable energy, these problems limit the effective contribution which renewables can make to the energy supply.

- With the exception of pumped storage, there are no means of storing energy on a large scale and for a significant period to smooth the contribution of wind and solar generation, which often peaks at times of low demand. Even pumped storage can only provide backup over a timescale of hours rather than the days or weeks necessary to guarantee continuity of supply in a renewables-based system. With the current state of knowledge, there is no foreseeable possibility of developing practical and affordable options.

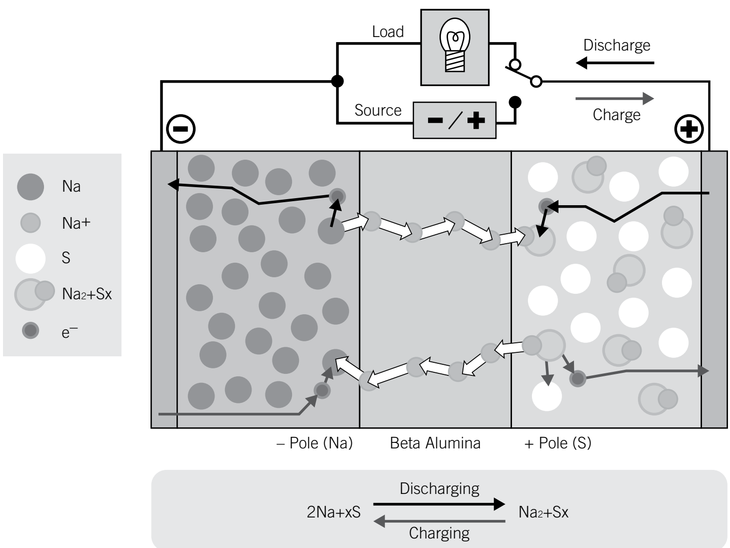
- There is no prospect of most renewable technologies – particularly solar and off-shore wind – being competitive with conventional power sources in the foreseeable future.

- In light of this assessment, we conclude that taxpayers' money would be far better spent on measures to increase energy efficiency, plus investment in proven nuclear and gas generating capacity to provide energy security as many of the UK's coal-fired stations – and nearly all existing nuclear reactors – are decommissioned over the coming decade.

Appendix – Battery Technologies

The Sodium – Sulphur (NaS) battery: manufactured by the Japanese ceramic insulator company NGK.[130] The principle of operation is shown in the following figure.

Figure 42: How the sodium sulphur battery works



130 http://www.ngk.co.jp/english/products/power/nas/index.html

These batteries have liquid sulphur at the anode and liquid sodium at the cathode, and a sodium ion-conductive ceramic separating the electrodes. This hermetically sealed battery is operated at an internal temperature of 300°C to keep the active materials liquid. It comes as a module that contains roughly 5kWh of useful storage for each kW of power output, although its nominal storage is 6kWh/kW output. Some 300MW of batteries have been delivered, mostly in Japan (following the earthquake and tsunami in March 2011, owners were highly appreciative of the standby services their batteries were able to provide).

However, the technology is not without its problems. In September, there have been a number of fires: most recently in a sodium sulphur battery installation at a Mitsubishi Materials plant in Japan.[131] *Scottish & Southern Energy* installed such a 1MW, 6MWh NaS battery at its Lerwick, Shetland, power station during 2011, but commissioning is being delayed until the root cause of the problem has been found and appropriate safety systems put in place.

Figure 43: 34MW NaS battery operating at a 51MW wind farm in Japan[132]

131 NGK Insulators Ltd: NAS battery fire incident and response
132 http://www.ngk.co.jp/english/products/power/nas/installation/index.html

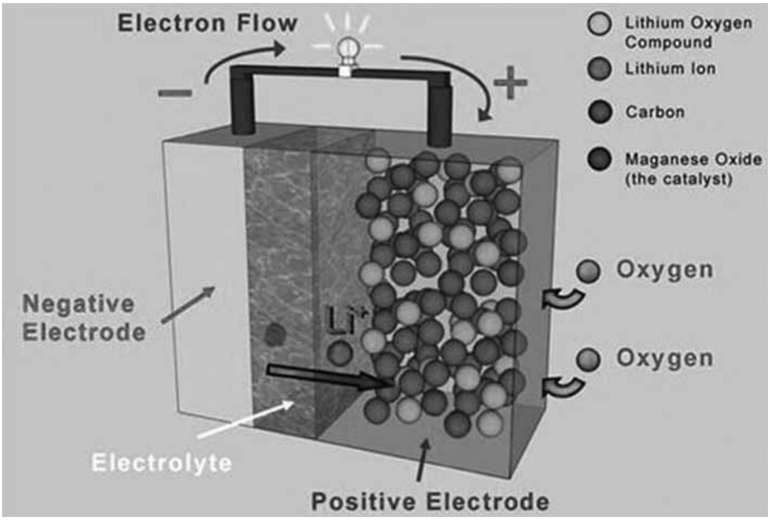
The battery must be maintained at high temperature; if the liquid electrolytes cool and solidify, the system cannot be restarted on site and the stacks must be replaced. Also, like most other electro-chemical processes, its performance deteriorates with repeated deep cycling. This explains why the battery in figure 43 is so large (34MW) in relation to the host wind farm (51MW). This is a technical demonstration of how electricity storage can turn wind power into a predictable resource, but only at an enormous upfront cost. The cost of such a 51MW power station is US$183 million at least, or $3500/kW. The capacity factor will depend on the location of the wind farm and the weather during each year as for any other wind power plant. And of course, the five hours of storage will not allow the wind power station to provide electricity during long-lasting anticyclones. Xcel Energy in the USA published a detailed and remarkably frank report on its NaS battery in 2010[133] for those interested in more details.

Lithium Ion batteries: Because of its light weight and relatively high energy density, the lithium ion battery is seen as the workhorse of the (possibly) coming electric vehicle market. It is already the main battery type used in laptops, tablets and mobile phones. There are hundreds of manufacturers worldwide, including Altairnano, A123 Systems, Samsung, Sanyo and BYD. There are also a large number of chemical and physical configurations.

The three primary components of a lithium-ion battery are the anode, cathode and electrolyte. The anode of a conventional lithium ion cell is made from carbon, the cathode is a metal oxide, and the electrolyte is a lithium salt in an organic solvent.

133 The Xcel Wind battery report can be down-loaded at http://apps1.eere.energy.gov/news/news_detail.cfm/news_id=16228. (The redacted parts can be accessed by copying and pasting into MS Word.)

Figure 44: How a lithium ion battery works[134]



During discharge, lithium ions (Li+) carry the current from the cathode to the anode, through the non-aqueous electrolyte and separator diaphragm. During charging, a higher voltage forces the current to pass in the reverse direction. The lithium ions then migrate from the positive to the negative electrode, where they become embedded in the porous electrode material in a process known as intercalation.

Anyone who owns a laptop or tablet is only too aware that using a lithium battery causes it to wear out within a few years of use. There are high hopes that mass-scale development of this important technology, on which the whole future of the electric car business currently depends, will result in even higher energy density, extended life and lower cost.

134 http://blog.leasetrader.com/archive/2009/08/18/Toyota-advances-lithium-ion-battery-output.aspx

The reality is that 75% of the cost of lithium ion batteries is raw materials, so unless these commodities fall in value, which seems unlikely, the price for lithium batteries will remain stubbornly over $1000/kWh. Bolivia, having 50% of the world's known lithium deposits, intends to control extraction and transformation of this metal, using Saudi Arabia (and perhaps Norway) as role models. This political weakness in the supply chain might be a "ticking bomb" under the whole industry.

Figure 45: AES 1 MW, 1.25MWh battery operating for grid operator PJM Pennsylvania USA[135]

The profitability of lithium battery manufacturing , despite the huge scale of the industry and the voracious global demands for rechargeable batteries, remains very low. Some leading manufacturers are actually losing money.[136] Because of its intrinsic high cost, it is not economic for applications that require high energy storage, relative to power output. So in grid applications, it is being sold for applications like dynamic frequency regulation and reactive power (VAR) support which require relatively small charges and discharges of very limited duration.

135 http://gigaom.com/cleantech/aes-building-worlds-largest-lithium-ion-grid-battery-projects/
136 http://seekingalpha.com/article/285490-lithium-ion-batteries-and-8-track-tapes-will-the-potential-market-be-capped-forever#comments_header

Nickel Metal Hydride (NiMH): The rechargeable, nickel metal hydride battery remains in common use for many small-scale applications and is still used in the Toyota Prius. The "metal" in question is the rare earth lanthanum. Kawasaki in Japan remains an important technology developer but for the time being, the technology seems to be losing market share to lithium ion technology.

Nickel Cadmium: The nickel cadmium battery was the first non-lead acid battery used on a small scale for portable power electronics applications. This is actually a very successful technology, having a long life, tolerance to multiple deep discharge, and being a relatively mature technology. However, it suffers from the major flaw of being forbidden for use within the EU on account of the toxicity of cadmium!

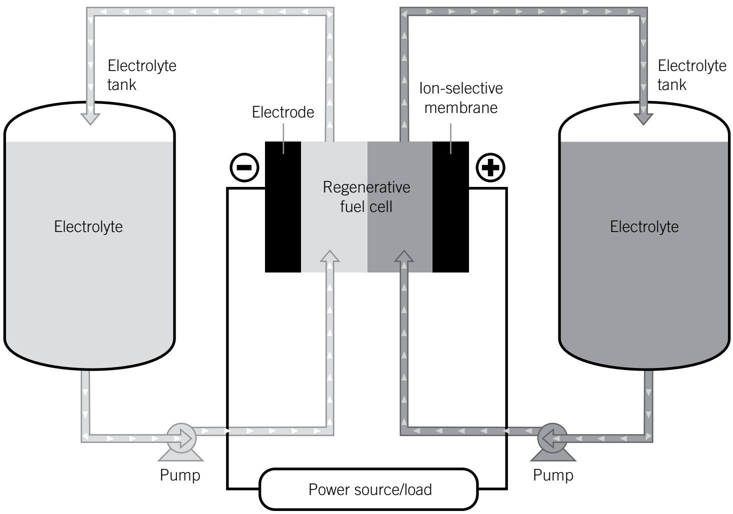
Figure 46: 40MW, 15 minute nickel cadmium battery, Golden Valley, Alaska (1992)[137]

137 Can utility scale batteries rescue intermittent renewable? http://www.masterresource.org/2010/03/can-utility-scale-batteries-rescue-intermittent-renewables/

The flow battery: Unlike conventional batteries, which store their reactive materials within the cells, a flow battery stores electrolytes in tanks, one for positive and another for negative reactants. These electrolytes are pumped through the cells when the current flows, and then return to the same tanks. The positive and negative electrolytes do not actually mix; a thin, proton exchange membrane (PEM) separates them so only selected ions flow through the cells.

This feature means that the power (kW) function is scaled by adding cells in parallel and series to deliver more power, while additional energy is provided by increasing the quantity of electrolyte and the volume of the tanks to contain this. It is possible to provide up to 30 kWh of energy for each kW of power delivered.

Figure 47: How a flow battery works[138]



In this way, the flow battery can "compete" with pumped hydro, although in the distributed part of the grid rather than the high voltage end typical for pumped

138 http://www.pdenergy.com/products_whatisvrb.html

hydro. It can therefore be used in a much wider variety of grid applications than solid metal batteries like lithium ion and nickel metal hydride.

Furthermore, in the case of the vanadium redox battery, which is probably the leading type of flow battery commercially available, they can be full cycled indefinitely without any loss of performance, which distinguishes this technology from all other electro-chemical solutions.

Figure 48: Part of the 500 kW, 1000 kWh *Prudent Energy* installation for China Grid, 2011

There are other flow battery chemistries. The leading non-vanadium flow battery is based on the use of zinc with bromine. The battery consists of a zinc negative electrode and a bromide positive electrode separated by a micro porous separator.

An aqueous solution of zinc bromide is circulated through the two compartments of the cell from two separate reservoirs. The electrolyte stream in contact with the anode contains bromide which is maintained at the desired concentration by equilibrating with a bromide storage medium. This is immiscible with the aqueous zinc bromide solution. All battery components are made from a bromide-inert plastic.[139]

Flywheel energy storage system (FES)

The FES works by accelerating a rotor (flywheel) to a very high speed, so converting electrical energy into rotational energy. When energy is extracted from the system, the flywheel's rotational speed is reduced as a consequence of the principle of the conservation of energy; adding energy to the system correspondingly results in an increase in the speed of the flywheel.

Most FES systems use electricity to accelerate and decelerate the flywheel, but devices that use mechanical energy directly are being developed. Advanced FES systems have rotors made of high strength carbon filaments, suspended by magnetic bearings, and spinning at speeds from 20,000 to over 50,000 rpm in a vacuum enclosure. Such flywheels can come up to speed in a matter of minutes and are therefore able to take up energy much quicker than some other forms of energy storage.

Because this technology can offer only short duration storage, typically under 15 minutes, it is targeted at the market for dynamic frequency regulation and reactive power support.

At the Beacon Power website, there is an announcement about a 20MW, $53 million FES contract[140] implying a price of $2,650 per kW and therefore a likely price of over $10,000 per kWh. If this is the case, even for its chosen niche, it does not seem likely that this technology can survive without grant aid. Indeed, recently Beacon Power filed for bankruptcy, following two catastrophic failures of its flywheel installations.[141]

139 http://www.zbbenergy.com/products/flow-battery/zn-br-battery-technology/
140 http://investors.beaconpower.com/releasedetail.cfm?ReleaseID=598243
141 Beacon Power goes bankrupt despite federal, state support

Figure 49: Beacon Power's Smart Energy 25 flywheel[142]

142 http://bostonherald.com/business/technology/general/view.bg?articleid=1377313&srvc=business&position=3

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