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## **Sustainable Energy : choices, problems and opportunities**

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# **Sustainable Energy : choices, problems and opportunities**

## **ABSTRACT**

The development of patterns of energy generation and use which can be sustained into the future is increasingly seen as urgent, given growing concerns about the potential social and economic impacts of climate change due to the combustion of fossil fuels.

The prospects for the main non-fossil energy options, nuclear power and renewable energy, are reviewed, as are the prospects for energy conservation and carbon sequestration. The economic, social and environmental implications of the development of sustainable energy system are then explored, and some of the strategic technological choices that lie ahead, both for the UK and elsewhere, are identified.

## **Contents**

1. Introduction
  2. Climate Change
  3. Carbon sequestration
  4. Energy Efficient generation
  5. End Use Energy Efficiency
  6. Nuclear Power
  7. Renewables
  8. Progress with Renewables
  9. Assessing the Costs of Sustainable Energy
  10. Risks
  11. Carbon Accounting and Energy Analysis
  12. Land use
  13. Choices for a sustainable energy future
  14. Conclusions
- References

Captions to tables

Tables

# **Sustainable Energy : choices, problems and opportunities**

## **1. Introduction**

The development of patterns of energy generation and use which can be sustained into the future is increasingly being seen as urgent, given growing concerns about the potential social and economic impacts of climate change. This article reviews the energy options for a sustainable future, focussing on options which might reduce or limit the level of carbon dioxide emissions.

The climate change issue is a global one and, increasingly, developing countries will begin to contribute to it as they industrialize. However, the industrialized countries bear the responsibility for having developed the technologies that have created the problem. It would only be reasonable to expect them to play a leading role in developing some of the technologies which might help reduce it.

While the overall view is global, this article draws on examples of developments chiefly from the UK, which has embarked on a major programme of sustainable energy development. That is not to suggest that there are not other developments going on elsewhere; indeed the UK is in many respects following behind initiatives pioneered by countries like Denmark and Germany, particularly in the wind power field.

The main focus of the review is on the new renewable energy technologies, since this is the main topic area of this book. However, to set the scene, the prospects for the other main options, including carbon sequestration, energy conservation and nuclear power, are reviewed. Subsequent sections then attempt to make a comparison of the merits of each option, so as to provide an overview of the choices ahead.

The basic criteria for the energy choices facing the world are, of course, not just environmental. Economic factors remain crucial. But short term economic prosperity may mean little if the health, well being and livelihood of the populations concerned cannot be maintained. At one time a major pre-occupation of many environmentalists was the fear that supplies of key fuels would soon be exhausted. Nowadays, although the price of fuels remains a key political issue, fuel scarcity is less of an immediate concern. Instead the main concern is whether we can safely use the reserves of fuel we have left. <sup>(1)</sup>

## **2. Climate Change**

The scale of fossil fuel combustion has increased dramatically since the industrial revolution, by a factor of more than twenty, and unless changes are made to the way energy is generated and used, this growth seems likely to continue. World energy consumption is projected to increase by 59% from 1999 to 2020, with fossil fuels providing the bulk of this energy <sup>(2)</sup>. In the industrialized countries, their use is split roughly equally between electricity generation (coal), heating (natural gas) and transport (oil), although gas is increasingly replacing coal for electricity generation and the transport sector is expanding continually.

However, the use of fossil fuels creates environmental problems. In addition to problems with acid emissions, the combustion of fossil fuels in power stations and vehicle engines inevitably generates carbon dioxide gas, and these emissions, along with other greenhouse gases like methane, are claimed to play a significant part in the process of global climate change that seems to be underway. While there are few who now doubt that climate change is a reality, not everyone agrees that it is necessarily the result of human activities, or that we should and could do something about it. However, the Intergovernmental Panel on Climate Change (IPCC), representing the bulk of the world scientists, has concluded that the human activities are the main cause and that, unless action is taken, we can expect increasing ecological, social and economic problems around the world. As weather patterns become more erratic, there are likely to be increasingly violent storms and floods and at other times droughts, and as average temperatures rise, sea levels will rise, with low lying areas in the world being inundated.<sup>(3)</sup>

It is hard to put accurate figures on the economic cost of the potential damage and dislocation, not least since much of the impact of climate change could fall on developing countries in terms not just of loss of food growing areas, but also increased disease and social disruption. However, just focussing on the industrial countries, the insurance company Munich Re has estimated that if carbon emissions doubled then that would impose direct costs on the UK of around \$25bn pa and \$150 bn pa for the USA, which is 1.4% of the USA's current GDP. This assessment is likely to understate the full magnitude of the global problem. The former UK Government Chief Scientific Advisor, Sir Robert May, has noted that, in addition to the costs of the direct damage to property and the economy, there could be major impacts on natural ecological processes such as soil formation, water supplies, nutrient cycling, waste processing and pollination, which would have indirect economic implications around the world. He reported rough estimates of the economic value of these processes as being around £10-34 trillion per year, about twice the conventional global GNP, and noted that *'large swathes of this £10-34 trillion are at risk from the possible environmental and ecological changes sketched by the IPCC.'*<sup>(4)</sup>

Some of this damage seems likely to occur whatever is now done, since the carbon dioxide imbalance that has already been created is likely to persist for some while (although there are continual interchanges between the air, the sea and the other carbon sinks, the net excess carbon dioxide can take many decades to be absorbed). Moreover, unless radical changes are made, the situation could be made even worse, as demand for energy increases. World CO<sub>2</sub> emissions are projected to rise from 6.1 billion metric tonnes of carbon equivalent in 1999 to 9.8 billion metric tons in 2020, a 60% increase, possibly rising to 15.1 billion metric tonnes by 2050, a 152% increase on 1990 levels.<sup>(2)</sup>

By contrast, the Intergovernmental Panel on Climate Change has recommended that, to try to avoid the worst excesses of Climate Change, carbon dioxide level in the upper atmosphere should be limited to around 550 parts per million by volume, which is about twice pre-industrial levels. The current level is around 363ppmv. This implies that a 60% reduction in emissions (from 1999 levels) should be made globally, a target which has

also been recommended as relevant for the UK by the Royal Commission on Environmental Pollution, which also proposed a target date of 2050<sup>(5)</sup> Given that nearly 80% of the energy generated around the world at present comes from fossil fuels, making a reduction on this scale will be difficult.

### **3. Carbon sequestration**

One way to try to deal with the problem of carbon dioxide emissions is to collect the gas and store it safely somewhere. Clearly this is not realistic for most vehicle exhausts, but it might be possible for power stations. However, it is far from cheap to capture carbon dioxide that would otherwise vent up the power station chimney. Estimates suggested that it might add 50%-80% to the cost of electricity, and could reduce the efficiency of energy conversion by around 10%.<sup>(3)</sup> Moreover, finding somewhere to store the large volumes of gases is far from easy. The most promising option is to store it as compressed gas in depleted oil and gas wells.

There is a symmetry in this 'carbon sequestration' concept, since that is where at least some of the carbon originally came from. There are also situations where CO<sub>2</sub> gas injection can be used to improve the efficiency of gas or oil extraction before the wells are empty. However, overall there may only be space in empty wells for a few decades of emissions. Estimates of storage capacity range from 40-100 giga tonnes for oil wells and 90-400 giga tonnes for gas wells.<sup>(6)</sup> Given that in 1999 some 6 giga tonnes of carbon dioxide was emitted world-wide, and emission levels are increasing, this storage capacity could only be sufficient for at most 80 years worth of emissions.

There could however be much more space in some saline aquifers, although there are relatively few 'closed' or sealed aquifers suitable for secure storage, possibly sufficient for around 50 giga tonnes. By contrast there is much more room with less secure 'open' aquifers, possibly enough for up to 13,000 giga tonnes, or around 2000 years worth of current emissions. However, there is the problem of ensuring that the gas does not escape at some point due to geological shifts and there is a range of other environmental unknowns.<sup>(7)</sup>

Another somewhat more conventional sequestration option is biological storage in biomass, which absorbs carbon dioxide as it grows. For example, there have been moves to plant trees to compensate for carbon emissions from vehicles. However, there is not room to store all the emissions in this way. For example, to sequester all the UK's continuing carbon emissions in trees would require new forests to be planted over an area the size of Devon and Cornwall every year.<sup>(8)</sup> In addition, the storage is not permanent. Although some of the carbon may remain trapped in the roots, forests can burn and trees eventually decay, releasing the stored carbon dioxide.

It is usually argued that it would be more effective in carbon mitigation terms to plant and then rapidly harvest fast growing short rotation coppices of willow, and use these energy crops to produce electricity in a power plant, assuming the energy produced substituted for energy that would otherwise have been supplied using fossil fuels. Nevertheless,

reafforestation has its attractions as interim carbon store, since it is relatively cheap, assuming land is available, and it offers other benefits, such as enhanced biodiversity .

Forestry is only one option for creating new biological carbon sinks. The adopting of different farming practices can also offer routes to carbon sequestration. For example, a 'no till' policy can enhance the absorption of carbon dioxide by the soil. There is also the newly emerging, but very speculative, option of ocean sequestration. In addition to the idea of pumping carbon dioxide into the depths, there is some interest in the idea to enhancing sequestration in the oceans by seeding areas with iron oxide. However, modifying the ecology of large areas of the sea could create a range of environmental problems and this approach has been seen as likely to be expensive and inefficient.<sup>(5)</sup>

Leaving ocean sequestration aside, overall, it has been estimated that, globally, the various types of land based carbon sinks (trees, soil) could at best absorb about 100 peta gram of carbon emissions per annum, which is 25% of the 400peta grams of carbon emissions that would have to be offset in order to meet the 60% by 2050 overall emission reduction target mentioned above. Within this context, sequestration in soil and in trees are seen as about equally viable in carbon mitigation terms.<sup>(9)</sup>

In the end, despite its attractions, carbon sequestration might be seen as a rather inelegant approach to dealing with the problem of emissions- essentially trying to deal with the problem after the event. Surely it would be better not to produce so much carbon dioxide in the first place.

#### **4. Energy Efficient generation**

The most direct way to reduce carbon dioxide production is by burning less fossil fuel. There are various ways in which this can be achieved. The simplest is for people to actually use less energy, i.e. to make do with lowered energy services, which implies something of a frugal approach to lifestyles. While there may well be some benefit in turning off lights when not needed, donning a pullover rather than switching on more heating, or voluntarily forgoing some particularly energy intensive activity like flying, in general 'energy conservation' ( or more accurately fuel conservation) can also be achieved by technical measures which reduce the waste of energy.

It is possible to use fossil fuels more efficiently, so as get more useful energy for each tonne of carbon dioxide produced, or to put it more positively, the get the same amount of useful energy with less carbon emissions. This can apply both to generation and consumption. The classic example in terms of generation is **Combined Heat and Power (CHP)**- the co-generation of heat as well as electricity in power plants. Traditional coal fired power plants typically reject 70% or more of the energy in the fuel they use into the environment, mostly radiated out as heat from cooling towers. About half of this heat can be reclaimed and used to feed district heating networks. That can double the overall efficiency of energy conversion, or allow plants to deliver the same amount of total power from about half as much fuel, with proportionate decreases in carbon emissions. CHP technology has been adopted quite widely in some parts of the world, notably in

Northern Europe, but in recent years, instead of large coal fired CHP plants for city wide heating, the emphasis has moved to much smaller gas fired units – micro CHP. Overall, the UK government's target is for there to be 10GW(e) of CHP in place by 2010, in effect saving nearly 5GW's worth of fossil fuel use, with much of this new capacity being at the small to medium scale.

Worthwhile as CHP is, the electrical power industry has mostly preferred another option-switching over to medium sized **combined cycle gas turbines (CCGT)**, without CHP. The reasons for their popularity is that gas has been cheap and gas fired turbines are quick to install - essentially they are jet engines driving a generator, with the hot exhaust gases also used to produce steam for a conventional turbine, in a two stage system. They are not as efficient as CHP, but are much better than conventional plants, achieving overall energy conversion efficiencies of 50% or more

As a result of this increased efficiency, and since burning natural gas (methane) rather than coal results in lower carbon dioxide production per kWh generated, the use of CCGTs produces about 40% less carbon dioxide per kWh of energy generated than burning coal in conventional plants. Switching over from burning coal to burning gas to generate electricity, has meant that the UK has been able to reduce its carbon dioxide emissions to keep in line with the international targets agreed following the Rio Earth Summit in 1992, without having to do anything much else.

The scale of this 'dash for gas' in the UK has been remarkable. Whereas 80% of the UK's electricity used to come from burning coal, now it is down to 28% ,and gas provides 40%. However, there is a limit to how many more coal fired plants can be replaced by gas plants, so the growth in emissions savings will tail off. As demand for power increases, as seems likely, then once again net emissions will increase. There are also limits to gas reserves. For example, with the north sea reserves becoming depleted and expensive, by 2020, on current trends, the UK could be getting 70-80% of its gas from remote regions in the north east of Russia or, if that proves difficult, from countries like Algeria. Given the geo-political uncertainties, not everyone is convinced that this would be a reliable scenario in terms of ensuring security of supply. <sup>(10)</sup>

There has been some interest in trying to clean up emissions from coal combustion, given that around the world coal reserves are more extensive than those for gas. There are two main technologies. Fluidized bed coal combustion plants are more efficient in burning coal than conventional coal plants and can reduce acid emissions. With Integrated Gasification Combined Cycle technology (IGCC), coal is converted into gas which is then burnt in a CCGT. However, these as yet only partially developed technologies are likely to be expensive, with capital costs/kW for fluidized bed plants perhaps twice that for CCGT, and even more in the case of IGCC. Moreover, the overall energy conversion efficiencies of these plants seem likely to be lower than for gas-fired CCGT plants, possibly only around 40% compared with 55% and higher for CCGTs. So they will produce more carbon dioxide per kWh generated. <sup>(11)</sup>

With the IGCC, there is the advantage that it is easier to collect the CO<sub>2</sub> from the coal gasification process than from the emissions of conventional coal combustion plants, so sequestration could be easier. However, it is unclear whether that would compensate for the extra cost and lower efficiency of the plant. A DTI report on Cleaner Coal Technology (CCT), published in 2001, concluded that there was 'no economic case for building new coal plant ...at present electricity prices. Even without carbon capture and storage, new CCT plant would produce electricity in the range 2.6-3.7p/kWh; with carbon capture and storage, this would rise to something like 4.8- 5.8p/kWh'.<sup>(12)</sup>

## **5. End Use Energy Efficiency**

While the use of gas and CCGT clearly has benefits, and is the dominant new energy option in many countries at present, given its reliance on a finite fossil fuel, this approach may only offer a temporary and partial solution to the emissions problem. By contrast, energy conservation at the point of use would seem to have more fundamental attractions. Certainly the potential for energy savings from the introduction of more efficient systems at the point of use is very large. This is in part because, until recently, energy has been relatively cheap and energy efficiency has mostly been ignored. Given the increased level of concern about climate change, new policies have now emerged, aimed at improving the efficiency with which fuels are used, thereby reducing emissions. For example, the UK Cabinet Office's Energy Review, published in 2002, suggested that the efficiency of energy use in the domestic sector could and should be increased by 20% by 2010 and a further 20% by 2020.<sup>(13)</sup>

There has already been some success in making significant savings in other sectors in the UK, notably industry, where energy demand has been cut by nearly 40% over the last three decades, chiefly on the basis of the cost savings that could be made by investing in new more efficient technology. However, savings like this may not be possible to achieve in all sectors, with the transport sector being the most obviously problematic, given the seemingly inexorable rise in vehicle ownership and mileage around the world. Nevertheless, overall, the Carbon Trust, an agency set up with government support to promote a low carbon UK future, has estimated that overall energy conservation measures could perhaps achieve up to half the target of a 60% reduction in carbon emissions by 2050 proposed by the Royal Commission on Environmental Pollution.

Certainly, the enthusiasts for energy efficiency believe that spectacular savings can be achieved. For example, it has been claimed that a mixture of efficiency measures and demand management measures could possibly offer overall 'factor 4' improvements in energy use in most sectors, and possibly more.<sup>(14)</sup> However, while this may be possible in theory, in practice there may be problems. Once the cheap and quick energy saving options have been exploited, the opportunity for further energy savings may begin to reduce, while the costs could increase. Moreover, while there will hopefully be many technical and operational innovations that can improve efficiency, it is hard to see how efficiency improvements can be replicated continually, so as to keep pace with the projected 2% pa increase in basic global energy demand into the future.

To take a large scale example from the transport sector, although the world aircraft fleet has doubled its fuel efficiency over the past 30 years, global air traffic has quadrupled since 1970, from 350 billion passenger miles to 1,500 billion passenger miles a year, and is forecast to more than double or even triple by 2050. To put the issue starkly, while typically fuel efficiency has risen by around 3% pa, in the year 2000 the use of aviation fuel in the UK rose by 10%. Aviation is currently responsible for around 3% of global carbon emissions (and around 10% of total greenhouse gas emissions) and as a result of increased demand, according to the IPCC, carbon emissions from this sector could increase by 478% between 1992 and 2050. Unless demand is somehow curbed, it would require major technical fixes and efficiency improvements to reduce this.

Similar challenges exist for most other types of consumer demand. Indeed, in some cases the situation can be worse, due to the so called 'rebound effect', which can undermine attempts to reduce emissions by improving energy efficiency.<sup>(15)</sup> To put it simply, the money that domestic consumers save by adopting energy conservation measures may be spent firstly on maintaining higher temperature levels, and then on other energy intensive goods and services, like foreign holidays by plane. The result can be that at least some of the initial energy and emissions savings may be cancelled out. The exact scale of this rebound effect is debated, with optimists suggesting that, since most products and services are less energy intensive than direct energy use, the rebound effect associated with extra spending on goods and services might only account for a 10% reduction in emission savings that would otherwise have been achieved.

However, overall, it does seem likely that, all other things being equal, if any commodity becomes cheaper then more of it used. The optimists sometimes argue that there may be saturation levels for demand in the affluent industrial countries, so that any new wealth will be spent on increasing efficiency of energy use rather than on energy use. However, so far, at the macro economic level, energy use shows no sign of decreasing, despite dramatic increases in energy efficiency. Moreover, as more people around the world join in the race to material affluence, demand seems certain to continue to increase.

This is not to suggest that energy conservation is not vital, since it is foolish to waste energy that has been produced at such a large potential environmental cost and, in general, increased efficiency should make for economic competitiveness. However, as pressure for an improved quality of life from an expanding world population grows, the increased energy demand could outpace the increase in savings that can be made, even given major commitments to improved energy efficiency. It may be that, at best, energy conservation via the adoption of energy efficiency measures and demand management, will only be able to slow down the rate of increase in global carbon emissions. To actually reduce it requires a switch to non-fossil fuels. The options are nuclear power and renewable energy.

## **6. Nuclear Power**

At present the world obtains around 6% of its primary energy from nuclear power plants, but it has been suggested that this could be expanded as a response to climate change,

since nuclear plants do not generate carbon dioxide, at least not directly. There is believed to be sufficient uranium for several hundred years at current use rates, although, if the nuclear programme is expanded dramatically, to try to respond to climate change, then reserves would diminish rapidly, leading to the use of more expensive lower grade ore or possibly, at even higher costs, uranium extracted from sea water. Alternatively, recourse could be made to fast breeder reactors, which in effect stretch the uranium resource, so that nuclear could conceivably play a role for some while.

For nuclear power to be able to play an expanded role, it would have to overcome the problems that have seen it fall from favour in the last few decades. This is not the place for an exhaustive review of the complex and often contentious issues surrounding the use of nuclear energy, which have been the subject of several recent publications from varying perspectives, but in summary the key issues seem to be cost, safety and security. (16, 17, 18)

The cost issue was brought into sharp focus when an attempt was made to privatize the UK's nuclear plants in 1990. With nuclear generation costs, in the private sector context, of up to 6p/kWh it was clearly unviable compared with gas/CCGT, at less than half of that figure. A non fossil fuel levy was imposed to meet the extra costs, over fossil fuel generation, of the 20% or so of the UK's electricity that was then coming from nuclear plants. This levy put around 10% on consumers fuel bills, although a small part of the levy, initially 2%, did go to support some renewable projects. The levy initially raised around £1.2 billion pa for nuclear, before being phased out in 1998, by which time all but the old MAGNOX plants had passed into private ownership. The industry claims that new technology will soon be available (notably the Westinghouse AP 1000 redesign of the Pressurised Water Reactor) which will be able to generate at competitive prices, possible 3p/kWh, but so far this claim has yet to be tested. Similarly, the claim that the new so-called 'Advanced Passive' designs will be safer has yet to be confirmed.<sup>(19)</sup>

Clearly safety is a major issue, not least since it is one reason for the relatively high costs of nuclear plants, which can cost up to three times as much to build as conventional plants, with the safety and control systems accounting for up to half the nuclear generation costs. One of the attractions of adopting passive fail-safe features like convection cooling is that there would be less need for expensive, complex, and potentially unreliable emergency control systems.

However, it is unclear whether, even if the nuclear industry can develop cheaper, safer reactors, that this will necessarily reduce the level of public opposition to nuclear power. Overall, typically around 70% of the public in most countries is against nuclear power, with opposition mounting after each major nuclear accident. A recent UK opinion poll found that 68% of those asked felt that the UK should not build more nuclear plants in the next ten years.<sup>(20)</sup>

Public opposition, coupled with poor relative economics, meant that, following the Three Mile Island accident in the USA in 1979, no new nuclear plants were ordered in the US and, following the Chernobyl disaster in the Ukraine in 1986, most of W. Europe has

backed away from nuclear, with Germany being the most recent country to opt for a nuclear phase out. Even France, the one-time mainstay of the European nuclear industry, imposed a moratorium on new projects, following the election of its red-green government in 1997. The UK has a policy of 'diminishing reliance' on nuclear. Given that currently no new plants are planned, that amounts to a phase-out.

Nevertheless, the nuclear industry still has ambitions for expansion. Some countries in Asia are considering expanded nuclear programmes, notably Japan and China, and Russia still has a nuclear programme. Moreover, the USA is trying to relaunch its nuclear programme and the nuclear industry is keen to see the UK follow suit, on the basis of avoiding carbon emissions.

Assuming the cost and power plant safety issues can be dealt with, for these ambitions to be realized, there still remains the unresolved problem of dealing with long-lived nuclear waste, which has to be kept isolated from the biosphere for millennia. Whatever happens to the UK nuclear programme, around 500,000 tons of nuclear waste of various types will be produced in the UK over the next century, including the wastes arising from the process of plant decommissioning. Similar problems exist around the world. However, at present, although some countries are exploring possible sites, no repositories exist for the indefinite storage of long-lived high level nuclear waste. Moreover, perhaps inevitably, there is usually strong local opposition to any proposed site. In this situation many feel that it would be irresponsible to expand nuclear power. The environmentalists argue, why try to solve one global environmental problem- climate change- by creating another- yet more radioactive pollution? <sup>(21)</sup>

The final issue is the increasingly worrying and topical problem of nuclear weapons proliferation and diversion of weapons-making material from the plutonium extracted from spent fuel. The UK has around 70 tonnes in store, some of it of high grade. Given nuclear expertise, a few kilos of weapons-grade plutonium can be used make a crude bomb. Equally worrying, following the events of September 11<sup>th</sup> 2001, is the possibility of terrorist attacks on nuclear plants or interim waste stores, potentially releasing wastes over a wide area should the containment be breached. <sup>(22)</sup>

It may be that new technology and new operating procedures could reduce the amount of waste produced. Certainly the abandonment of plutonium extraction by reprocessing spent fuel could reduce the amount of medium and low level wastes produced, and keep the plutonium in a form that would make it difficult for terrorists to use. At present only the UK and France are continuing with reprocessing on a significant scale. Given that the UK and France, along with the USA, have closed their breeder programmes, the only use for the plutonium, other than in weapons, is for a new 'Mixed Oxide' fuel, with Japan currently being the main customer. However, given that there are ample and much cheaper supplies of uranium, the market for this new fuel is likely to be limited, and trading with it around the world presents potential risks of terrorists attacks. <sup>(23)</sup>

While the nuclear industry still seems keen to promote nuclear fission as part of the solution to climate change, there is also the longer term option of nuclear fusion. This is

still at the R&D stage and, despite around £20 billion having been spent on fusion research world-wide so far, at best a commercial reactor is still many decades away. Fusion is sometimes portrayed as being a cleaner and safer option than fission. However, most of the likely approaches to fusion would involve a plasma of radioactive tritium running at 200 million degrees Kelvin, and the risk and impacts of accidental release could be significant. In addition, the neutron radiation in the fusion reactor core would produce radioactive materials which would have to be stored. Although they would have shorter half-lives than the products from fission, there would still thus be a waste problem to deal with. The science is certainly exciting but, in terms of energy supply, fusion is a long shot, with unknown costs and some safety problems and, perhaps more importantly, it is unlikely to be available in time to help deal with the urgent problem of climate change.<sup>(24)</sup>

## **7. Renewables**

Fortunately, we may not need to, in effect, create little suns on earth with fusion reactors. The sun is a working fusion reactor that already supplies more energy than human beings could use, if technologies can be developed to tap it efficiently. The incoming solar energy drives the climate system, creates winds, waves and rain for river flows and sustains biomass growth. The use of these climate and weather-driven energy flows and sources would represent a rather elegant closing of a circle, since we are talking about using the climate and weather system to help us avoid climate change by substituting for the use of fossil fuels.

Not all the natural energy flows available are climate driven. In addition to the continually renewed solar sources, the gravitational pull of the moon on the sea results in tides - lunar power. Although not strictly a fully renewable resource, there also the heat deep underground created by radioactive decay, a source of geothermal energy.

The total energy available from the various renewable energy sources is very large. At present the total energy generating capacity of the various energy conversion systems built by mankind amounts to around 14TW. The continuous solar input is equivalent to 90,000TW, of which about 1000TW could, in principle, be captured for energy conversion to forms we can use.<sup>(25)</sup> Of course there are also efficiency losses and land-use constraints to take into account, but even so, there should be sufficient energy from these sources to meet our needs many times over.

Estimates of the practical contribution that might be made by the renewable sources in the years ahead inevitably depend on the assumption made about the level of financial support, and the scale of constraints on the conventional and nuclear options. The renewables energy systems involve new technologies seeking to win a place in a market dominated by the existing energy technologies, with oil and increasingly gas dominating the energy market. Energy scenarios are widely used to describe possible paths ahead and the sustainable growth scenario produced by Shell International in 1995 has been very influential. It suggested that by around 2060, renewables sources could be meeting about half the world's total energy needs.<sup>(26)</sup> Subsequent studies have suggested that, in principle, by 2100, renewables could perhaps be meeting over 80% of global energy

needs, assuming that they were seen as a priority for environmental reasons.<sup>(27)</sup>

Inevitably long term projections like this are very speculative. What matters in reality is practical progress towards technologically and economically viable energy systems. The renewable contribution started out from a relatively low level, basically traditional hydro and traditional biomass. Even so it is worth noting that around 17% of the world's energy comes from these two sources. Although funding levels have been relatively low compared with nuclear technology, progress on the so-called new renewables has been quite rapid since the 1970s, when interest in these sources first emerged as a consequence of the oil price crises. By 2000, the new renewables were supplying around 2% of world energy, or about 3% of its electricity. The contribution is expanding rapidly, stimulated by some quite demanding targets. For example, the European Union is aiming to have 12.5% of its electricity produced from renewable sources by 2010, with some member countries aiming for much higher targets. Denmark is aiming at 29%, Finland 21.7%, Portugal 21.5% and Austria 21.1%, these figures excluding the contribution from large hydro.<sup>(28)</sup>

## 8. Progress with Renewables

Some comprehensive and up to date reviews of technological progress have been published recently.<sup>(29,30)</sup> Consequently, what follows is an overview of key developments in the main fields.

**Wind power** has been one of the leaders, with an initial market growth rate of over 20% pa, accelerating up to 30% pa after 1997. By mid 2002 there was around 23,000 MW of wind-turbine capacity in operation, with Denmark, one of the pioneers, obtaining around 18% of its electricity from wind projects. In Germany the rate of installation has risen to around 1.5 GW pa, with nearly 9000 MW in place by 2002. The technology has developed rapidly, from small fixed speed 100-200 kW machines to variable speed machines rated at 2 MW and more. Similarly, generation costs have fallen dramatically. For example, whereas in the UK in the early 1990's wind projects were receiving 11 p/kWh under the Non Fossil Fuel levy, by 2000 wind projects were going ahead in some locations at around 2 p/kWh, without the need for subsidy.

The next stage is to go offshore, where environmental constraints are lower and wind speeds generally higher and more consistent. That can partially compensate for the increased cost of offshore location and of delivering power back to land. By 2002 there was nearly 100 MW of offshore capacity in place in the EU. The Netherlands, Denmark and Sweden have been pioneers, and they are now being followed by Germany, the UK, Ireland, Belgium and France. For example, Germany has a very ambitious programme, with a target offshore wind capacity of 10 GW by 2030, supplying around 25% of the country's electricity. Overall the EU's total ultimate offshore wind resource has been put at around 900 TWhpa. Currently offshore wind projects generate power at around 4 –6 p/kWh, but prices are falling as experience is gained and new technology emerges, with capital cost/kW installed falling by around 30% over the past decade. Evidently then, the wind power success story is likely to continue.<sup>(31,32)</sup>

While windpower has attracted most media attention, the use of **biogas** from biomass wastes has actually proved to be the most immediately economic option, with sewage gas and gas from landfill sites being amongst the cheapest renewable energy sources. Although also economically attractive, energy recovery via the combustion of municipal and domestic solid wastes has been less successful, mainly due to opposition by local residents concerned about the potential for emissions of dioxin from the combustion of plastics. In addition, most environmentalists do not see these waste as genuinely renewable sources since they rely on the production of materials which ought, they feel, to be avoided where possible, and recycled where not.

Specially grown **energy crops** are, by contrast, usually seen as attractive options by most environmentalists as long as the rate of use is matched by the rate of replanting to maintain rough overall carbon neutrality. Liquid fuels, derived from rape seeds or sunflowers, have niche markets for transport use in the form of biodiesel in some parts of continental Europe. The UK is pressing ahead with an energy crop programme based on the use of wood chips from short rotation coppices as a fuel for advanced gas turbines plants. Costs are still relatively high, with the 10 MW ARBRE scheme in Yorkshire expected to generate at 8 p/kWh.

**Photovoltaic solar (PV)** is even further away from commercial competitiveness, with commercial cells generating power at around 5-10 times the cost of conventional power. However, there are major efforts underway to reduce costs and, since solar PV is widely seen as having a very significant future, major programmes of PV installation have been supported around the world, particularly in the USA, Germany and Japan. For example, Germany has a 100,000 PV roof programme. The main improvements are expected to be in relation to the use of new materials with higher efficiencies and lower costs. Current commercial devices have energy conversion efficiencies up to 12-15%, but lab devices have been developed with efficiency up to 25%, and some multi-junction devices have even higher efficiencies. In terms of costs, ease of manufacture is an obvious issue and thin film amorphous silicon technology has proven to be attractive, despite its lower efficiency. There are also exciting prospects for some of the newer polymer cells.<sup>(33)</sup>

However, the economics is not just a matter of the device. Equally, new applications and new patterns of energy generation and use are opening up new markets for PV. PV is rarely seen as a way to compete directly with conventional grid-linked power plants, but rather as providing a way to generate energy directly at the point of use, thereby avoiding transmission losses over long distance. In many developing countries off-grid PV can be the only option, apart from imported diesel or petrol, for power generation at the village level. There are around 2 billion people in the world who are without access to electricity and who are never likely to get access to it via grid links. Even in the industrialized countries, it may be that houses and offices will increasingly be equipped with PV cells on the roof, meeting most of their light electrical load, with any excess power being exported to the grid, and any shortfall being made up by power imported from the grid. Several examples already exist in the UK with 'net metered' power actually making a profit for the home owner. Clearly for the moment, installing a PV roof still involves a

significant capital investment, with payback times put in the decades. However, having a building -integrated PV roof made up of the new generation of PV tiles avoids the cost of a conventional roof, which can reduce overall costs, and it is certainly interesting to have a roof that earns its keep . Moreover, as take-up in niche markets expands and volume production grows, so prices should drop, so that the use of PV could become widespread within a decade or so. <sup>(34)</sup>

The newer renewables include offshore **wave** and **tidal current** power. The UK's wave energy resource is quite significant; possibly 50% of UK electricity could be generated from this source and maybe more if generators can be located further out to sea where the largest resource is to be found. Research into wave energy started in the UK in the 1970s. However, after some initial trials , it was claimed that the cost of generation would be high and the government-funded programme was wound down. Some work nevertheless continued, both in the UK and elsewhere, and recently there has been something of a renaissance for wave development. In the UK, Wavegen were the pioneers, with a 500 kilowatt LIMPET shoreline device on Islay commissioned in 2000. They are currently going offshore with a new floating device, backed by a £1.67 M DTI grant. Ocean Power Delivery are testing their Pelamis wave snake device in Scottish waters. Elsewhere there is a wide range of device types under test, including the Dutch Archimedes Wave Swing and the Danish Waveplane. Japan has the floating 'Mighty Whale' test platform and a novel wave focussing device is being developed in Australia. <sup>(35)</sup>

Tidal current technology is a more recent development. At one stage there was interest in the idea of building large tidal barrages across suitable estuaries to create a head of water by trapping tidal flows . The Severn estuary was one of the most promising sites, capable of housing a barrage with 8 GW of generating power. France built a small barrage on the Rance estuary in the 1970's. However, the capital costs of barrages is very high and such projects, with their long leads times, are unattractive in the contemporary private sector investment context. By contrast, the use of small free-standing turbines mounted on the sea bed in the tidal flows is seen as a better option. They would be modular and much less environmentally invasive than large expensive barrages. The total resource for barrages and tidal currents is about the same in the UK. If fully developed, both could generate around 20% of UK electricity. <sup>(36)</sup>

There are still some novel ideas for building circular tidal basins offshore to capture high tides for barrage-type operation, but in the main the future for tidal power in the UK looks like being linked to the use of tidal flows. Prototypes are currently under test. For example, Marine Current Turbines are testing a submerged 300 kW tidal turbine off the coast of Devon, with an EU grant of 1M euros matched by £1M from the DTI, and a novel sea-bed-mounted hydroplane system, the Stingray, is being tested off the Shetlands, with a £1.1M DTI grant. <sup>(37)</sup>

Marine energy sources like wave and tidal are more predictable and less variable than wind power. Waves are in effect stored wind energy, and the tides are driven by the regular lunar cycle. Practically, they could fit in well with the other major offshore

energy option, wind power. For example, there have been plans for combining offshore wave or tidal devices with wind turbines, although there are some trade-off issues, since the best tidal and wave sites are not always the best offshore wind sites. But they all share the same major advantage, they are offshore, so there is far less visual intrusion and the environmental impacts on marine life and marine ecosystems seems likely to be minimal. Indeed some might be positive, in terms of providing a habitat for some sea creatures.<sup>(38)</sup>

While there are plenty of sites around the UK coast for tidal current devices, wave energy is more concentrated, most of it being off the North Atlantic coast. That implies that it would have to be landed mostly in Scotland. However, the main power demand is in S.E.England. Given there are constraints on building large new grid links across the north of the country, there is interest in the idea of an undersea High Voltage DC power cable from Scotland to England and Wales, which might add 0.5 p/kWh to the price of the power.<sup>(39)</sup>

So far most of the wave and tidal device teams are expecting their first prototypes to deliver power at around 7 p/kWh, which is far better than on-land wind achieved at an equivalent stage in its development. Most of the wave and tidal teams hope that commercial scale devices will deliver at around 4 p/kWh, making them viable for take up under the Renewables Obligation (three of the wave projects already have contracts under the Non Fossil Fuel Obligation).

Although much of the initial work has been done in Europe, the marine renewables are being deployed around the world. There are wave energy projects in India and the Azores and the Canadian company Blue Energy has an ambitious tidal fence planned for installation in a causeway between islands in the Philippines, which could ultimately be expanded to deliver 2,200 MW. There have also been even more ambitious proposals, including the idea of using arrays of submerged turbines to tap the very large energy flows in the Gulf stream.<sup>(40)</sup>

There are many other renewable energy options on the large and small scale. While concerns have begun to be raised about the environmental impact of large scale **hydro** projects, small scale hydro is widely seen as a useful option. Although it is not strictly renewable, since the local heat flux can be exhausted at least for some while, there is around 7 GW of **geothermal** electricity generating plant installed around the world. In addition geothermal sources are widely used for heating, as of course is direct **solar energy**.

Roof-top solar collectors for water heating are ubiquitous in many of the sunnier parts of the world, but can also play a role for space or water heating in other climates. Passive solar design has an even larger role to play. Solar heat can also be concentrated to power so called 'solar thermal' electricity generation plant, several of which have been constructed. There is also the more novel idea of building solar chimneys, with the updraft created by a large ground level conservatory driving an air turbine mounted in the chimney stack. In addition there are a variety of biogas and biofuel options, for example

anaerobic digestion of biological materials and pyrolytic conversion to liquid fuels, which can provide fuel both for heating and for power production and, in some cases, for use in vehicles. For example, it may be possible to generate hydrogen gas from biomass and wastes. While electricity production has tended to dominate the commercial development of renewables in recent years, there are clearly just as many options for production of heat and also of fuels for transport use.<sup>(41)</sup>

## 9. Assessing the Costs of Sustainable Energy

The forgoing review of technological options should have highlighted the large range of energy options that exists and, to the extent that they compete for funding, the need for some way to make choices between them. This is particularly difficult since they are all at different stages of development. As we have seen, most of the new renewables are still at a relatively early stage, and yet some at least are likely to have to play a major role in the future.

Economic assessment, in terms of the cost of energy produced, is the most obvious way to try to compare the viability of energy systems. However, making judgements as to which options to emphasise based on prototypes at the early stages of development costs clearly has its limitations, as was demonstrated in the case of wave power in the UK. Early cost estimates of 20 p/kWh or even 50 p/kWh, at a time when only small models had been tested, led to the withdraw of funding, first in 1982 for deep-sea wave and then in 1994 for the remainder of the programme. It was almost 20 years before a re-assessment suggested that much lower prices might be attained, with, in March 2001, the DTI commenting “*The decision was taken in the light of the best independent advice available. With the benefit of hindsight, that decision to end the programme was clearly a mistake.*”<sup>(42)</sup>

Of course, the validity of that reassessment still to be demonstrated. But in general, rather than trying to ‘pick winners’ at an early stage, it seems wiser to allow a range of developments to proceed, especially since the level of expenditure at the R&D stage is relatively small. Selection becomes more important at the next, more expensive stage in the innovation process, when moving on the full-scale development and commercial deployment. Some renewables have reached that point, and market assessments are therefore beginning to be made, but most are further back in the process.

Although current prices are sometimes a poor guide to what prices might be in the future, it is still possible to identify trends. The Energy Review carried out by the Cabinet Office’s Performance and Innovation Unit made use of learning curve analysis to try to identify trends in price reductions. If prices at successive stages in the innovation process are plotted against cumulative production volume on a log-log scale, then in many cases a straight line results. The slope varies with the technology, but the range is not great - gradients of between 10 and 20% are typical. Not all the energy options reviewed could be assessed in this way, and in some cases parametric engineering assessments and proxy assessments had to be used.<sup>(13)</sup>

The results for some of the key new renewables, compared with conventional sources, are shown in Table 1 . Clearly these long term estimates are speculative and rely on a range of assumptions about policy developments. For example, if funding is not provided for new renewables or new nuclear technologies, then the picture could look very different.

[Table 1 here]

One of the main uncertainties is over how the relative environmental costs of the various options will be assessed in future. If, for example, the full social and environmental cost of carbon dioxide and acid emissions from coal combustion is added to the cost of generation, then the comparisons would alter dramatically. As we have seen, although nuclear plants do not generate carbon dioxide there are other impacts and risks with the nuclear option. Moreover, even the most benign renewable sources will have local impacts.

To help make comparisons, the EU EXTERNE study has tried to put a price on the environmental and social impacts of energy use, focussing on electricity production in the EU. The results suggests that the cost of producing electricity from coal would double and the cost of electricity production from gas would increase by 30% if external costs such as damage to the environment and to health were taken into account. It is estimated that these costs amount to around 1-2 % of the EU's Gross Domestic Product (GDP), not including the cost of damage caused by global warming.<sup>(43)</sup>

The methodology used to calculate the external cost is called impact pathway methodology. This methodology sets out by measuring emissions (including applying uniform measuring methods to allow comparison), then the dispersion of pollutants in the environment and the subsequent increase in ambient concentrations is monitored. After that, impact on issues such as crop yield or health is evaluated. The methodology finishes with an assessment of the resulting cost.

The EXTERNE methodology could be applied to other energy-related sectors like transport. In fact, preliminary work has shown that aggregated costs of road transport, the dominant source of damage, add another 1-2% of GDP to the bill.

The results for electricity as shown in Table 2:

[Table 2 here]

As can be seen, on the basis of this analysis, fossil fuels have much larger environmental impacts than any of the other options, with coal clearly being the worst. By contrast, wind is relatively benign, having four times lower environmental costs than nuclear. .

Assessments like this are fraught with methodological problems, for example concerning how to calculate the cost of specific types of damage. Simple economic assessment, based on insurance replacement costs, may not provide a realistic measure of , or proxies

for, the human value of amenity loss or health damage, much less the ecological value of any disruption. Even more contentious is the value put on human life, which, inequitably but seemingly inexorably, differs around the world.

Clearly then, some of these valuations are subjective and this is a problem which has perhaps even more influence on popular assessments of the impacts of renewable energy technologies. For example, although the scale of the local impacts from most renewables is small compared to the massive global impacts of burning fossil fuels, they can nevertheless lead to public concerns, as has happened in the case of local negative reactions to visual intrusion by some wind power projects in the UK.<sup>(44)</sup>

## 10. Risks

The problem of making impartial judgements of impacts and costs can be even more complex in relation to assessing the impact of accidents and health effects and their costs, one of the subset of assessments made within the EXTERNE analysis. The impacts are clear enough in general terms. Nuclear power introduces novel health risks related to the generation of long-lived radioactive materials, while there are large public health implications from the emission of acid gases from fossil fuel combustion. In addition there are safety risks with some renewables, such as large hydro.

Unfortunately, however, the scale of the health impacts and the degree of risk are often contentious, with disagreements on the data and its analysis being common, as witness the long debate over the results of early attempts to assess the risk of nuclear plants<sup>(45)</sup> and energy sources generally.<sup>(46,47)</sup>

Prof. William Nordhaus, a US based economist, and a proponent of nuclear power, has produced the following analysis of the death and disease rates associated with the use of fossil and nuclear fuels.<sup>(48)</sup>

[Table 3 here]

The most striking thing is the very large number of off-site public injuries and deaths/GWyr associated with coal and oil, compared with nuclear. Gas also comes out quite well on these comparisons. These figures reflect the significant impacts on public health (for example in terms of respiratory diseases) of the acid and other emissions from coal and oil burning, and the lower impacts of gas. In terms of occupational hazards, it is worth remembering that some of the nuclear occupational deaths and illnesses covered by Nordhaus will be associated with uranium mining, which have to be set alongside the deaths and injuries from coal, gas and oil extraction activities.

However, the Nordhaus analysis excludes 'severe accidents', which, given Chernobyl, might be thought to undermine its credibility. Unfortunately, there is some debate over the ultimate death toll from that accident. 31 people died immediately, or shortly after the accident, but initial estimates suggested that there could be up to 40 000 early (i.e. premature) deaths in the years ahead.<sup>(49)</sup> Certainly, subsequently, there have been reports of serious health impacts and continuing deaths attributed to the accident, for example amongst the workforce of approximately 200 000 'liquidators' who were hired

or ordered to gather and bury radioactive material released by the blast. A study by the International Atomic Energy Agency, the World Health Organization and the European Commission, produced on the tenth anniversary of the accident, projected that this population of workers would suffer an excess burden of 2500 cancers as a result of their clean-up work. Moreover, it suggested that the residents of communities off-site might also be expected to suffer an excess burden of 2500 cancers as a result of exposure to fallout from the accident.<sup>(50)</sup>

However, some more recent reviews have produced much lower estimates. For example, a study by the UN Scientific Committee on the Effects of Atomic Radiation published in 2000 concluded that, apart from the initial deaths and 1800 cases of thyroid cancer in children, most of which were seen as potentially treatable, there was *'no evidence of a major public health impact.'*<sup>(51)</sup> It was suggested in a subsequent UN report that some of the illnesses emerged as the result of the stress of over-zealous evacuation and forced relocation, and that some could even be put down to psychosomatic effects.<sup>(52)</sup> Clearly there is room for disagreement about these assessments. What about renewable sources of energy? Surely there is less room for debate there. One estimate of fatalities associated with energy production, reported by the Uranium Information Centre, puts the figure for accidents (such as dam failures) associated with large hydro plants at 4000 immediate deaths amongst the public world-wide during 1970-92.<sup>(53)</sup>

Given that the total amount of electricity supplied by hydro and nuclear plants world-wide is roughly the same, it is perhaps reasonable to compare the hydro accident figure with the deaths associated with the Chernobyl accident. However, in addition to these figures for major accidents for nuclear and hydro, it should be noted that the normal operation of the nuclear fuel cycle will lead to nuclear related deaths and injuries, as reflected in Nordhaus data above, which will not occur with hydro plant operations.

Comparisons are harder to make with windpower, since this is a relatively new technology. So far, with, in early 2002, around 23 GW installed (compared with around 350 GW of nuclear capacity), there have been around 21 operator deaths associated with wind turbines around the world, mostly due to falls and injury by blades, and no offsite injuries to the public.<sup>(54)</sup>

Clearly, in all but the most straightforward cases, making comparisons of risks is fraught with statistical and conceptual problems, and disagreements abound over the interpretation of data. What initially might seem like a simple, if grim, exercise in body counting, turns out to be a far more complex and conflict-laden activity. We are therefore still some way from having a reliable approach to making comparisons of impacts amongst the options.

## **11. Carbon Accounting and Energy Analysis**

Rather than trying assign costs to impacts or measure health risks, another increasingly popular approach to attempting to reflect the environmental significance of energy technology is to use the resultant carbon emissions. If nothing else, this might help reduce the level of subjectivity involved in making comparisons between the various energy options. In effect we are thus moving one step backwards in the EXTERNE analysis.

Certainly carbon emissions are a central factor in climate change, and it could be argued they can be used as a proxy for most other types of impact. One early estimate put the total fuel cycle emissions for coal fired plant at 1058 tons of carbon dioxide per gigawatt hour, and 824 tons for combined cycle gas fired plants, compared with nuclear at 8.6, wind at 7.4 tons and 6.6tons for hydro.<sup>(55)</sup> A more recent life cycle study by Hydro Quebec, published in 2000, covers all greenhouse gas emissions and translates them into equivalent carbon dioxide terms. It puts emissions at 974 tons/GWh for coal plants and 511 tons/GWh for combined cycle gas plants, compared with 15 tons/GWh for both nuclear plants and hydro dams and 9tons/GWh for wind plants.<sup>(56)</sup>

A study on greenhouse gas emissions by the International Atomic Energy Agency in 2000 summarizes the ranges as follows: gas plant 439-688 grams of carbon dioxide equivalent/kWh, coal plants 966-1306 g/kWh; nuclear plants 9-21 g/kWh and wind plants 10-49 g/kWh.<sup>(57)</sup>

To be comprehensive, carbon accounting must also include not just the emissions during operation, but also the emissions associated with the energy use in construction of the plant and the materials used in its construction, as well as the energy used in decommissioning and (where relevant) waste disposal. Full 'life cycle' energy analysis of this sort is becoming increasingly important for all products and systems as part of their environmental assessment. In the case of power plants, the results can be revealing. For example, the Hydro Quebec study mentioned earlier suggested that the overall energy output to input ratio for nuclear was only 16, compared to 39 for wind. The figure for coal plants was 11, gas/ CCGT 14, while that for hydro dams was put at 205, presumably because of the long lifetimes and large outputs of the plant. PV solar and biomass plantations had the worst ratios at 9 and 5, respectively, reflecting the large energy debt incurred in PV cell manufacture and the mechanical energy used with the harvesting and transportation of energy crops.<sup>(58)</sup>

Carbon accounting is becoming increasingly popular given the various proposals for carbon emission permits and carbon trading arrangements that emerged from the Kyoto Climate change accord.<sup>(59)</sup> However, while comparisons of the carbon and greenhouse gas emissions are useful, and central in terms of global climate change, there are also clearly other impacts to consider in order to give a complete picture, not least acid emissions and radioactive emissions. There is thus a danger that seeking to optimize for low carbon emissions may in fact be sub-optimal for the environment as a whole. Of course, it could reasonably be argued that climate change is so important that other issue must take second place. However, even so, in terms of assessing the various low carbon options, the other impacts become significant. This is clearly the case in terms of radioactive pollution from the nuclear fuel cycle, although unfortunately that takes us back to the health issues discussed in the previous section and to debates about the impact of low level radiation.

By contrast, there seems to be more opportunity for clear analysis in relation to renewables. Certainly, most renewables have low carbon emissions, so that local

ecosystem effects ( e.g. in relation to disruption of wildlife, biodiversity and, in the case of water flows, erosion) could be more important in choosing amongst them. A parametric approach to making comparisons of direct impacts has been developed in the case of renewables, based on the degree of local disruption of the natural energy flux that is involved.<sup>(60)</sup> On this measure, solar devices have very low impacts and at the other end of the scale hydro dams and tidal barrages have large impacts. In part this is because the latter two attempt to extract a large proportion of the very concentrated natural energy flows, whereas solar only intercepts a small proportion of a diffuse flow. Wave and wind devices fall in between these extremes, in terms both of energy extracted and the scale of the impacts. Wave devices attempt to abstract quite large amounts of the high flux incident energy and can have moderate impacts, but wind devices only extract a relatively small part of a low density energy flow and have low impacts. The key issue, on the basis of this analysis, is to look at what the energy flows normally do in the local ecosystem, and then assess how much of this energy can be extracted without unduly disturbing key natural processes.

Hydro has a special problem in that it seems that in some locations (for example in warm climates) the anaerobic digestion of biomass brought continually down stream and tapped by the dam, can create methane gas to such an extent that a coal fired plant of the same capacity would produce less net greenhouse gas impact.<sup>(61)</sup> What we are seeing here is the result of the disruption of a natural energy flow, which previously ensured the continual agitation of the water , so that anaerobic processes were minimized .

It is relatively easy to see how this energy flow functional analysis approach can be applied to ‘flow’- type renewables like wind, hydro and wave power, but it may also apply to those involving ‘stocks’ of renewable energy, such as biomass. The issue then becomes the ecological value of the material being used, rather than just its energy value. Although it can be carbon neutral if the rate of burning is balanced by the rate of planting, the use of biomass has potential impacts, both from emissions produced by its combustion and because combustion destroys valuable organic material. These problems are shared by combustion of solid domestic and municipal wastes. Indeed, given the presence of plastics in the waste, the toxic emission problem can be much worse. But on the basis on this functional analysis, the main problem could be the sterilization of valuable organic material.<sup>(62)</sup>

It could be that this functional analysis can also be applied to conventional fuels, albeit at a rather general level. For example, it could be argued that whereas when the energy in fossil and nuclear fuels was safely trapped underground it had no environmental impact, once released in the form of heat ,combustion products and/or radionucleides, its pathway through the ecosystem involves environmental risks.

## **12. Land use**

Another, perhaps more concrete, way to assess the merits of energy systems on a quantitative basis is to compare their land usage. Given that there are competing uses for land, including obviously food production, but also increasingly housing, industry and

leisure, this criterion could become more important. Since most renewable energy flows are diffuse the collection technologies are likely to take up more room than conventional energy technologies..

However, there is a wide range of land use implications.<sup>(63)</sup> Energy crops (e.g. Short Rotation Coppicing of willow) are the most land-using renewable source. Depending on location, coppices can take up to 20 times more land per kWh eventually generated than wind farms, and this may matter if land is scarce. Although it is currently still expensive, PV solar (on roof tops, so there is actually no real land-use implication) can also deliver more energy/ hectare than energy crops, which is not surprising when the energy conversion efficiency of PV (up to 15%) is compared with the efficiency of photosynthesis (less than 1%). Indeed, according to the Hydro Quebec review mentioned earlier, PV comes out even better than wind, by a factor of nearly 2 in terms of energy /hectare.<sup>(64)</sup> Although energy crops can be stored, which gives them an advantage over intermittent sources like wind and solar, they are a bulky fuel, which will usually have to be transported to combustion plants, which can have implications for local road infrastructures.

Hydro dams have obvious land-use implications (since areas are flooded to make reservoirs), a problem not shared by tidal barrages. However, the latter can have significant impacts on the local and even regional ecosystem, so some land-use changes might occur, although some impacts may actually be positive. Offshore wind, wave and tidal current devices have no land-use implications although, if they are near shore, there can be visual intrusion issues.<sup>(65)</sup>

While the visual impacts of the offshore options are likely to be very low, wind farms on land are seen by some as ugly and intrusive, and energy crop plantations may also prove to be unpopular if they cover large areas. However, these are human perceptual and aesthetic judgements, possibly also reflecting instrumental concerns (e.g. the belief that house prices will fall).

Here we are returning to subjective, perceptual concerns, and to debates over values and , in the end, personal and political priorities. It could be argued that if people want more energy they must be prepared to accept some form of intrusion and that, for example, wind farms are one of the most environmentally benign options (as well as being economically attractive). This argument may, however, not be accepted by those who see any disruption to treasured views as deplorable, and 'anywhere but here' as a viable policy for sustainable energy. Nevertheless, there is clearly a problem of aesthetics to address and a need for careful location and sensitive consultation.<sup>(66)</sup>

Opposition to wind projects has been particularly strong in some parts of the UK. However, the scale of this opposition has to be put in perspective. Regular opinion surveys have indicated overwhelming support for wind energy in principle, typically 70-80% being in favour . Indeed, the most recent survey, carried out in 2001 for the Royal Society for the Protection of Birds, found that only 3% of those asked were opposed to building wind farms on land.<sup>(20)</sup> However, campaigns by local opponents have been very

effective at slowing down the wind programme. Around 70% of projects proposals have been turned down in recent years. It is interesting, by comparison, that in Denmark, where around 80% of the wind projects are locally owned, some by local co-ops, the level of opposition has been much lower. Similarly in Germany, most projects are locally owned and, as noted earlier, Germany has installed nearly 9000 MW compared with just over 500 MW in the UK, where there is only so far one wind co-op.. Evidently, having an economic stake in the projects changes attitudes.<sup>(67)</sup>

To be fair, some opponents of wind projects are genuinely concerned about nature conservation and some believe that there are better options, including energy conservation or perhaps offshore wind. However, if the scale of the climate change problem is as large as some predict, and if we wish to avoid facing the risks of nuclear power, then there will be a need all the renewable energy sources as well as all the energy savings that can reasonably be mustered. It may be that, as already noted, carbon sequestration can also provide some help, by storing some of the emissions produced by the continued use of fossil fuels. However, in terms of new energy supply technologies for the longer term, renewable energy seems to be the most promising option. In which case we may have to get used to a landscapes in which windmills are, once again, common sights.

### **13. Choices for a sustainable energy future**

All technologies have impacts, and that implies that there is a need to make choices. In this review we have seen that energy technologies can be ranked on the basis of carbon dioxide emissions, which some see as not only the crucial environmental issue, but also as a useful proxy for other environmental impacts. Nuclear and renewables come out well in this comparison. However, this type of comparison leaves out the potential for major accidents and associated health risks. It is hard to see how many of the renewables, large hydro apart, could impose risks on the general public on the same scale as do nuclear power plants. Nevertheless, nuclear plants do not generate carbon dioxide, so there remains some interest in this option, although the issue of what to do with the radioactive wastes that are produced has yet to be resolved. Certainly most environmentalists argue that it would be foolish to try to deal with one problem (climate change) by creating another (radioactive pollution).

Carbon sequestration may offer a way to store emissions for a while, but underground storage may be not a reliable option for the long term. While much can be achieved by using energy more efficiently, we will still need to generate energy, and in terms of impacts, renewable energy seems like the best supply option for the future.

In the Energy Review carried out by the UK Government's Cabinet Office, the Performance and Innovation Unit concluded that the *'immediate priorities should be on energy efficiency and promoting renewables'*, although it added that the clean coal/carbon sequestration and nuclear options should be kept open in case renewables or energy efficiency did not deliver as much as was hoped.<sup>(13)</sup> A similar policy was also supported by the major 'World Energy Assessment' carried out by the UN Development

Programme, the UN Department of Economic and Social Affairs and the World Energy Council. It concluded that *'if the energy innovation effort in the near term emphasizes improved energy efficiency, renewables, and the decarbonized fossil energy strategies, the world community should know by 2020 or before much better than now if nuclear power will be needed on a large scale to meet sustainable energy goals'*.<sup>(7)</sup>

Assuming this approach is adopted, there then emerges a set of strategic issues concerning how best to develop renewables, which options to develop and on what scale. Most of the renewables are relatively small scale, compared with the technologies which have gone before, such as 1.2 GW nuclear and coal plants. However, as a result of the dash for gas, the trend has been to smaller multi-megawatt scaled plants, and some renewables are now operating at this level. For example, typically wind farms have around 10- 20 MW of generating capacity and the ARBRE biomass plant is rated at 10 MW. Some renewables are better exploited on a smaller scale, right down to the house or building level, notably roof-top PV solar and solar heat collectors.

It could be that we will see a shift to a more decentralized and dispersed energy system, using small scale local 'micropower' generators, both in the developing countries and in the developed countries. In the latter, some power will continue to be generated by medium to large scale power stations remote from consumers (including, increasingly, offshore wind, wave and tidal plants), but some power will be generated by users direct, possibly feeding any excess into local area grid networks. The national power grid could then become more of a two-way networking system, balancing out local power generation and local power demands around the country. With some generating capacity being embedded in local grids in this way, and with some local needs being met from local sources, transmission losses over long distances can be reduced. In addition, linking up local sources in this way can help deal with the problem of the intermittency of some renewable sources - the grid, in effect, balances out local variations.<sup>(68)</sup>

At the level of renewable energy contribution existing at present in the UK, intermittent inputs presents few problems for the national grid. The variations are hardly detectable by the grid operators, and are much smaller than the variations from the conventional inputs, and the variations in demand. However, as and when the renewable contribution grows beyond around 20-30% of total electricity demand, then intermittency becomes more of a problem. Energy can be stored in batteries, flywheels, as compressed air, or by pumped storage of water, as at Dinorwic, but energy storage is at present expensive. It may be that an interim option would be to use cheap small fast start-up gas turbines as back up, possibly fuelled by biomass or biogas. Another option is fast start up fuel cell devices, or the novel Regenesys energy storage device.

However, as and when we move over to using hydrogen as a new fuel, then this could provide a major storage medium for power from intermittent renewable sources, with hydrogen being generated by the electrolysis of water. As long as basic safety procedures are followed, hydrogen has many attraction as a new energy vector. In addition to being storable, it can be transmitted along gas grids, possibly mixed in with the remaining methane, at low cost and with low energy losses. It can be burnt directly as a heating or transport fuel, or to generate electricity in a power plant, or used to power a

fuel cell, for houses or for vehicles. Hydrogen could thus become the key to a sustainable energy future, linking up with a range of renewable energy technologies.

A major attraction of the renewable is that there are so many options on so many different scales. The risk of failure is thus spread across a range of differing areas. Most of the plants can be installed quickly on a flexible, modular basis, and most can be easily decommissioned or removed if necessary, with minimal environmental disruption and no wastes. These attributes were evidently seen as important by the PIU, who commented *'the desire for flexibility points to a preference for supporting a range of possibilities, rather than a large and relatively inflexible programme of investment such as is being proposed by the nuclear industry.'*<sup>(13)</sup>

Of course, there may be new developments which change this assessment at some point in the future. For example, there has been some interest in the development of smaller nuclear plants, like the 110 MW Pebble Bed Modular Reactor, being developed in South Africa with the support of BNFL and, until it recently withdrew from the project, the major US utility Exelon. It is claimed that the PMBR could be installed quickly and operate nearer to loads, thus making it suited to use in developing countries. However, it will be some years before this technology has been proven, and, to the extent that nuclear power is adopted, or in the case of the USA re-adopted, it seems more likely that upgraded versions of conventionally sized plants will be used, like the 1000 MW Westinghouse AP 1000.

Clearly the mix of energy options used will depend on the local context and local resources. For example, for the UK, in its Energy Review the Cabinet Office's Performance and Innovation Unit suggested a target of obtaining 20% of UK electricity from renewables by 2020, with on land wind and biomass being the main early entrants, possibly followed by PV solar and the marine renewables – offshore wind, wave and tidal current turbines. That would obviously make sense for a maritime nation with limited land area but excellent offshore energy resources and well developed offshore energy expertise.

By contrast, countries like China have very large land-based renewable resources, so a different pattern of development might be expected. Given its population size and rapidly growing economy, China is probably the pivotal country in terms of energy patterns in the industrialising world. China's on-land renewable energy resource, leaving aside large conventional hydro, is put at the equivalent of over 400 GW, which is more than the currently installed conventional generating capacity. The new renewable options include over 90 GW of small hydropower, about 250 GW of wind, approx 125 GW of biomass energy, about 6.7 GW of geothermal energy and an abundance of solar insolation. The current contribution from new renewables is around 19GW, with most of this from small hydro, accounting for around 5% of total electricity. Large hydro supplies around 18%. For the future, wind looks like being the biggest growth area for China. On current plans, wind is expected to expand from 500 MW as at present to 3 GW by 2005 and 5 GW by 2010. Small hydro is expected to rise to 22 GW by 2005 and 25 GW by 2010. By 2005, the total renewable capacity could be around 26 GW, rising to over 30 GW by 2010.<sup>(69)</sup>

Although China's economic modernization and rationalization programme has improved the efficiency of its energy and industrial systems, demand for energy is increasing rapidly. At present the bulk of China's energy is produced from coal and there are large reserves. However, the combustion of this coal is already creating major air quality and health problems, as well as contributing to carbon dioxide emissions. While, as noted above, there are very large renewable resources and a programme of expansion, China is also keen to expand its nuclear programme. Whether it can or should expand both remains unclear.

Whereas it seems that most of Europe has made its choice, and is pushing ahead with renewables rather than nuclear, China, like many other rapidly industrializing countries around the world, is, it seems, still at an energy cross-roads.

#### **14. Conclusions**

Although there are clearly many choices to be made, and many difficult technical and economic problems to overcome, there is nevertheless something of an emerging consensus that, as the UN/World Energy Council 'World Energy Assessment' report, published in 2000, put it: "*there are no fundamental technological, economic or resource limits constraining the world from enjoying the benefits of both high levels of energy services and a better environment,*" although, a little more cautiously, it added "*A prosperous, equitable and environmentally sustainable world is within our reach, but only if governments adopt new policies to encourage the delivery of energy services in cleaner and more efficient way*"<sup>(7)</sup>

The threat of Climate Change has evidently galvanized most of the world's leaders into making commitments to reduce emissions, with most industrialised countries, the US notably apart, supporting the Kyoto Protocol which calls for a reduction in greenhouse gas emission by around 5% compared with 1990 levels, to be achieved during the period 2008-2012. Within this framework, some countries are opting for larger reductions. The UK for example has volunteered to cut carbon dioxide emissions by 20% by 2010. What remains unclear is whether these targets can be reached, what further reductions will be seen as necessary and viable in the future, and what role will be played by the various energy options discussed in this article.

As we have seen, the UK government is considering a target of obtaining 20% of its electricity from renewables by 2020. Most of the rest of Europe could probably do even better than that. The EU Renewables Directive suggests that some should achieve 20% or more, leaving aside large hydro, by 2010. Interestingly, Scotland is already considering a 30% target for 2020 and it has been suggested that the UK as a whole could also achieve this target.<sup>(70)</sup>

Gas will, of course, remain the dominant fuel for some while, but nuclear seems likely to decline, at least in Europe. That may, of course, present interim problems in terms of carbon emissions, if renewables cannot be expanded fast enough to take over. However, there could be some interim solutions. For example, although, in the UK, around 9 GW of

old nuclear plant is set to be retired over the next two decades, as noted earlier, by 2010 the UK is planning to have 10 GW(e) of CHP capacity installed, with presumably more to follow. The widespread adoption of gas-fired CHP would provide heat (which would not otherwise not have been available for use), which would release gas currently used for heating ,for use in electricity generation. This could in effect replace the output of nuclear power plants as they retire, without leading to any increase in carbon emissions, leaving renewables to begin to replace coal burning and also to begin to provide electricity, hydrogen and biofuels for transport use. Carbon sequestration might be seen as performing a similar interim role, by allowing gas to replace nuclear without creating any extra emissions. In parallel, investment in energy efficiency and demand-side management should be able to hold down the rate of increase in demand, with, ideally, the cash savings from energy conservation being used to fund the expansion of renewables.

Clearly the rapid expansion of renewables will be a major technological challenge, but equally it could be seen as a major opportunity for economic and well as environmental benefits, given the prospect of a large international market for renewable energy technology. It may not be entirely rhetorical to talk, as have some government ministers, of the UK being on the threshold of a ‘green industrial revolution.’

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**Captions: for Tables 1-3**

**Table 1 Cost of Electricity in the UK in 2020**

**Table 2 Extra cost resulting from environmental damage**

**Table. 3 Comparative Risk of Electricity Production by Fuel Cycle**

**Table 1 Cost of Electricity in the UK in 2020**

	pence/kWh
On-land wind	1.5 - 2.5
Offshore wind	2 - 3

Energy crops	2.5- 4
Wave and tidal power	3 - 6
PV solar	10 - 16
Gas CCGT	2 - 2.3
Large CHP/cogeneration	under 2p
Micro CHP	2.3 - 3.5
Coal (IGCC)	3 - 3.5
Nuclear	3 - 4

Source: UK Government Cabinet Office, Performance and Innovation Unit, Energy Review, 2002 (Ref.16)

**Table 2 Extra cost resulting from environmental damage**

Cost to be added to conventional electricity cost - assumed as 0.04 euro/kWh average across the EU, in **Euros/kWh**

Coal	0.057
Gas	0.016
Biomass	0.016
PV solar	0.006
Hydro	0.004
Nuclear	0.004
Wind	0.001

Source: EU EXTERNE study (Ref 47)

**Table. 3 Comparative Risk of Electricity Production by Fuel Cycle**

Number of deaths and diseases per GWyr - including entire fuel cycle, *excluding severe accidents*

Occupational hazards

Public (Off-site) hazards

	Fatal	Non-fatal	Fatal	Non-fatal
Coal	0.2-4.3	63	2.1-7.0	2018
Oil	0.2-1.4	30	2.0-6.1	2000
Gas	0.1-1.0	15	0.2-0.4	15
Nuclear (LWR*)	0.1-0.9	15	.006-0.2	16

\*LWR= Light Water Reactor, the generic term for reactors using ordinary water for cooling, like PWRs.

Source: William Nordhaus, 'The Swedish Nuclear Dilemma: Energy and the Environment', Resources for the Future, 1997. ( Ref.52)