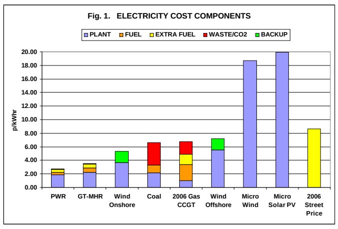
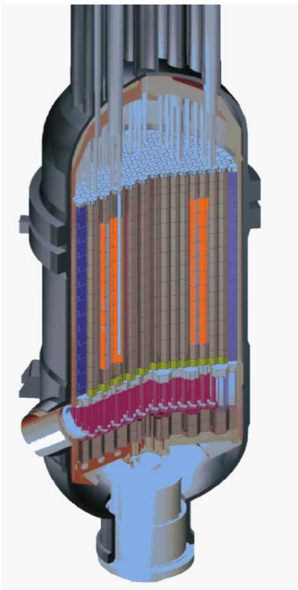
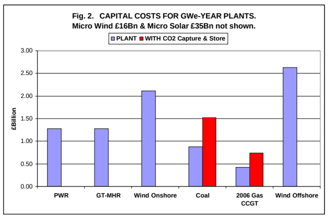
Leabrook Computing
Bournemouth, England

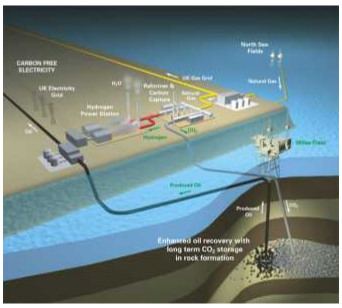




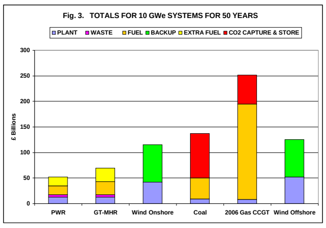
COSTING FUTURES FOR CLEAN ELECTRICITY



Brendan McNamara
November 2006



How Wind, Nuclear, & Coal Can Beat Global Warming



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Summary

The UK Departments of Trade & Industry and of Environment (DTI & DEFRA) have published the conclusions of their 2006 Energy Review, starting the process to issue a White Paper on replacements for our aging energy infrastructure. Unfortunately, they have not published any of the vast amount of written and oral evidence collected in the Public Consultation process. Fortunately, the UK House of Commons Environmental Audit Committee (EAC) published a report of their own review, called 'Keeping the Lights On: Nuclear, Renewables, and Climate Change' in April 2006. This is a collection of views quite representative of the spectrum of DTI-DEFRA evidence.

The 'Energy Challenge' report gives a more rational assessment of the situation but, as a political document, is unable to go further than public opinion, media analysis, or political authority permits. This work is not so constrained.

Here we focus on a single issue: In three charts, we give a comparison of the unit costs for each electrical energy system, the costs of delivering a Gigawatt-year of electrical energy (a million kilowatt hours, every hour, for a year is 1 GWe-yr) , and the lifetime cost of a complete 10 GWe-yr system over a 50 year timescale. The estimates on which these are based were found by backtracking all the references in the EAC evidence, by updating the 2003 numbers for fuel costs to those published in 2006, and by using recent reports like the new Intergovernmental Panel on Climate Change (IPCC) report, not then publicly available to EAC. That is to say, I have used the exact same data as that referred to frequently in the EAC review. All the results of this simple arithmetic can be readily checked.

1. **Rooftop Micro-power.** Current technologies for Solar PhotoVoltaics and Wind based micro-power in the UK will not recover their initial investments. Emerging thin film Solar PV could change this.
2. **Wind power** is the most competitive renewable energy source but new transmission lines, grid controls, and intermittent industries or new energy storage mechanisms are needed to take full advantage of it.
3. **Gas is the Most Expensive Long Term Option.** Electricity from gas will definitely be the most expensive option over a 50 year timescale. It will have to be abandoned as a principal (>25%) electricity source after 2030. It will be much more useful as a transport fuel stock.
4. **Carbon capture and storage**, (CCS) could make Coal power Carbon free. However, using the IPCC numbers, it seems too expensive for the UK. , though several energy companies are proposing pilot plants. As pulverised coal plants retire in the UK they should be replaced by nuclear power till CCS is commercially available. No new coal plants should be built anywhere without a full CCS system.
5. **CCS & Extended Oil Recovery**. This is a good way to fund the CCS infrastructure for the EU.
6. **Nuclear Power** is the cheapest carbon-free electricity source by p/kWh or by long term costs and offers the greatest security of supply. The UK already has a Uranium stockpile sufficient to supply ALL our energy needs for 600 years.
7. **Global CO_2 Emissions by 2010** will be over 30 Giga-tonnes a year, the maximum average for this century if global warming is to be controlled. With carbon free electricity generation by 2050, Transport can use most of the world's safe ration of CO_2 emissions.

The Energy reviews, and the work of the UK Committee on Radioactive Waste Management (CoRWM) have been conducted with a 'canyon horizon', walled in by available technologies and projecting forward by little more than a decade in the search for instant answers. Fossil fuels are responsible for the threat of huge climate change so cannot continue to be used as at present. The most important topics missed by the UK reviews are:

- Global warming is progressing faster than expected and must set the pace for Energy Research, Development, and Deployment.
- No consideration has been given to the imminent coming of the peak of cheap oil and gas production.
- No account was taken of the R&D achievements in nuclear power which will introduce new reactor types within 20 years and solve the nuclear waste problems.

The details of the calculations, the assumptions, and the open issues behind the comparisons, are given in the body of

this paper. Every effort has been made to make the numbers accurate, the extrapolations conservative, and the interpretations fair.

I. ENERGY POLICY ISSUES

An overriding consideration in predicting our energy future has become the modelling of the rapid impact of our greenhouse gas emissions, in particular CO_2 , on global warming and possibly irreversible climate change. This would be eventually catastrophic for human civilisation and so a political goal has been set to reduce our global emissions by 60% by 2050. Since every vehicle and every power station on the planet will be replaced in that period it is quite possible to make electricity generation carbon free, and to make all vehicles far more efficient or use alternative fuels.

It is apparent from every measure and observation that strong Global Warming is now happening (Houghton) and swift remediation is needed. All the climate modelling and studies of greenhouse gas production and re-absorption show that industrial activity is the direct cause. Studies of external influences from solar radiation and wobbles in the earth's orbit show that we are now in a long stable period and the next ice age is estimated to be 50,000 years away. We must therefore either reduce industrial activity drastically, the social solution, or switch rapidly to energy systems with low emissions, the technical solution.

The mass of CO_2 in the atmosphere is about 0.037%, or 2800 billion tonnes, adjusted to this tiny level by our biosphere, and so was steadily changed by industrial scale technologies. Emissions of CO_2 were 24 billion or Giga-tonnes (Gt) per year in 2002 and have to be kept below an average of 30Gt/year throughout this century to stabilise the concentration below 550 parts-per-million (ppm). We could overshoot badly, to 44Gt by 2030, and would need very steep reductions to 17 Gt/year by 2050 to meet the 100 year target.

However, three sets of big events have been omitted from the Energy Review processes. The first is that no energy or economic modellers have taken account of the fact that our oil and gas supplies will peak and decline within the next 30 years. Indeed, many oil analysts predict 2010-2015 for the peak of cheap oil (Campbell). This will have huge economic consequences less than halfway into the lifetime of the next tranche of gas fired power stations. The EAC evidence shows that the DTI modelling predictions for oil and gas markets between 2001 and 2005 have been completely wrong and prices are even out of the range of variations they considered.

The second set of big events which will influence the future are the substantial strides made in (i) The development of new coal technologies which are more expensive but safe. (ii) The success of Wind power. (ii) The research & design in new nuclear reactors, beyond the Generation III Westinghouse and EdF replacements for the old UK reactors. Imminent Generation III+ reactors can run solely on the high level, long lived waste from the 20^{th} century reactors, burning most of it by 2050. Reprocessing spent fuel for re-use will allow the world to run 10,000 Generation IV reactors for 1000 years. Nuclear power based on Thorium can extend this for another 1000 years or more.

Only a combination of these carbon free technologies can restrain global warming and allow for economic growth to include developing countries fully. Solar power is not yet able to contribute on the same scale.

Opponents of nuclear power are fighting old battles which have already been won in the nuclear laboratories of France, Japan, Russia, and the USA. Other energy sources will also benefit from accelerated R&D programmes proposed within the EU.

None of the nuclear developments were discussed in the EAC review by government, academia, or industry in a mistaken belief that more information would only confuse the public. Neither was the urgency in the deployment of new coal technologies recognised. The UK Wind programme is likely to miss its 2010 targets.

The third set of big events which will affect our energy future are all derived from our failure to respond adequately to global poverty or to acknowledge it as a driver of social unrest. This is part of a general failure of governments to deal equitably with global problems.

I reject predictions of doom except as warnings of avoidable futures. Let us see how some simple arithmetic, based on published data from the Royal Academy of Engineering (RAE), the Intergovernmental Panel on Climate Change (IPCC), and others will show ways to achieve a stable energy future.

II. PRICING A KILOWATT HOUR

Our electricity bills are priced in pence per kilowatt hours (p/kWh) consumed. A typical quarterly household bill would be about 3500 kWh/year at a current "street price" of 8.6 p/kWh, including all services, profits, and taxes. A typical, natural gas consumption for hot water and central heating in a well insulated home is 30,000 kWh at 2.4 p/kWh, a price which could well be 5p/kWh by 2010. The annual energy bill is therefore about £1021 and rising. The electricity will run a hundred different appliances and gadgets in a home while the gas runs one – the furnace – reflecting the huge importance electrical energy plays in our lives.

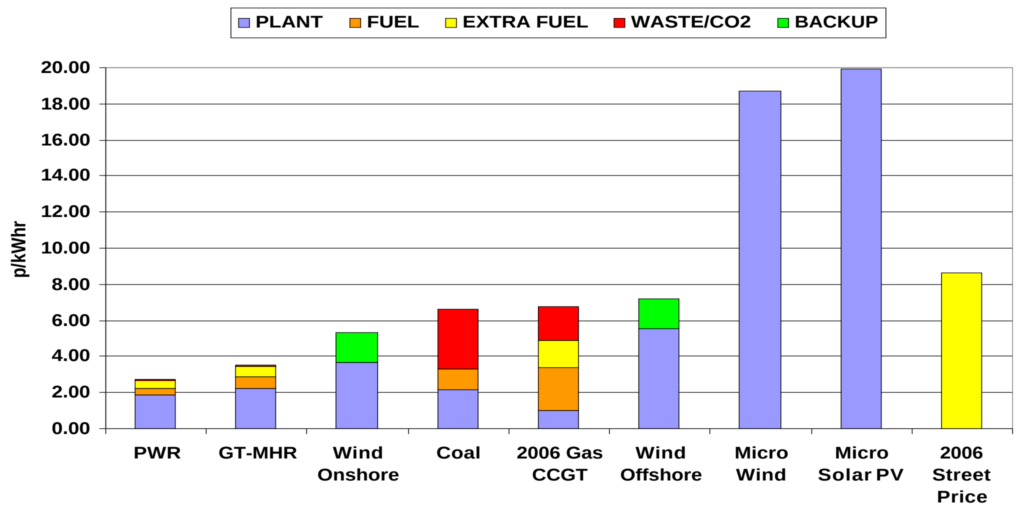
We note that projected savings by conservation could be large but a policy of 'encouragement' is dependent on overcoming the social problems of self indulgence and a very slow rate of adoption of new technologies. The idea that every little helps can only persuade the public that they are doing something. Turning off TVs on standby is extremely little help.

Conservation, carpooling, cold showers, and woollen sweaters are becoming important. In energy efficient homes, doing without is the final conservation option.

The charge rate of p/kWh conceals everything about the means of supplying this energy and the scale of national expense needed to secure it. At the very least we should understand how it is broken up into capital, fuel, waste disposal, and any other special costs for all the energy sources we are asked to use.

Here is a chart for the eight energy systems we will consider and the current street price consumers pay:

Fig. 1. ELECTRICITY COST COMPONENTS



Let us begin with the obvious highlights …

The base costs are for the capital cost of PLANT or equipment plus Operations and Maintenance and Management, and for the fuel, if any. The capital cost numbers used by RAE to compute the p/kWh also include interest at 7.5% over a 20 year period. The cost of anything is very sensitive to the interest rates on capital. The 2003 MIT Study on 'The Future of Nuclear Power' applied much higher rates to the reference case for Nuclear than for Coal or Gas to match US public opinion on relative risks. Here we will show that, for various reasons, the risks for all power sources are similar.

To compute the cost of electricity, the total cost is divided by the expected number of kWh generated in this period.

The FUEL cost for natural gas has been increased to reflect the price increase by 2006 over the price used in the 2003 RAE report. Electricity from gas is then more expensive than from coal, though the capital cost is still the lowest of all.

The Micro power sources for individual homes lose all large scale benefits and are far more expensive than electricity from any grid source. The savings on grid electricity are too small to recover their costs within their engineering lifetimes.

Waste disposal is seen as a major problem for nuclear power. However, the new reactors on which the above figures are based are designed to be easily serviced and dismantled. Disposal of the high level wastes in the fuel rods of a Pressurised Water Reactor (PWR) like the Westinghouse AP1000 or the larger European Pressurised water Reactor (EPR) is estimated at 0.1p/kWh over their 50+ year lifetime, and barely shows up on the chart.

The cost of capture and storage of from coal and gas stations is a different category and could make coal as expensive in the UK as Offshore Wind.

Let us now discuss the detail behind each source, starting with the most expensive. This is not an attempt to discredit or promote any particular technology, but merely a cold evaluation of the facts and numbers behind the EAC evidence. As a Fusion scientist I have always viewed Nuclear as the enemy, but Fusion has been denied funds for 25 years while nuclear has solved most of its problems and will have its place. (McNamara – The Coming Energy Winter ...)

II.1 Micro Solar Photovoltaics

Solar power is clean, green, and desirable but ludicrously expensive at present in the UK as a source of power. Few proponents of Solar PV ever give a cost in p/kWh for this reason. Even so, it is getting close to competitive in very sunny places. In England it does have many excellent niche applications.

An Oxford study (Jardine et al) of 11 sets of Solar Panels found that the top performers, like the Siemens ST-40 panel, using a copper-indium-diselenide as the most efficient collector for the UK, produced 1004 kWh/year per kW-peak rating in Oxford and 1590 kWh/year/kWp in Mallorca. There are 8760 hours in a year. Sometimes the panels output their rated power, but most of the time they output nothing. Despite this, Solar PV and other intermittent sources are always quoted by their rated or peak power output.

The Clean Skies website, run for the government's renewable energy programme, gives the installed price of a Solar PV rooftop system as £4000-6000/kWp, depending on the rooftop. Taking the low figure and dividing by the total lifetime output we get an average cost of 19.9p/kWh (blue), or 30p/kWh for a more expensive installation. At this price and an 8.6p/kWh rate for mains electricity, the system will never recoup its investment in its lifetime. There are no interest charges on your cash payment for the system, but you may expect to pay £25/year for maintenance. The DTI's Micropower Council carefully omitted any cost evaluation of Solar PV in its EAC submission.

There is some discussion of 'Smart Meters' which could feed these puny amounts of power back to the grid when they cannot be used immediately. This just glosses over the fact that there is a whole family of missing appliances, controls, and storage methods yet to be developed to get the best use out of Solar power anywhere.

At an industrial scale above 100kWp the cost of the PV panels is about half the domestic cost, putting UK Solar PV somewhere above Offshore Wind as an energy source. However, no power company is proposing to build any such plants in the UK.

There is a continued hope that better PV materials will be found which are much more efficient, cheaper to manufacture, and capable of long service. This goal has been vigorously pursued in US, Japanese, and EU laboratories for over 30 years and the Siemens ST-40 represents the best of what that achieved. More recently, thin films of a copper, indium, gallium, selenium semiconductor, (CIGS), are being economically printed on rolling sheets which look more promising in cost and efficiency. If the first factories are successful then a new form of Solar PV could be available within a decade. This would change the picture.

In the southern USA, the peak of solar power occurs at the peak of the need for air conditioning. When they become cheap enough to cover whole buildings then solar panels could sell back power for homes not so equipped. The intermittency of supply and demand would be matched.

II.2 Micro Wind Power

The story for small wind turbines to be mounted on rooftops is quite similar. Small 1-2kWp turbines are just coming onto the market and Windsave (www.windsave.com) is typical. The installed cost of £1874 seems modest for a 1kWp windmill. However, a typical annual output is about 1000 kWh, which is also 1 megawatt-hour, which sounds bigger. Advertised life expectancy is 10 years so the average electricity cost is 18.7p/kWh and even this small investment can not be recovered. At most 1/3rd of a windy household's annual electricity bill may be saved, but the gross electricity cost goes up by £50 per year. The Micropower Council claimed 4.63p/kWh in 2004 before actual equipment was available.

The Windsave system currently runs only when the wind is blowing AND some appliance in the home is switched on. This is clearly a fatal flaw which will doubtless be fixed for later systems. Water heating would be a good energy storage method.

More serious is the fact that very few UK cities are built in windy areas so wide deployment is simply not workable. Of course, there are many windy country farms which always need to pump water or run equipment and get the full benefit of such systems.

Despite the costs many people will be persuaded that micro-power is somehow worthwhile. After all, isn't paying a few more pennies per kWh worth it for the emissions saved? Small government grants may seem to be an incentive but they will already have been absorbed in the vendor's pricing structures and are actually a subsidy to the industry, not the consumer. Regrettably, the numbers show that investment in micro-power for the UK is presently an enormous waste of the public's money.

II.3 Commercial Wind Power

This is a successful technology based on a century of design of electric motors and generators and the arts of engineering towers and large propellers. Because they are installed in the open to contend with all weathers the windmill lifetimes are only rated for 25 years. A key element is that ambient wind speeds are greater and more constant above 25 metres from ground level. This is even better offshore since the sea interferes far less with the wind flows than does a variable landscape, though the marine engineering requirements increase the cost by about 50%. Current windmill designs run best at speeds of 10 m/sec. over a range of 8-15 m/sec. Needless to say, regions with such high wind speeds are mostly far from heavily populated areas and so new, long distance transmission lines are needed. This is fortunate since wind farms require huge areas of around 16 hectares per windmill. Additional 'first of a kind' costs for this are not included in Figure 1.

What is included is the RAE cost for rapid standby power, like open cycle gas fired turbines, to replace 35% of the peak output when the wind has dropped, or reached storm conditions in which the windmills abruptly shut down while the demand is still high. Conversely, the windmills may have to be shut down if there is insufficient demand. The standby power may be required only 15% of the time which makes it expensive. The RAE standby cost is no more than a fair estimate of what may be needed.

Denmark has some of the largest wind farms in Europe and maximises its output by exporting it to a very large market including neighbours like Germany and Norway. The USA spans three time zones which help to level the load factor. The UK does not have such options.

II.4 Coal and Gas

The 2003 RAE report estimated the fuel cost for Closed Cycle Gas Turbine power at 1.53 p/kWh. All forward planning for the next 30 years by all energy agencies in the US and the EU have held fast to the idea that gas prices will remain this way for the foreseeable future and that oil would remain at $20/barrel forever. The predictions completely ignored the obvious rise of Chinese and Indian economies and the imminent peak of cheap oil supply. Gas easily turned out to be the cheapest power source, especially since a power station is just a direct connection between gas supply and the turbines, making the capital investment the lowest of all. The recent price increases have had market driven spikes but the new averages are far above $20/barrel and 20p/therm are permanent and will rise further. At 270p/therm gas fired electricity would cost the same as Solar PV in the UK. The gas power stations are cheap enough that the next round to be built can simply be phased out in 25 years time.

The RAE measure for fuel cost has therefore been raised in proportion to the new 2006 average price of 33p/therm for gas – not the high peaks of last winter, or the August rate of 60p/therm - to 2.52 p/kWh. This promptly makes gas more expensive than Coal and Nuclear and just below Onshore Wind power. Figure 1 also makes an allowance for EXTRA FUEL costs in gas (1.5p) and a doubling of nuclear fuel prices (PWR - 0.4p, GT-MHR - 0.6p) over the next 20 years.

II.4.1 CO_2 Emissions.

The next consideration is CO_2 emissions. Transport and Electricity are equally important in keeping our civilisation going. Globally, transport produces 40%, or 12Gt/year, of these emissions, which could continue as half our annual allowance. More efficient engines, electrified public transport, and conservation measures can slow the decline of cheap oil.

Coal and Gas globally produce over 18 Gt/year of this greenhouse gas, which accumulates in the atmosphere and will take 500 years for the biosphere to recapture it. The Proven World Reserves of fossil fuels, in their usual units and their equivalent Carbon content, are (BP 2006):

	OIL	GAS	COAL
Gb/Tcf/Gt	1189	6337	909
Gt Carbon	148	95	698
Gt CO2	**542**	**347**	**2454**

At the present and projected consumption rates, all of these will be almost gone in 100 years. Coal alone could increase the CO2 concentration in the atmosphere by 90%.

There are only two sensible proposals for dealing with this: (a) Stop using Coal and Gas for electricity or (b) Capture and safely store all the CO_2waste in deep geological depositories (CCS), and also capture all the solid particles, Sulphur, and other pollutants, making for clean 'New Coal'. This will take the carbon in coal or gas from the earth and return 90% of it to the earth in waste form.

There were no good cost estimates publicly available at the time of the EAC or DTI reviews – though the results were known internally. The Intergovernmental Panel on Climate Change (IPCC) has now published its report which includes a detailed study of CCS technology. It takes energy to capture the CO_2 and pump it onto a national CO_2 grid for deposit in the North Sea oil fields. The UK is densely populated and so a grid will be very expensive, at £1.1/tonne/100 miles/year, with many detours, pumping stations, and so on. Ocean burial, at £18/tonne, is the most expensive option and the North Sea probably the worst environment in which to do it. We have therefore shown the top end of the IPCC estimates at 1.9 p/kWh for gas and 3.29 p/kWh for coal, almost double the low end estimates which are what the USA and China would have to fund.

There is relief to be had by using some of the CO_2 for Enhanced Oil Recovery (Sharman). By pressurising depleted oilfields with CO_2, up to 3.3 barrels per tonne of CO_2 may be recovered. This can lift the total recovery from an oilfield by about 10%. In the case of the North Sea this would amount to a further 3 billion barrels over the next 20 years, capturing 1 billion tonnes of CO_2. With oil at £35-£45/barrel the oil companies could afford to buy CO_2 .and build or refurbish North Sea pipelines for an ongoing CCS system.

BP has the only onshore, UK, billion barrel oilfield in Poole, Dorset, with an 11km. long set of wells under the bay at Bournemouth. It is in decline and will need some EOR by 2015. This is a one off opportunity to build a 3GW clean coal power station in Poole and pump the CO_2 under the bay for about 50 years. This could yield an extra 100 million barrels of oil at £40+/b.

The required technologies have been demonstrated in several places and EOR has been in use by oil companies for several years. But, at the normal pace for such large engineering projects, it is likely to take 15 years to design and approve it and 5 years to build it, by which time the North Sea oilfields will have closed down.

The IPCC used the six standard economic models of energy growth and emissions in the 21st century. Only two could possibly hold atmospheric CO_2 below 500 parts per million: Growth with widespread use of advanced technologies – A1T, or decline to a low technology IT and services world with low real growth – B1. Between war, the decline of oil and gas, and unresolved poverty, none of which are included in the models, B1 is the more likely outcome of these two. For the technology path to succeed the best technologies must be pressed forward on an unprecedented scale. The UK government has rightly set Climate Change as one of its principal policy drivers and is already a B1 economy.

II.4.2 Coal to Diesel - CTL

It has long been possible to convert the Carbon and hydrocarbons in coal, tar sands, or biomass into a clean diesel fuel. However, the energy intensive processes for coal cost \$35/barrel of diesel and produce about 2 barrels per tonne of coal. This diesel will already have double the emissions yet to be made from vehicles. All the coal carbon is burned to emit 2.7 tonnes gross of CO_2 per tonne of coal. Such plants are under construction in the Wyoming and Nebraska coal fields.

If we scale this up to produce 1 million barrels of diesel per day – the US uses about 22 million barrels of oil a day – the process would emit over 500 million tonnes a year of CO_2. Without CCS on the conversion process this represents a huge burden on emissions if repeated around the world. This will raise the production cost, not the price, to about \$50/barrel, which is far above the costs for cheap oil from oilfields. A pilot plant of this type is proposed in Australia.

A cheaper alternative could be to use nuclear power to produce hydrogen and oxygen for efficient, high temperature processing of coal or biomass to diesel (Forsberg). This then puts all the carbon in the coal into the atmosphere as CO_2 from burning the diesel. With oil set to be in final decline this century, coal could provide the transport fuel ration for three or four centuries.

II.5 Nuclear Power

The nuclear industry has been quietly working to solve all its 20th century technical problems. Despite the US-EU moratorium on building new reactors the industry has learned a great deal about safe, efficient operations, and about design of third generation systems which are far cheaper to build, disassemble, and decommission.

The latest Generation III reactors discussed with EAC are the Westinghouse AP1000 with a passive cooling system in the event of an accident, and the French EPR with four separate active cooling systems to control any accident. Both are Pressurised Water Reactors (PWRs) to be run in a Once Through fuel cycle in which highly radioactive spent fuel is described as waste. The world supply of known, expected, and possible mineable Uranium, as listed in the IAEA Red Book, is only sufficient for about 750 PWRs over the next 50 years (McNamara, Uranium). The MIT Study of nuclear economics assumes even more will be found, because nobody has looked for 25 years, and estimates that 1000 reactors could be run. Like all other finite resources the price of Uranium will soar hugely in that period, but this is not the end of nuclear power.

II.5.1 Future Reactors

Although the US, the UK, and many other countries have largely dropped out of nuclear power research, the French, Japanese, and Russians have maintained vigorous programmes. The EAC and DTI reviews contain no discussion of the advanced systems.

For this reason, the General Atomics GT-MHR is included in our comparisons because it can (i) run entirely on recycled waste from our old nuclear stations, (ii) burn up all the legacy of high level radioactive fuel wastes (HLW), (iii) has a reactor core which is non-flammable and completely safe against loss of coolant events, and (iv) will be 45% more efficient than PWRs and use proportionately less cooling water. (v) Its encapsulated fuel will contain all fission products for a million years, allowing for 'deep burn' of all fissile materials, and (vi) preventing contamination of the rest of the structure by contact with Plutonium. This means that all the Intermediate Level Waste (ILW) will lose its induced radioactivity in only 300 years.

These reactors could supersede the PWRs from 2025 as the principal power producers. They set a new standard for Generation IV reactors.

The only comment on future nuclear technologies in the EAC review was from Sir David King, UK Chief Scientific Advisor:

'Widespread use of fast breeder reactor technology could increase the utilisation of uranium sixty-fold or more.'

The comment went unnoticed in the EAC Executive Summary, and Sir David's comments on the use of stockpiled Plutonium for electricity generation were dismissed. They chose instead to support the spurious work on CO_2 emissions from nuclear power (see McNamara, Opposition…) and other weakly researched reports on Uranium supplies.

II.5.2 Spent Fuel is not Waste.

Advanced reactor and fuel developments were removed from consideration at an early stage of the study by the Committee on Radioactive Waste Management (CORWM) which therefore can now only recommend deep burial of everything. The recommendation is also for early closure of the repository, including back filling of stores as they are filled. The ideas that spent fuel is still fuel, or that depleted Uranium is fuel, appears throughout their report as an unlikely afterthought, matching US Dept. of Energy positions. This long, costly, laborious consultation process declared;

'There was insufficient time in the programme to commission new original research.'

This meant that all the considerations for new systems, with a service life of 30-50 years, were based around technologies available now for deployment over the next 10-20 years. The few expert reports produced were similarly constrained and amounted to little more than literature survey exercises. Many other organisations, from the Sustainable Development Commission to local councils and environmental groups, have copied this uninformed path.

It is likely that our new reactors will be French and that they will manufacture the fuel, as is planned for Finland. When recycling starts for GT-MHR type reactors the French would be able to reprocess the spent fuel for the steadily increasing fleet of reactors in the EU. Hopefully, no fuel rods will have been concreted away and will still be available for re-use in the 2025-2050 time frame. Local French fuel factory and storage facilities will be needed to minimise the transport problems. The final high level waste to be buried will be one tenth of the currently planned volume, will generate little heat in storage, and will decay to a natural background radiation level in a few hundred years.

II.5.3 Nuclear Plant Costs

We show the GT-MHR as slightly more expensive than the new PWRs , though GA would claim it will be cheaper. Similar reactors are in operation in Japan and China and a weapons Plutonium burner is to be built in

Russia, so these reactors could become widely deployable from about 2020. General Atomics would like to see a full scale GT-MHR demonstrator built in the USA. Further details were given in my submissions to the DTI Energy Review (McNamara).

The RAE Plant costs quoted here include decommissioning but not high level waste disposal. British Energy expect to pay into some government waste fund about 0.1p/kWh, or about £500 million per reactor over a 50 year timescale. This is TINY compared with the CCS costs, even with the least expensive versions, because the total waste to be treated is about 10,000 tonnes per reactor in 50 years time as against the 260 million tonnes of CO_2 processed for a coal system.

An arbitrary 'EXTRA FUEL cost of 0.6p has been added in Fig. 1 to take account of the additional processing.

II.5.4 UK Nuclear History

The notorious Sizewell B event was a great environmentalist achievement in filibustering the UK government into delaying the project so long that applications to build the other 8 reactors were never made. The destruction of the British nuclear energy industry, and the elimination of nuclear engineering from our universities, was also set in train and has been completed this year, 2006, by the government sales of all remaining assets. The only vendors capable of building new nuclear stations in Britain are the French, the Japanese, and maybe the Americans. The vendors clearly do not need financial assistance to enter the high priced UK market, as was strongly emphasised by the fine evidence from EdF to EAC, but they do need to be assured that licensing and planning will not be allowed to be challenged endlessly or that government departments will not be allowed to procrastinate and demand continual changes to internationally accepted designs. These vendors will not enter the market without such assurances and will not wait 14 years before walking away.

One other historical comment is worth making: The British reactor designers sought to use natural Uranium as the fuel, as did the Canadians, to avoid the huge expense of fuel enrichment. Since then diffusion enrichment has been replaced by the far cheaper centrifuge systems. The decision led to the Magnox reactors and later to the Advanced Gas cooled Reactors, the AGRs. These have turned out to be far less efficient and harder to maintain than the American Pressurised Water Reactors, the PWRs. Accepting a PWR at Sizewell was an admission that the UK natural Uranium reactors had come to the end of their engineering capability. The design, construction, and control systems for these reactors look quite antique by modern standards.

The Generation III+ and Gen IV reactors are now designed on supercomputers. The many nuclear reactions, the hydraulics, the heat flows, and the materials problems, can all be modelled in 3D and time. Like a fly-by-wire airliner, the future reactors will be much easier – and therefore safer – to manage than the 20th century plants.

II.6 The p/kWh Comparison.

The DTI/DEFRA submissions found it necessary to firmly support the 2003 White Paper on Energy and to claim that little had changed since then and that its conclusions were still sound. The final Energy Challenge report is, of course, very different.

The figures we present included equivalent costings for micro-power, the cost of waste disposal for each source, and new information on fuel prices since 2003 which completely re-order the rankings. You may prefer other reports and data sources and choose to criticise the IPCC report and stand firm on a return to cheap energy costs, but this tide will not be rolled back.

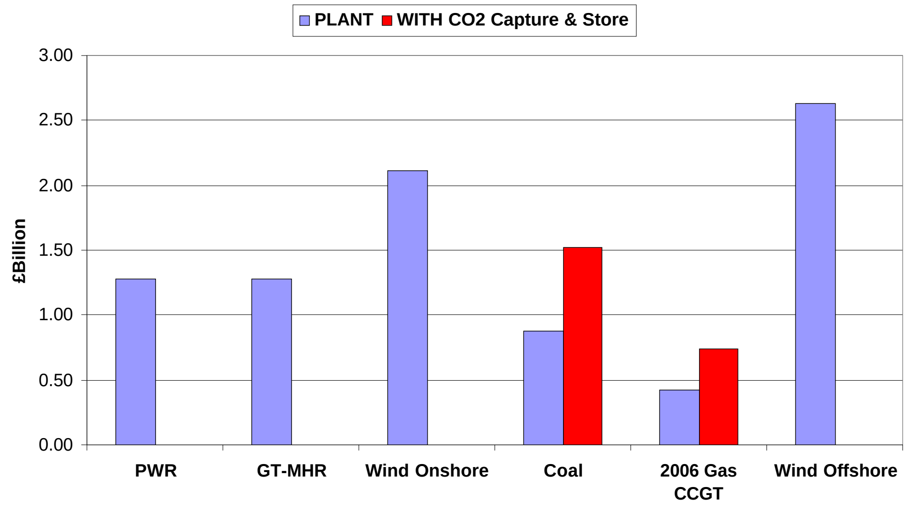
A basic, unanswered economics question is 'what is the level of energy costs which leads inevitably to global recession?' If we can build electricity systems which can always deliver below a 10p/kWhr 'street price' then we expect to avoid that.

The analysis is not complete. Pence is money in your pocket and a kilowatt hour will produce 10 pots of tea. Let us see what a complete electricity supply system really costs.

III. CAPITAL COSTS PER GIGAWATT YEAR.

Cities and industries need billions of kilowatt hours. Large power plants can produce an average of one million kWh per hour – a Gigawatt – every hour of the year, a total of 8.76 billion kWh – a Gigawatt year.

Fig. 2. CAPITAL COSTS FOR GWe-YEAR PLANTS. Micro Wind £16Bn & Micro Solar £35Bn not shown.



Each energy source has a duty factor which limits its actual annual output. The Westinghouse AP1000 is rated at 1100 MWe so, at a duty factor of 90%, will deliver a Gigawatt year of electricity (GWe-yr). This is the duty factor currently achieved by most US nuclear stations, making their marginal cost of power production today around 1c/kWh. Coal fired power stations face UK emissions restrictions and many Gigawatt size UK plants run at 1/3 of capacity

Capital costs for Wind farms are always quoted by their peak output, making them look extraordinarily cheap (1/3 of the values shown). The annual average duty factor is claimed to be 35% but Danish and German wind farms have not done better than 27%, partly because they have to be shut down when the markets cannot absorb the power. We have used the 35% figure for comparisons and so a GWe-yr of wind power needs 3 GWe of installed capacity and would cover some 12,000 hectares. The down side of this is that in some periods the system will actually be delivering 3 GWe and so the swings between peak, average, and shut down, which can happen in hours, are very large and difficult to handle on a grid. It has been suggested (Sharman) that UK Wind power should not exceed 10 GW-peak for this reason. In the face of expensive gas it may be preferable to have a lot of wind power to supplant gas whenever possible. Selected users may have to accept some supply interruptions.

It may be possible for some energy intensive industries to operate intermittently and use whatever excess wind power is available. The people of the island of Lewis, where the UK's largest wind farm is to be built, may also be able to operate a substantial industry in this way.

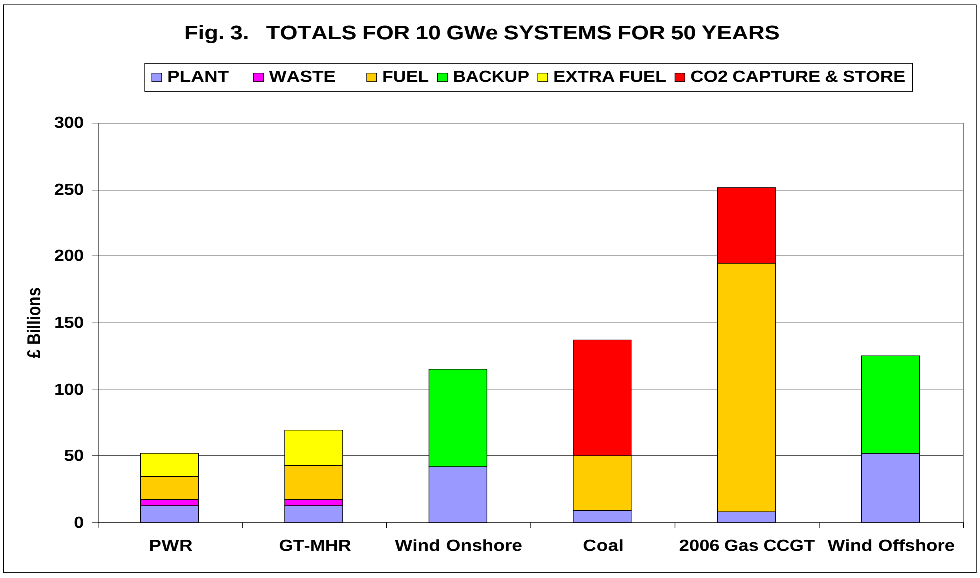
Rooftop Micro-power comes in at a miserable duty factor of 11% and so a GWe-yr needs 9GWe installed and will never recover its investment. We had to drop micro-power from this chart as a Gwe-yr would cost **£16.4 Bn** for micro-wind and **£34.9 Bn** for micro-solar. About 4.4 million homes would have to have installed an £8000-£12000, 2kWpeak system, about 4000 acres of Solar panels to provide 1GWe-year. Despite the enthusiasm from EAC, rooftop micro-power is just not a sensible or economic way to generate large amounts of electricity. We drop it from any further consideration.

To be practical we will only consider a 25 year period for capital and plant costs of an imminent round of new power sources, even though Coal and Nuclear plants are rated for 50-60 years.

The capital costs for the various power sources shown in Fig. 2 clearly favour gas, even with CCS. Commercially this would make for the best investment and quickest return on capital, but only if the price of Natural gas fuel had remained at 20p/therm. Since price rises can simply be passed on to the users the investment still might be safe if recession can be avoided.

It must be emphasised that no interest or discount rate on capital has been applied to these capital costs. The rates could be between 5% and 15%, depending on how much profit the investors can persuade us to yield to them in each case. Nuclear has been labelled as the riskiest investment, and treated as such in the MIT Study, but fossil fuel plants must now allow for CCS systems, the risks of rising emissions taxes, and soaring fuel prices.

IV. TOTAL COSTS OF 10 GWE, 50 YEAR SYSTEMS



The above costings only cover the equivalent of a single large power station. A complete system would be built in tranches of 10 GWe, along with their waste treatment and fuel supply facilities. We choose a 50 year time span to cover the lifetime of Coal and Nuclear stations and to run into and beyond the peak of oil and gas. This doubles the capital investment needed for Wind and Gas systems. A nother perspective is gained by calculating the value to consumers of a 10GWe system running for 50 years. At a street price of 10p/kWh the System income, including service and supply, would be £438 Bn.

IV.1 Natural Gas

For gas, the conservatively estimated price increases make gas the most expensive option of all. If we assume the latest date for the global peak of gas supply of 2036, then prices might be held stable at 33p/therm till 2026 as supplies continue to expand, even against a large rise in demand. This would be well after the peak of global oil, so markets would then understand what is to come. The price may double to 66p/therm as the peak is approached and go to 85p/therm after 2036. The 50 year fuel bill comes to £185Bn. If the price merely goes up steadily by 2.5 times over the next 50 years, the bill would be higher.

This simplistic calculation is not even a pretence at a global economic model but demonstrates clearly the economic collapse of gas fired power stations as prices rise. It seems highly likely that a no more gas fired power systems will be built after about 2030.

IV.2 CCS: Managing CO_2 Waste

The CO_2 wastes from Coal, Gas, and Oil are the main drivers of global warming from human activity. The emissions from electricity generation could all be captured. Those from transport cannot, and the only totally clean options are to change to electrified transport and alternative fuels or to assign most of our global CO_2 emissions allowance to transport. The use of CCS wherever possible seems the best option and, in less difficult situations than the UK, could be quite competitive with nuclear.

I have to question the value of emissions trading schemes. They are like a licence to double park in Mayfair because a parking space has been purchased at Lands End.

As a real example, the emitter of a potent refrigerant waste, HFC-23, in China, is to receive £400M to add equipment to destroy this. The Carbon Abatement certificates obtained can then be sold at a profit to a pulverised coal plant in the UK. Half the pollution will be eliminated and the UK energy company will have £400M less in its accounts.

The world's annual government support for CCS RD&D is about £100M, the UK contribution being close to nil (Tjernshaugen). There is a belief that market forces will solve any problem, despite much evidence to the contrary, a belief similar to the faith of physicists in $E=mc^2$. In the absence of an actual market, government agencies are willing to create a fictitious one. The EU Emissions Trading Scheme is one such, designed to encourage companies to reduce their emissions. UK firms parted with £470M in 2005 to buy ETS certificates.

There is much discussion of the recycling of Carbon taxes back through, for example, dissipation as a general National Insurance Tax relief. There is no discussion of putting these large funds where they will have the greatest impact – directly into development and deployment of key technologies.

The Stern Review on The Economics of Climate Change declares that solutions to the problem are urgent but fully endorses new Taxation and Trading Schemes as the primary way for the UK Government to produce action. It also suggests that global Energy Research, slashed by almost 90% in the 1980s should now be doubled.

Other weak demands are that new Coal plants should be 'CCS-ready'. The Governors of Nebraska, Texas, and Wyoming do not face even that restraint. The world is set to increase coal capacity by 80%, building over 800 coal plants by 2030 – US 150, China 500, India 100, EU 2. Without CCS, the needed emissions reductions will be impossible to achieve.

Recent predictions (Hawkins) show the full deployment of CCS emerging from 2027, too late to ensure control of global warming. This is entirely a result of public policy and need not happen. The scale of the management problem seems greater than the size of the needed infrastructure.

IV.2 Backup for Wind Power

This would most likely be gas, but no increment has been applied here for the steady price rise in gas over 50 years. Note that a 10GWe Wind system has a peak rating of 30GWe and is something of an elephant in any power supply mix. Other solutions to the problems of intermittency and power spiking will be developed to get the best out of wind power, but we may simply be grateful for every affordable kWh. Developing countries cannot afford backup power sources but the modularity and low cost of Wind power makes every kWh valuable.

IV.3 Nuclear Power

Finally, nuclear power turns out to be the cheapest and most reliable source of electricity over the next fifty years, including decommissioining and waste treatment. The stability and independence this would give could guarantee 10p/kWh electricity for 50 years.

IV.3.1 Breeder Reactors

The thermal neutron flux in a PWR, coming from the fission of Uranium 235, converts a small percentage of the natural Uranium 238 into fissile Plutonium 239, which then provides about a third of the power output. In fast reactors the neutrons are not cooled down from nuclear levels so then the reactor can produce more fissile Plutonium fuel than Uranium 235 consumed. Four of the six Generation IV reactor development efforts are for just such fast breeder reactors. These will generate their own fuel and supply fuel for GT-MHR type power producers.

The fact that Breeder reactors and Fusion are not yet ready for deployment is largely due to the collapse of energy R&D in the US and the EU in the 1980s. However, the promise is huge and well worth the investment required.

IV.3.2 Depleted Uranium Fuel

All the isotopes of the heavy elements, Thorium, Uranium, Neptunium, Plutonium, up to Americium are fissile or can be transmuted by neutron capture to fissile nuclei. Every tonne of these elements is capable of producing an enormous 1000 Gigawatt-thermal days of energy. In a 50% efficient reactor this generates 1.37 GWe-years, though in multiple reprocessing cycles only a conservative 50% of the Uranium may be finally manufactured into fuel. At a street price of 10p/kWh the energy value to society of a tonne of depleted Uranium is £600M. Gold currently sells for £10.5M per tonne.

The UK will have about 106,000 tonnes of depleted Uranium – 99.7% pure U-238, in stock by 2020 (Nirex), This could produce 72,600 GWe-yrs of electricity. The total 2005 energy production of the UK is equivalent to 20 GWe-yrs by coal, 45 by gas, 42 by oil (mostly transport), and 9 by nuclear – a total of 117 GWe-years.

We conclude that the UK already owns enough depleted Uranium to satisfy its total energy needs for 623 years, using a mix of 117 breeder and burner reactors. Appropriate conservation measure and the use of wind farms, solar buildings, and other renewable carbon free energy sources would reduce the number of reactors needed to about 75 and extend the availability to about 1000 years. The USA currently has a depleted Uranium stockpile of about 500,000 tonnes.

So where would a vigorous deployment of PWRs lead over the next 50 years with their Once Through To 'Waste' fuel cycle? About 750 reactors would 'use up' all the known Uranium supplies by transferring it all to fuel vaults in the nuclear powered countries. The UK energy supplies would double.

The problem of proliferation of nuclear weapons would be tightly controlled by the nuclear countries as they would own all the fuel and only supply reactors and returnable fuel elements to those who agreed to real time checks on all nuclear materials. Others could simply be supplied with power through transmission lines or could use Wind and New Coal.

The Nuclear Industry would operate fuel vaults, with Fort Knox like security, for depleted Uranium and even tighter for radioactive Plutonium and Actinides fuel, and geological waste stores for the various radioactive wastes which cannot be recycled for 300 years or so. This is quite a different scenario from the CoRWM schemes.

IV.4 A Secure UK Energy Future

It seems that the simplest option for UK Coal is to replace it with Nuclear and Wind power until a CCS system is built. Electricity from Gas will become uneconomic by 2030 and gas will be more valuable as transport fuel stock.

The simple calculations shown here have levelled the playing field for electricity cost comparisons. The differences between systems are very large and so another choice of well worked data sources which differ from the RAE, IPCC, and other reports, will not alter the broad conclusions. While my simplified, conservative extrapolations are open to much debate they do expose the very weak position of the UK Energy Challenge report.

Nuclear, Coal, and Wind power, and maybe Fusion, should by 2050 dominate the long term energy prospects of the planet, along with other carbon free energy sources like New Solar. This goal can only be reached through a vigorous development of the technologies we have described. There is a huge range of new energy alternatives and a tiny degree of support.

V. BUILDING A CARBON FREE ELECTRICITY FUTURE.

We now have to pay the price for 25 years of neglect of our energy future. Solar power remains too expensive. Advanced coal technologies are still in the development and demonstration phase, while the standard pulverised coal plants are recognised as dangerous, if global warming is to be controlled, but will be built by an uncaring energy market. The seemingly easy option of Natural Gas is becoming unaffordable as demand outstrips supply. Wind has arrived at a commercial scale and will be integrated over the next decade. Nuclear has come up with much better versions of the PWR workhorse reactor and can provide as much affordable base load electricity as we need, as fast as we are prepared to build them. The final demonstrators for high temperature nuclear waste burners await funding and the breeders which will secure our future for millennia are still largely in computer design studies and laboratory science. Fusion has become an international project, running at half the normal pace of such a development activity (McNamara – Future of Fusion) Commercial scale demonstrators for New Coal or Nuclear technologies will only cost around £500M - £1000M each.

Beating Climate Change is a global task, with a short time scale for action, and requires three new sets of global treaties:

(i) A Fossil Carbon CCS Treaty to deploy CCS before any more new coal or gas burning power stations, or high emissions plants for liquid fuels can be built. This would be part of the next Kyoto Protocols.

(ii) The Oil Depletion Protocol, promoted by ASPO, to share the declining supplies of cheap oil and gas in an orderly way (www.oildepletionprotocol.org). Agreements are also needed to restrain the total emissions from Transport.

(iii) A Nuclear Energy Supply & Non-Proliferation Treaty to handle nuclear power safely, firmly, and equitably (IAEA).

It is not necessary to wait for these global agreements. Like new reactors, new policies need demonstration packages.

California was the first to legislate for noxious emissions reductions by automobiles, against fierce opposition from the industry. California has now legislated that no long term electricity supply contracts may be agreed with suppliers who generate large CO_2 emissions. This extends *their* emissions restrictions to other states, a tough way to implement policy which reflects their sense of urgency.

Rapid implementation of CCS in several places could make a Fossil Carbon Treaty a realistic goal and make unilateral restrictions an acceptable way to begin implementation. China's huge coal reserves will run out by 2050 at the projected consumption rates, so China may have the greatest interest in a Fossil Carbon CCS Treaty.

The fact that most governments, their Agencies, the IPCC, and many oil companies choose to ignore the coming Oil Peak really vitiates all their long range economic planning scenarios. Optimistic claims about tar sands, oil shales, or coal-to-liquids, conceal the economic fact that energy costs will never return to their historic lows. A Peak Oil Protocol will not be adopted by people who claim the peak will not happen. The lack of any convincing economic models of how the transition can be managed is a deterrent to admitting the need for this Protocol.

The Nuclear Energy Supply and Non-Proliferation Treaty envisaged here addresses the global trust required for both the achievement of a thousand year energy supply and the avoidance of any nuclear war. We all see the need but the discussion requires volumes. Politicians from nuclear powers have been responsible for both weapons proliferation and restraints on nuclear energy. Other politicians claim new 'inalienable rights' to both, but populations may prefer that none of them had nuclear weapons and that they had adequate nuclear energy sources. These issues really do need to be resolved soon. The current proposals to create an IAEA Nuclear Fuel Bank do not address the scale of nuclear power described here and will be ineffective without close IAEA monitoring of all nuclear materials throughout the fuel cycles.

We have not discussed the many other energy options like biofuels, wave power, or biomass, because they are much smaller contributors. Even so, the realpolitick of our energy predicament means that every effective technology should be pursued, especially if the scale is accessible by local initiatives. Rooftop power may yet prove useful to individuals if our society fails to deliver.

The final decline of cheap oil and gas by the end of this century remains an unsolved problem for Transport. We have enough coal to maintain the present level of coal power for 168 years (BP, 2006). Wind and Solar and other Renewables will last indefinitely. Nuclear and Fusion will last for hundreds of thousands of years on this planet. The neglect of world poverty continually adds fuel for social instability, making every global agreement more difficult to achieve. What folly it would be to engage in energy wars or fall into economic collapse in the midst of such plenty.

Author

Brendan McNamara worked on Fusion Theory and Computations with AEA Technology, Culham (1961-71) and at the Lawrence Livermore National Labs in California (1971-85). He also ran a series of Plasma Colleges at the International Centre for Theoretical Physics, Trieste, 1974-84. He was V.P. of a Supercomputer Center in Princeton (1985-88) and now operates Leabrook Computing as a Consultancy.

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