PART TWO: ENGINEERING A ZERO CARBON FUTURE

Part Two outlines a vision of a zero carbon society:

- First, the economics of a zero carbon society are evaluated. Such as society cannot be achieved by energy efficiency alone: it must involve large-scale zero carbon energy sources.
  - It is further argued that all economically available low- and zero carbon electricity sources should be employed (not including biofuels).
- Second, we consider the specific question as to whether nuclear energy should be considered part of the energy mix.
- Third, a detailed practical plan for a zero carbon economy is outlined.
- Finally, the costs of electricity generation from fossil and zero carbon sources are estimated.

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ENERGY EFFICIENCY OR LOW-CARBON ELECTRICITY?[1]

An economic assessment of two alternative options for preventing 'dangerous' climate change in the light of diminishing returns and economies of scale.

There is much concern about the future effects of anthropogenic climate change. in order to prevent 'dangerous' climate change, industrialized countries must reduce their total emissions of CO_2 by at least 60%, and perhaps by as much as 90%, within a few decades. Energy efficiency is often suggested as a solution. I will examine one drawback to this approach, the so called 'rebound effect', where increased efficiency leads to an increase in associated economic activity. I shall then investigate environmental impact directly, and develop some simplifying assumptions. Although only 35% of present energy use takes the form of electricity, it is technologically and economically feasible for 60-90% of all energy requirements to use electricity. In our economic model, we therefore assume for simplicity that electricity caters for all energy requirements, and generates all impact (CO_2 emissions).

We consider three alternative strategies for a transformation to low emissions: (1) limiting or reducing national income, (2) increasing energy efficiency, or (3) an investment in low-carbon energy (for arguments sake, nuclear and solar power; which by assumption have no resource constraint when considered together). It is found that options (1) or (2) suffer from diminishing returns: it requires ever more harsh reductions in income, and ever higher capital expenditure on energy efficiency, the greater the required reduction in emissions. For option (3), however, the opposite is true. Investment in non-carbon-generating technology allows economies of scale. For simplicity we model the cost of nuclear to be rapidly declining and then constant past a certain point. This suggests that some government investment is necessary to reduce uncertainty and to realise social gains, but then a well-designed market may be able to take over to realise the lowest cost. Electricity is a convenient form of energy and storage technologies are developing rapidly. In summary, a conceivable electricity requirement of 60-90% of forecast total energy use could be met entirely with nuclear, at little or negative cost relative to the best alternative option for meeting energy needs. Such a plan would reduce CO_2 emissions to a sustainable level, and enhance the country's long-term strategic and economic position.

Energy efficiency is likely to provide the cheapest options for marginal reductions in greenhouse gas emissions, and therefore are important in *'lower carbon'* scenarios but those options become increasingly expensive, due to 'diminishing returns', an effect associated with the exhaustion of easy options. Alternative, low-carbon energy sources, such as nuclear power, become cheaper at larger scale (so long as the technology is not constrained by other factors) and therefore may provide the most promising route to *complete decarbonization* of the energy system.

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Does increased energy efficiency imply reduced use? The rebound effect

One might think that increasing energy efficiency by, say 10%, would lead to a 10% decline in energy use. But this opinion would be false. Efficiency improvements may lead to increases in use that could be so large as to swamp the original gain. This is known as *Jevons Paradox*, from the 19th Century economist, William Stanley Jevons (Jevons 1879). He suggested that improvements in steam engines might lead to greater, rather than less, overall coal use.

There is both a micro and macroeconomic issue of the net effects of efficiency improvements on resource use. is there a '*rebound*' effect (efficiency improvements lead to greater output, and less than proportionate decreases in total fuel use) or even '*backfire*' (efficiency improvements lead to much greater output and therefore *greater* fuel use)? Given the interest in the aggregate effects, i thought the macro perspective was more interesting (and perhaps more difficult).

Technological efficiency in the use of energy is important for a number of reasons, e.g. CO2 emissions. it is important to distinguish between improvements in efficiency that are currently projected (according to ongoing trends i.e. technological change and the continuation of past patterns of government intervention) and *additional* improvements. One framework for clarifying the two is seen in Socolow and Pascala's work on emissions wedges . Socolow and Pascala approximately project 'business as usual' future CO_2 emissions by the continuation of a straight-line increasing trend. Such a trend already includes substantial reductions in the emissions intensity of GDP. These improvements have happened in the past and are likely continue in the future. We need *further* improvements on top of these projections. For example, we may be able to induce benevolent technological change by energy taxation or other methods.

So in addressing the backfire/rebound debate, we need to consider contexts where energy efficiency is discussed:

1. Efficiency in the presence of increased energy taxation, is a mechanism such that abatement costs are much less than would seem at first sight. Rises in energy costs (through increased taxation) lead to reductions in energy use. Energy efficiency is a mechanism for accomplishing this.
2. Efficiency, in the absence of energy taxation, instead is an 'avoidance' strategy. The argument might go something like: "Efficiency improvements are the most cost-effective method of cutting emissions. So long as each sector 'does its bit' to improve efficiency, the government need not act. And each sector is doing its bit! Look at these technological efficiency improvements!!!"
3. Mandated efficiency standards are somewhere between these two extremes. if they are relatively cheap to enforce, then they are helpful, so long as the improvements wouldn't have happened anyway. if the improvements are hard to enforce, energy taxation may be a less expensive and more economically efficient method of achieving the same result.

There is a massive economic difference between 1) and 2). in 1), the argument is that we need to reduce emissions so therefore we put up the price of those emissions. in 2) it is argued "we don't put up the price of emissions, since technology will save us." Argument 2) says we don't need to worry. But this argument is false. Technology is *already factored in* (at current trends anyway). We do need to worry! Especially because of rebound and backfire...

Argument 1) says we should worry, but if we try hard to reduce emissions it won't turn out to be too difficult. Abatement isn't as expensive as we thought it would be. Great! Let's do it!

So if we are evaluating policy we need to be clear which argument we are considering. is it, say, a question about the effect of price increases on energy consumption (microeconomics)? Or is it a question about growth theory (macroeconomics) viz.: what effect does factor productivity have on total consumption of that factor? We could generalise the question regarding improvements in energy efficiency to the general issue as to whether increases in a factor's productivity, lead to overall increases (Backfire hypothesis) or decreases (no Backfire) in that factor's use. There is now a consensus that increases in labour productivity do not reduce employment.

The answer to the question depends on 'which factor?' and 'how granular?'. First consider the factor productivity of a relatively narrow factor (such as, say, burning oil in combustion engines, where the alternative is burning coal in steam engines). In this case, I would say that there is 'backfire'. More efficient oil combustion will sometime pass some threshold where they start to replace steam engines (in say trains). Efficiency improvements in the use of oil lead to greater oil burning. *Backfire*!

Why limiting use is difficult: the open economy rebound effect

There is an (open economy) ‘rebound’ effect if one part of the world (say the OECD) reduces is consumption, whilst the rest is unconstrained. The following diagram illustrates the problem. OECD countries reduce their resource consumption, by a shift in their demand curve. This leads to a reduction in total demand and therefore a reduction in the world price for these resources. However, this reduction in price induces other countries to increase their consumption, partly counteracting the original reduction (a sufficiency ‘rebound’ effect).
The magnitude of the rebound will depend on the elasticities of supply and demand. The rebound effect will be more, with lower elasticity of supply or higher elasticity of demand. For completely inelastic supply, the change in demand will lead entirely to lower prices rather than reduced consumption.

Direct Calculation of Environmental impact

We are interested in total environmental impact, I, where I = P * A * T and
P is population
A is affluence
T is the impact per unit of affluence
Assume for simplification:

- Y = A.P
- Affluence defined as real GDP per person at current prices (Measures a weighted sum of *physical* output but measured in $ terms at current prices)
- Population is fixed and can be ignored
- One unit of impact = One tonne of CO_2 emission
- There is one form of usable energy, electricity, which is a commodity and can be transported without cost or attenuation.
- All emissions are caused by electricity generation.
- Economy is assumed to be closed
- Our impact equation becomes: I = Y*T

it may be useful to consider energy efficiency in different sectors of the economy. We assume that the output of the economy consists of a number of goods (and services), which each require some electricity in their production.
So,

$$I = (S_i O_i / g_i) * b$$

or

$$T = (S_i o_i / g_i) * b$$

Where:

- I Total Emissions
- T Emissions per unit income
- Y Total real output (= income) measured at current prices
- O_i (Physical) Output of good i, $S_i O_i = Y$
- o_i (Physical) Output of good i as a proportion of total output, $o_i = O_i / Y$
- E_i Electricity required to produce good i.
- g_i Efficiency of production of good i (Electricity required per unit of output)
- E Total electricity consumption: $E = S_i O_i . g_i$
- b Emissions intensity of Electricity Production, b = i / E
-

However, since we have assumed all energy is used through electricity, we can separate our efficiency strategy from the question of the emissions intensity of electricity.

$$I = E * b$$

To reduce emissions (I), we need to either reduce electricity consumption (E) or the emissions intensity of electricity generation (b). This paper deals with the level of electricity consumption.

$$E = (S_i O_i / g_i)$$

The total emissions are the sum of the outputs of the goods divided by the energy output of those goods. Or, in financial units, total output equals the sum of the value of output of different sectors multiplied by the electricity used per unit of output:

$$E = (S_i V_i * r_i)$$

Where

- P_i Price of good i
- V_i Value of Output of good i, $V_i = P_i * O_i$
- r_i Energy used per unit value $r_i = P_i / g_i$
- o_i (Physical) Output of good i as a proportion of total output, $o_i = O_i / Y$

In order to reduce emissions, there are two possible strategies likely to be effective. We could reduce the importance of those sectors which require a lot of energy. Or we reduce energy needed for those goods which are large portion of the economy.

The problem with rebound/backfire is that autonomous (b) efficiency improvements where it is needed most (in the larger sectors) may lead to growth of energy use in these same areas!!! Aircraft fuel efficiency improvements lead to more flying!!! if efficiency increases in a sector by 10%, but that sector grows by 10%, then the net effect wll be zero. if the sector grows more, then we have a 'backfire' effect. In conclusion, when dealing with a sector (home heating, aviation and personal transportation) the most effective strategy would be to always target efficiency and level of use at the same time. Efficiency could be improved and use capped, for example. This 'double therapy' (even if each of the targets would be modest on their own) may be much more effective than targeting efficiency or use alone. Price increases are effective since they both discourage use and encourage efficiency. Taxation revenues can be recycled so net transfers are zero and internationally competitive sectors are protected. Finally, since most energy use occurs via the 'nexus' of electricity, reducing the emissions intensity of electricity is likely to be very effective at cutting emissions.

In the next section we shall consider the problem from the perspective of neoclassical growth theory. in particular we shall compare energy efficiency and reduced growth with a third possibility, the expansion of nuclear power (or other alternative energy source.

Neoclassical growth theory and environmental impact

The analysis here extends that seen in Nordhaus (1992).
We consider a neo-classical aggregate production function:

$$Y = F (L, R, D, K ; H)$$

Where

- L: Labour
- R: Flow of Natural Resources
- D: Land
- K: Capital
- H; Level of Technology

In particular, we follow Nordhaus in assuming a generalised Cobb-Douglas Production Function:

$$Y = H\, L^W R^L D^G K^D$$

Imagine that R represents the flow of extraction of oil.
Energy efficiency measures usually require increased capital. if we increase capital, income rises, but there is no necessary affect on Resource use. if resource use is constrained, it will remain so. if it is not constrained, the diminishing returns on capital increases may put pressure on other factors of production. Perhaps not all capital is the same? Maybe we should also consider energy-saving schemes to be different to other capital: they are different if (as we argue) if there is market failure in this respect.
Consider two separate types of Capital, K_1 and K_2. K_1 and K_2 are thought to be totally separate and not substitutable.
K_2 can be thought of that good that augments the use of Energy directly. Energy resources cannot be used without this.
K_1 is any other capital. Our production function becomes

$$Y = H\, L^W (K_2^e R)^L D^G (K_1)^{D'}$$

Then we have

$$Y = H\, L^W R^L D^G K_1^{D'} K_2^{eL}$$

So we see that even under the assumption of some sort of difference between energy-saving capital and other capital, there is no difference in our result. Energy efficiency measures may increase total output; they do not decrease resource use, unless resources are constrained.
Another macroeconomic model as follows:
We assume Labour and Land to be constant. These terms are subsumed into a multiplicative constant, which also includes technological change. instead of R resources we consider only the use of energy resources. All resources must be converted into electricity E before they can be used. We assume for simplicity that electricity generation is the choice between gas (generating CO_2 and therefore environmental impact) and nuclear energy (not generating CO_2 and therefore without impact). impact is assumed to be proportional to the electricity produced by non-nuclear means (gas).

Our production function is:

$$Y = A\, K^D E^s$$

We assume impact is proportional to non-nuclear energy production.

Conservatively, we assume constant returns to scale for alternative energy (in fact there are likely to be positive returns to scale. However, a large part of these economies of scale and reductions in uncertainty are taken after the first few reactors are built of each type. A simple assumption, therefore, would be that investment has been sufficient to overcome the substantial first-of-series costs and uncertainties and has progressed past a certain point (x=~4GW?), where initial economies of scale have been taken: our analysis relies on a commitment to at least x of a reactor (or for each design of reactors if more than one reactor is chosen).

Hence: Impact = $b(E - aK_n)$
Where K_n is the capital invested in alternative energy generation ($K_n > x$)

$$E = Y^{1/s} / (A.K^{D/s})$$

impact = $(b/A).Y^{1/s}.K^{-D/s} - a.b.K_n$

Assessment of strategies

We have calculated the total impact as follows:
$\text{Impact} = (b/A).Y^{1/s}.K^{-D/s} - a.b.K_n$

We now consider three strategies: reducing output, increasing investment in energy efficiency and similar capital goods, or increasing non-polluting capacity such as nuclear generation:

1. Reduce output at fixed capital: $-d(\text{impact})/dY \mid K, K_n = -(1/s)(b/A).Y^{1/s-1}.K^{-D/s}$
2. Increase capital at fixed income: $d(\text{impact})/dK \mid Y, K_n = -(D/s)(b/A).Y^{1/s}.K^{-D/s-1}$
3. Increase non-polluting capacity: $d(\text{impact})/dK_n \mid Y, K = -a.b$

We have diminishing returns to reducing output (1), since it is guaranteed that $s<1$. Similarly, there are diminishing returns for increasing capital in energy efficiency (strategy 2), since (D and s being positive) $-D/s<1$. Note that in our model, investment in nuclear energy has constant returns to scale. The greater the required reduction in emissions, the more option (3) is to be preferred.

Conclusions

- Reducing output will involve large (human) welfare losses (note, however, that these economic values are not the only values of importance, we should also consider the impact on the environment, independently of human preferences).
- Induced efficiency may well be the most efficient way of decreasing emissions by a small amount in the next few years. But emissions reductions are subject to diminishing returns. Whilst initial increases in energy efficiency are likely to be achievable at low or even negative cost (turning off a light bulb here and there), one has to ask why these improvements have not been made already. Some inefficiency is usual in all theatres of economic life.
- Investment in non-emitting energy production may (or may not: see RAE 2004) be expensive at reducing emissions by a marginal unit. However, investment in technology has constant or increasing returns to scale. it can and should allow a totally carbon-free economy, so long as there are no other binding constraints. Experience with oil suggests that fundamental Uranium resource constraints are not likely to bite, at least not before new technologies (solar/fusion) arrive.

TECHNOLOGY CHOICE FOR A NEW ENERGY SYSTEM[2] (*Notes*)

"We need to choose a plan that adds up.
It is possible to make a plan that adds up, but it's not going to be easy.
We need to stop saying no and start saying yes.
We need to stop the Punch and Judy show and get building."
– Prof. David Mackay

In the first part of these notes I consider some desirable aspects of a resilient and low-carbon energy system. I argue that governments should permit and encourage multiple low-carbon energy technologies: including renewable electricity and, under certain conditions, nuclear (fission) power and carbon capture and storage (using fossil fuels and/or biomass as fuels): all the available low-carbon electricity generation options are needed.

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Aspects of A Carbon Free Energy System

"Carbon Free"

- CO_2 emissions "As Low As Reasonably Achievable" (ALARA) (Or "As Low As In Nature") (<1 tonne per person)
- Constrains Fossil Fuel use c.10% of current levels
- Everywhere has to decarbonize: excess low-carbon energy might be exported to other countries

Realistic Renewable Energy

- Integration of the grid <30% of total electricity
- Physical/Economic potential - Constrains UK renewable <20% of total energy

Resilience

- Fuel interruption / Technical Hiccups / Windiness or sunniness
- Load Following: Ability to follow peaks and troughs of demand
- Realistic: Some sectors need to use oil (10%)

Balanced Technology

- Use all technologies that can reduce emissions
- "Learning Effects"

Conclusions

- Domestic renewable can generate at maximum 20% of total energy demand and a maximum of 30% of electricity supply without storage.
- Oil will be needed for some applications such as aviation, military, emergency services, some industry.
- Coal/Gas will be probably be needed

Technology Choice

The Positive Principle

- Weak Positive Criterion: `We need low-carbon electricity; and these sources fit that criterion'
- Stronger Positive Criterion: `The market should be able to choose all low-carbon electricity options'

Why do we want more than one technology?

In the short term we need to prevent new coal construction. There is an argument for alternatives to coal, and in particular for cheap alternatives.

In the long term we need to have enough energy to power our country;without necessarily arguing for huge imports. Renewable energy is limited; so we can get other technologies.

Further Arguments

- Redundancy - if one technology doesn't work, we've got other options
- We haven't enough free land in the UK for renewable only
- Economic policy is better if we don't pick winners
- We need enough alternatives to coal
- There is no shortage of engineers within technology but between technologies
- The government could promote all technologies fairly easily
- Energy needed is huge
- Energy supply is likely to increase by 50pc to 2050
- Stop saying no start saying yes
- There is no `low carbon electricity' lobby. There is a renewables and a nuclear one and an energy one; but no lobby that brings together low carbon options.

Multi-criteria analysis

- Cost
- Density
- Input Finiteness
- Waste
- Non-proliferation

SHOULD WE USE NUCLEAR ENERGY TO TACKLE CLIMATE CHANGE?[3] (Speech)

One of the most controversial questions is whether we should use nuclear energy in our bid to tackle climate change. This document argues that we should, at least in the UK.

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What Is The Problem?

Will We Have Enough Secure Energy?

This question concerns our nation's future. Will we have enough energy in the future? Shall we, as in the past, obtain our fuel from secure, reliable sources? Or instead will we be forced to compete for dwindling supplies of natural gas from Nigeria, North Africa, or Russia? Yet there is an even more important issue. It concerns the future of Earth, and the plants, animals and humans, which live upon its surface.

The Greenhouse Effect

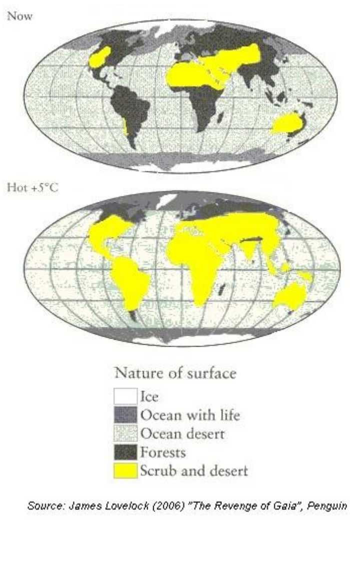
It has been known for one hundred years that Carbon Dioxide in the atmosphere traps heat in the so-called `greenhouse effect'. Carbon Dioxide is emitted in the burning of coal, oil and natural gas, which presently supply eighty percent of the world's energy needs. Humanity has now reached a point, such that, if we continue like this, we will double the concentration of Carbon Dioxide within fifty years. This would lead to an increase in average worldwide temperature of 2 - 5 degrees Celsius or more (IPCC 2007a).

Urgency of Issue

An increase in global temperatures of two or three Celsius will alter the Earth drastically and irreversibly. All coral reefs would be destroyed. The Greenland ice sheet melt would be irreversible, leading to an eventual sea level rise of seven metres. The earth's heat circulation system may shut down and the Amazon rainforest would collapse, releasing more carbon dioxide. Hundreds of millions of people would face drought and starvation.

In the 10,000 years from the end of the last ice age to 1750, just before the start of the industrial revolutions, global carbon dioxide concentrations were static at around 275-280 parts-per-million by volume (ppm). The concentration is now 388ppm (Tans 2010), and rising at 2ppm per year. Once other greenhouse gases are accounted for, the concentration is approximately 430ppm CO2e, and rising by 3ppm per year (Stern 2009). At current rates, by 2050, we will have doubled pre-industrial CO_2 levels (IPCC 2007b), leading to a temperature rise of approximately 3 degrees Celsius above the pre-industrial level. With strong industrialization, expected in the developing world, by the end of this century, total greenhouse gas concentrations could be equivalent to a quadrupling of pre-industrial level, leading to temperature rises of six degrees or more.

Impacts Of Climate Change



Source: James Lovelock (2006) "The Revenge of Gaia", Penguin

For a five-Celsius warming, much of what is now forest or fertile farmland would become scrub or desert (Lovelock 2006).

How would we feed the 9 billion people expected to be on the planet from 2050 (United Nations 2009)? The temperature would continue to increase for a century or more, and sea levels would rise for a thousand years or more (IPCC 2007a). For those who say that we should worry about other human or environmental problems, I say: Global Warming has the potential to make all these problems much worse, if we do not act now. So act we must.

International Agreements Are Difficult

Many have sought international agreement to reduce carbon emissions. Yet each country has its own individual needs, and nations are unwilling to sign agreements they cannot easily keep. We need to act with or without international agreement.

Possible Solutions

Energy Efficiency Cannot Eliminate Energy Consumption

Some say that energy efficiency is the solution. It is easy to turn a light bulb off. Yet once these easy savings are gone, it becomes increasingly costly to use less energy. And we must consider the fast growing giants of China and India. Who are we to say they must remain poor? In our industrial revolution, as steam engines improved, more rather than less coal was burnt, an effect known as Jevons' Paradox (Jevons 1879).

Renewable Energy Should Be Used But Is Limited

Some say renewable energy is the solution. Yet, besides their expense, wind or solar or energy crops cannot produce enough energy for economies with a high energy consumption per unit area. Some in the environmental movement might doubt that we want a large, modern, urban economy, but this remains a minority view. The Tyndall centre have estimated the total british renewable resource as 334Twhe/year or 38GW (Watson 2002); that's about 16% of our total final energy consumption. Wind energy, the most promising of UK renewable power can generate economically about one tenth of British energy needs (and only produces anything when the wind is blowing).
Solar energy from far away deserts is more promising (MacKay 2009). and with political collaboration could potentially contribute significantly to European and specifically British needs. But the

The 'Tragedy Of The Commons': What Can Compete With Coal On Cost?

An answer needs to be found not only for the UK, but also for the rest of the world. Yet this is not easy. Unless we invest in the correct technologies, we face a `tragedy of the commons' (Hardin 1968) on a global scale, where each country goes its own way and the planet goes to hell. Even if the UK were to reduce its energy consumption, would China and the US follow suit? Will China pay to fit Carbon Capture and Storage on its emissions?

Coal and nuclear are close substitutes. They both provide reliable baseload power at low cost. In other words, if we don't have nuclear, it is likely that we will have more coal, as revealed by the following news story about Germany, from *The Independent* (Tony Paterson 2007), "A Euro30bn (£20bn) scheme for the construction of 26 new coal-fired power stations by 2020 has been approved by Ms Merkel's grand coalition, as the country moves to abandon nuclear power."

Nuclear Energy

Density

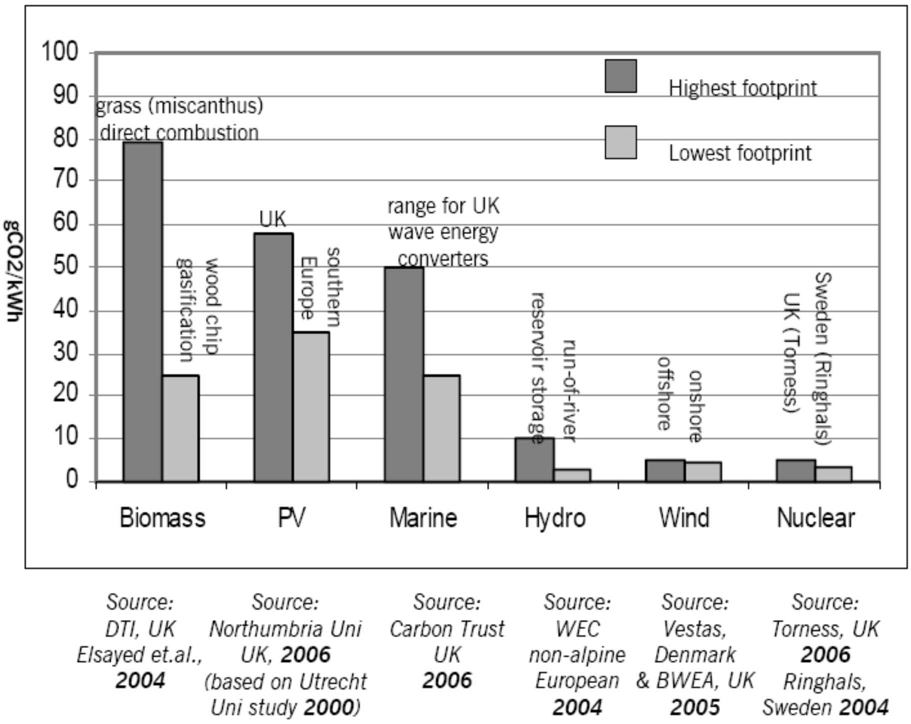
Yet there IS a solution that is attractive for all the major economies of the world. This is found in modern, safe nuclear energy. One kilogram of Uranium generates 40,000 times more electricity than a kilogram of coal. Proven resources are 85 years, estimated resources (what's actually in the ground) of 320 years: including seawater and thorium 8000 years; future fast reactors or fusion reactors perhaps ¼ million years. It is mined in stable, trading countries such as Australia and Canada.

Nuclear Is Low Carbon

The following graph from The Parliamentary Office For Science and Technology (Sustainable

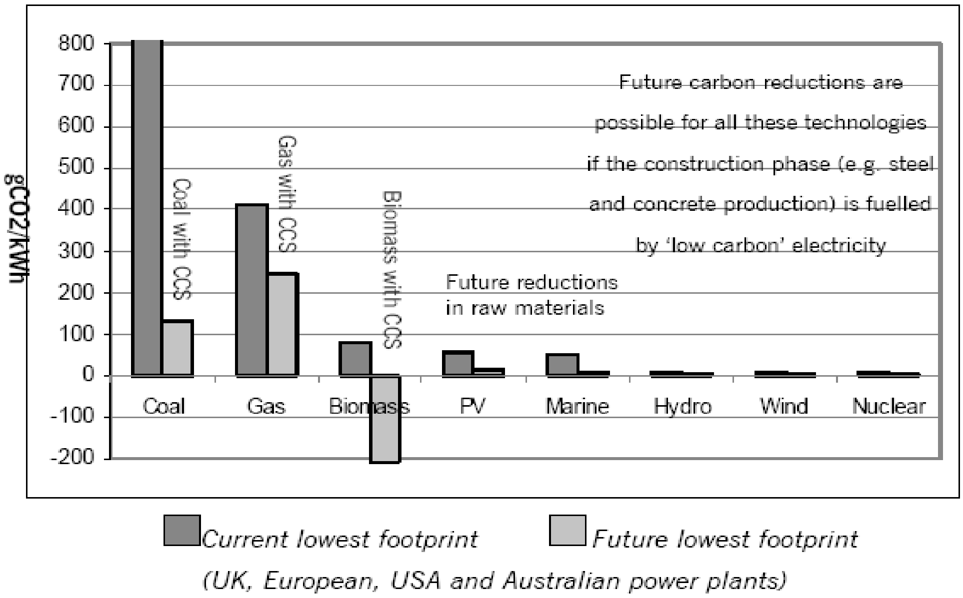
Development Commission 2006b) shows the carbon footprint of nuclear energy in comparison to other low-carbon sources: *Lifecycle Emissions of Low-Carbon Electricity Sources*

Figure 2. Range of carbon footprints for UK & European 'low carbon' technologies



Both renewable and nuclear energy have a carbon footprint low relative to fossil fuels, as shown by the following graph from the same publication:

Figure 3. Current and future carbon footprints



The issue of the emissions from nuclear energy is discussed in detail *(ibid.):*

> *"Nuclear power generation has a relatively small carbon footprint (5gCO2eq/kWh) (Fig 2). Since there is no combustion, (heat is generated by fission of uranium or plutonium), operational CO2 emissions account for <1% of the total. Most emissions occur during uranium mining, enrichment and fuel fabrication. Decommissioning accounts for 35% of the lifetime CO2 emissions, and includes emissions arising from dismantling the nuclear plant and the construction and maintenance of waste storage facilities. The most energy intensive phase of the nuclear cycle is uranium extraction, which accounts for 40% of the total CO2 emissions. Some commentators have suggested that if global nuclear generation capacity increases, higher grade uranium ore deposits would be depleted, requiring use of lower grade ores. This has raised concerns that the carbon footprint of nuclear generation may increase in the future (see Issues) A 2006 study by AEA Technology calculated that for ore grades as low as 0.03%, additional emissions would only amount to 1.8 gCO2eq/kWh. This would raise the current footprint of UK nuclear power stations from 5 to 6.8 gCO2eq/kWh (Fig 3). If lower grades of uranium are used in the future the footprint of nuclear will increase, but only to a level comparable with other `low carbon' technologies and will not be as large as the footprints of fossil fuelled systems."*

Safety and Security

Modern nuclear plants are very safe and secure, and produce very small amounts of waste, securely managed. They are already the least expensive energy source for the UK.(Royal Academy of Engineers 2005) The more that are built, the more the world will `learn by doing', making nuclear better still. America and China could then choose a zero-carbon future instead of returning to dirty coal.

False Arguments against Nuclear

"Nuclear Crowds Out Renewables"

Our Energy supply is 85% Fossil Fuels. Nuclear and renewable electricity are different. There is no reason why you cannot have both. In the UK, new nuclear will compete in the open market against fossil fuels If we are to make the changes required, we might need both renewables and nuclear electricity, as well as fossil fuels with carbon capture, if available.

"Nuclear Locks Us In To A Centralized Energy System"

Nuclear aids "System Change" Nuclear energy provides the backbone - always on. This security would allow low-carbon electric transport and storage systems to be developed.

"Nuclear Is Not Sustainable Because It Relies On Finite Resources"

It is true that nuclear resources are finite, but they are still relatively large. Booked reserves are 85 years at current rates; 300 years estimated. A 10-fold increase in nuclear use. Twice as much thorium as Uranium (Tripling resources). Use of a breeding cycle would multiply resources by a factor of 40.

"Nuclear Faces An 'Energy Cliff' – CO_2 Emissions Are Very Large For Low-grade Ores"

I have already earlier mentioned that the lifecycle greeenhouse gas emissions of nuclear power are around 5-7gCO2/kWh (compared to 800-100gCO2/kWh for coal and 400-500gCO2/kWh for gas (POST 2006).

The Sustainable Development Commissions, published an evidence paper (Sustainable Development Commission 2006a) collating evidence collating a large number of scientific papers and reports on the carbon footprint of nuclear. 29 out of the 31 studies suggested a carbon footprint in the range 2-40gCO2e/kWh (the remaining two studies considered either old reactor design or old enrichment technologies).

Some campainging organizations such as Greenpeace and commentators such as David Flemming (David Flemming 2007) have quoted a websitethat claims to deny that nuclear power is not genuinely low-carbon (Storm van Leeuwen & Smith, P 2005). The website argues, that, where the majority of world resources lay, at concentrations around 0.03%, the energy required to extract Uranium, and therefore the greenhouse gas emissions would be prohibitive.

However, this paper has been comprehensively debunked (NuclearInfo.net 2009):

> *"Employing Storm van Leuven and Smith's calculations predicts that the energy cost of extracting the Olympic Dam mine's yearly production of 4600 tonnes of Uranium would require energy equivalent to almost 2 one-GigaWatt power plants running for a full year (2 Gigawatt-years). [...] This is larger than the entire electricity production of South Australia and an order of magnitude more than the measured energy inputs." The Rossing mine has a lower Uranium concentration (0.03% vs 0.05% by weight) than Olympic Dam and the discrepancy is even larger in the case of Rossing. [...] SLS predict Rossing should require 2.6 Giga-Watt-Years of energy for mining and milling. The total consumption of all forms of energy in the country of Namibia is equivalent to 1.5 GigaWatt-Years, much less than the prediction for the mine alone. Furthermore, yearly cost of supplying this energy is over 1 billion dollars, yet the value of the Uranium sold by Rossing was, until recently, less than 100 million dollars per year. Since Rossing reports it's yearly energy usage to be 0.03 GigaWatt-years, SLS overestimates the energy cost of the Rossing mine by a factor of 80."*

In summary, I see no reason to doubt the POST estimate (POST 2006) of 5-7gCO2e/kWh.

"Nuclear Energy Is Not Sustainable"

What is important is not whether an energy source is 'resilient' or 'sustainable' in isolation, rather whether an energy source contributes to the resilience and sustainability of the whole system.

Conclusions

How Much Can We Do?

An immediate transition to a zero carbon economy could be achieved. For example at peak construction France built over 4GW of power per year. Sustaining 5GW per year for 20 years, we could build one hundred simple and safe nuclear power stations, over the next two decades. These would heat our homes, support our industry and power clean, quiet, electric cars. The cost would be less than what we currently spend on the armed forces. Furthermore, the *additional* cost, would be even smaller.

Climate Change Targets with Renewable Only Energy Are Not Credible

When the oil and gas run out, humanity will need a fuel to turn to. We could exploit the Arctic for tar shales. We could burn even more coal. Yet such options would be catastrophic for the earth and for our future. Nuclear energy is already the best way to fuel Britain. Let's work with the rest of the world to ensure a happy future on Earth for all. And let's keep the Amazon Rainforest, and our green and pleasant land.

Appendix: Response to the Commission for Sustainable Development report on the future of nuclear energy, March 2006.

The commission for sustainable development (CSD) has produced an important and timely report into the UK's future energy needs (Sustainable Development Commission 2006b). It acknowledges that nuclear is a low-carbon technology with an impressive UK safety record, which could contribute to stabilising CO_2 emissions and add to the diversity of the British energy supply. Yet the commission's report argues in the final instance against the construction of a new generation of nuclear power plants. Its overall conclusions must therefore be considered in conjunction with the scientific evidence pointing to ongoing climate change and the necessity for the security of future UK energy supplies.

Climate scientists predict significant environmental consequences such as the shutting down of the Gulf Stream, the collapse of the Amazon rainforest and the irreversible melting of the Greenland ice sheet, unless immediate, sustained, and significant action is taken to curtail the emission of greenhouse gases (GHGs) such as carbon dioxide (CO_2) (Schnellnhuber & Cramer 2006). The CSD, along with all environmental non-governmental organisations, and all three major political parties, accept the importance of the warnings of climate scientists and the relatively short window of opportunity (perhaps one decade) to turn around global habits and avoid 'dangerous' climate change. Such global action should be consistent with, but not limited by, the 1997 Kyoto agreement on climate change and the recent Copenhagen accord.

The UK will probably meet its Kyoto commitments due to the large-scale switch in the 1990s from coal to gas-fuelled electricity generation, which emits less CO_2. Further reductions (the UK aims for a 60% reduction on 1990 levels by 2050) must involve either a) using less electricity b) capturing the CO2 generated in gas turbines to store e.g. in aquifers under the north sea, or c) a large scale switch to a carbon-free source of electricity. In fact, in order to achieve such ambitious targets, it is probably necessary to do all three of these things. Furthermore, given the political concerns and resource constraints connected with gas imported from Russia, it seems that there are significant uncertainties in cost and security of supply, which would count against the reliance on this source of power over the medium and long term.

Nuclear is the only viable non-carbon emitting energy source for secure 24-hour-a-day ('base load') UK energy requirements. Wind power, the main renewable alternative, produces energy only when it is a windy day. It could be an alternative to gas for 'peak' load (when, during the day, electricity demand is particularly high and the wind is blowing) but is simply not reliable enough for base load requirements. Although it could be stored, for example in new pumped storage schemes in Scotland, this adds significantly to the overall cost of a delivered unit of energy. Even wind projects capable of generating a relatively small amount of electricity can attract massive local opposition (perhaps not as much as nuclear on new sites; but the amounts of electricity generated for wind are smaller)At reasonable cost, domestic renewable electricity can generate only about 10% of our total energy (Inter-departmental Analysts Group 2002). Coal with carbon capture and storage cannot yet capture more than about 85% of the total CO_2 from burning coal. In a fossil fuel dominated world all carbon-free energy sources at present compete with fossil fuels - not with each other

The CSD criticises nuclear on the grounds that:

1. it centralises energy supply
2. it undermines measures to reduce energy efficiency,
3. the problem of long term waste has not been solved
4. it is (according to the CSD) impossible to deny nuclear technology to less stable countries if the UK nuclear industry is expanding and
5. there are risks in construction cost which would be borne by the taxpayer.

Yet each of these criticisms is either misguided or not relevant to the issue of the renewal of the UK's nuclear generating capacity.

Making energy use sustainable and decentralising its production are both important and necessary. Yet investment in nuclear power in no way detracts from these initiatives. Even with a future of domestic micro generation of electricity, a significant amount of centrally generated power would always be required for industry, commerce, rail transport etc. Government incentives (taxes and subsidies) to promote efficiency without consumers increasing fuel use elsewhere (e.g. 'carbon taxes') would actually make nuclear energy more rather than less economically attractive.
It is true that the UK has so far failed to find a solution to the long-term disposal of high- and intermediate-level nuclear waste. However, there are geologically suitable sites. A political solution does need to be found for existing and future nuclear waste. But the political decisions, costs, and security requirements for this solution are mostly independent of decisions regarding renewed nuclear power plant construction. (The variable costs and risks of storing extra nuclear waste in a repository are small compared to the fixed and already sunk costs and risks of having to set up such a repository in the first place.) Furthermore, this is all less global risk than using fossil fuels. Great Britain already has a network of nuclear sites (where future reactors would be built) and an existing infrastructure for transporting and temporarily storing nuclear material. A well-funded domestic nuclear energy industry would be on balance more secure and more likely to contribute positively to international stability than either a declining sector or the absence of a nuclear industry in this country.

Great engineering improvements have been made in recent years in both reactor design and use. Such improvements mean that the nuclear industry is now globally competitive. (Sustainable Development Commission 2006b) Reactors of the Westinghouse AP1000 or European pressurised water reactor (EPR) types have already achieved regulatory approval in countries such as the US and Finland. They have a modular design and include 'passive' safety features, reducing both cost and complexity. Construction periods of 5-6 years are possible in the absence of regulator-induced safety modifications.

Current UK nuclear energy capacity is 10GW, of which almost all are older reactors that are scheduled to be retired in the next two decades. Typical UK base load energy requirements are approximately 25GW in summer and 35GW in winter. All of this could potentially be provided by nuclear power.

A renewed nuclear build could involve an initial fixed-cost contract of £2-3bn for 2GW of capacity offered to perhaps both Westinghouse and EPR. The best of the two bids would then be contracted to build the remaining approximately 30GW of base load capacity over the next 10-15 years. Does' ~ ' mean approximately? For such a program, costs of less than £1bn per 1GW power station and construction periods of 5 years or less are viable. If an appropriate regulatory framework is set up, nuclear reactors could be funded privately or through public-private-partnership (PPP) schemes, rather than directly through the public budget. A clear statement of intent would also allow universities and the nuclear industry sufficient time to act to avoid skills bottlenecks.

Large scale concerted practical action amongst the biggest economies (G8 plus China and India) could avoid the worst of the potentially devastating environmental consequences of climate change. These ten countries already have nuclear technology, and could massively reduce their GHG emissions through the renewal and expansion of their nuclear industries. The UK has consciously taken on a leadership role to avoid 'dangerous' climate change, in recent presidencies of the G8 and EU, and in the hosting of an international conference (Schnellnhuber & Cramer 2006). By re-embracing nuclear power now, the UK could both meet its long-term targets and send out a influential and timely message to the leaders of the other major economies.

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A ZERO CARBON ECONOMY WITH NUCLEAR ENERGY[4]

This article, first published in 2006, sets out a practical plan to decarbonize the UK energy system.

It is well known that releasing carbon dioxide (CO_2) into the atmosphere, by burning fossil fuels such as coal, oil, and natural gas, causes an overall warming of the Earth in the `greenhouse effect'.

Scientists estimate that an increase in temperature of 2ºC or more above pre-industrial levels (a common definition of `dangerous climate change') would cause the irreversible melting of the Greenland Icesheet, raising sea levels by 7 metres, widespread desertification, and the collapse of ecosystems that store carbon, such as the Amazon rainforest. We would possibly then further huge quantities of stored greenhouse gases into the atmosphere, producing positive feedback and an even larger eventual temperature rise. On our present course, within a few years we will have committed to such a rise (IPCC 2007b).

To avoid `dangerous' climate change, we must take immediate action to convert to a near-zero emissions economy. To stabilize the climate, global emissions need to fall to 7 billion tonnes of CO_2 per year (1 tonne CO_2 per person per year), which is the amount sequestered by the oceans each year. This compares to current UK emissions of 10 tonnes of CO_2 per person per year.
With the UK taking the necessary actions now, other countries in the rest of Europe, North America, China, and India might also make similar moves. It is feasible to move quickly to a zero-carbon economy and the required investment would have economic benefits.

1. The government should switch from taxing jobs and income to taxing carbon. This would help encourage substantial lifestyle changes aimed at using less energy, particularly in regard to road and air travel. Across the economy we need to use energy much more efficiently
2. We must construct sufficient low-emissions generation for all our energy needs. A large expansion in nuclear energy is required (in the UK, perhaps 100 nuclear reactors of 1GW capacity) using compact, passively safe, modern designs. The government must ensure the education of sufficient numbers of engineers to build these power stations.
3. Electricity price guarantees could be offered to all low-emissions electricity generators. Renewable energy should be used where practical; we must also significantly increase research into this area, and only deploy new coal plants with full carbon capture and storage.
4. We must get ready to transform domestic heating, transport and industry to use and store clean, low-cost electricity instead of burning fossil fuels (e.g. with electric cars). Any new homes must be constructed on an ecologically sound, zero-emissions basis (including heat pumps for domestic heating).

The issue is now urgent. As James Lovelock has pointed out (Lovelock 2004): "We have no time to experiment with visionary energy sources. Civilization is in imminent danger".

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Introduction

United Kingdom energy policy now needs to consider environmental impact, security of supply and cost. It will be argued that nuclear energy is by far the best option, on each of these three criteria, for the UK and for the other major economies of the world.

International agreement on Carbon Dioxide (CO_2) emissions is fraught with difficulties because we face a 'tragedy of the commons' with the private interests of countries diverging from the collective interests of the earth and its inhabitants as a whole. It might be said that countries such as the US and China are unlikely to sign agreements that will not be easy to keep in a highly competitive global economy. To solve this problem, we need an energy source that does not emit CO_2 and yet is attractive for nations that consider only the cost and local impact of generating electricity.

Renewable energy sources may be helpful, especially for those countries whose geography suits them. But due to the constraints of intermittency, land area, and cost, renewables are unlikely to provide the majority of the total energy requirements of the densely populated industrial (or industrialising) major economies.

Nuclear energy, however, can supply a large part of the energy needs of these countries over the next 40-50 years. Uranium is an abundant element on the Earth's crust, requiring little energy to extract, compared to that released in a nuclear reactor. The cost of fuel is a small part of the generating costs.

The scientific evidence concerning the risks from anthropogenic climate change now justifies massive cuts in carbon dioxide emissions. The UK should convert to a near zero-carbon economy in the next 20 years, with nuclear providing the large part of the electricity for all uses, including personal transportation and heating. If the UK were to order 100 new nuclear power stations, and train sufficient engineers to build them, the 'learning by doing' in this global industry would reduce the cost of the technology worldwide. The reduction in price of this environmentally friendly technology should align nations' private interests with the collective interests of humanity as a whole, without the need for global agreement and enforcement of treaties limiting the emission of greenhouse gases.

A collective action problem as difficult as this one requires countries to speak to one another. It requires institutions to be cherished and developed. But it also requires a country, or group of countries to take a lead in solving the problem. The UK, the US and the European Union as a whole need to take a global lead on converting to a zero-emission economy. Nuclear power is the only viable route to such a future.

Reaching UK Carbon Emissions Targets

The United Kingdom government has committed to a reduction of national CO_2 emissions of at least 80% (from 1990 levels) by 2050. Significant progress should be made by 2020. To achieve these targets, the polluter must pay the environmental costs of his emissions. Price increases in carbon dioxide-emitting energy sources will lead to improvements in efficiency and encourage movement to non-polluting alternatives. With appropriate regulatory changes, the UK can ensure a low-cost, early, secure, and orderly transition to a low-carbon economy, enhancing the UK's prosperity and international competitiveness.

This document will argue for:

1. The proper taxation of the environmental costs of carbon-based generation technologies,
2. A clear and consistent regulatory framework that has incentives consistent with the interests of society as a whole for secure and reliable electricity generation, and that aims to reduce risk to consumers and producers of electricity,
3. A sympathetic approach to the initial hurdles faced by renewed nuclear build such as regulatory compliance and first-of-series costs.

Nuclear power stations generate a secure, carbon-free, constant and reliable supply of electricity for 24-hour-a-day ('baseload') UK needs. The UK should make plans for:

1. The replacement of existing coal and nuclear baseload plant with new nuclear capacity
2. Additional expansion so that all baseload needs, or approximately three-quarters of total electricity requirements, are produced through nuclear;
3. In the medium term, a future growth in nuclear generating capacity concurrent with the transformation of other energy systems (industry, domestic heating, transport and storage technologies) to use clean, emissions-free, nuclear energy.

Such a plan, adopted in the UK and the other major economies, is the most practical and low-cost route to avoiding 'dangerous' climate change. In addition, Concentrated Solar Power could also be used.

There have been a number of government environment instruments designed to support non-carbon emitting technologies. After privatisation, a levy was imposed on electricity produced from fossil fuel. From 2002, the fossil fuel levy was replaced by the Renewables Obligation (RO), a system of tradable permits obliging electricity distributors to buy a certain proportion of their energy from renewable sources. A long-term ‘Non-Carbon’ Obligation, including new nuclear build, would reduce the risks and therefore the funding costs for new investors. A level playing field across all non-carbon power sources would allow us to reach our goals at lowest cost.

The European 'Emissions Trading Scheme' (ETS) is designed to cap total emissions so that the EU reaches its Kyoto targets. Once granted, permits to emit can be traded. This system ensures economic efficiency and, depending on the mechanisms of allocation, can avoid disruptive financial transfers. The ETS has been applied in the UK to industrial users of fossil fuels, with domestic users and electricity generation exempt at present. All parts of the economy should in principle be covered by either the ETS or an equivalent carbon taxation scheme. In particular, ETS should be extended to aviation, and CO2-emitting electricity should fall under the ETS or similar domestic 'carbon tax'.

With the full application of appropriate taxation/permitting, the cost of CO2-emitting energy, as seen by final users, will rise. The demand for such energy would therefore fall, reducing overall UK emissions. Revenues from the ETS or energy tax could be used to efficiently subsidise non-carbon generating energy sources, so that industry is close to financial balance (on energy-related payments) with the government. The electricity regulator should also make sure that domestic and commercial energy consumers always have the ability to choose a low-carbon energy supplier and should take the lead in choosing such suppliers within the public sector.

Delivering Secure Energy

Electricity supply remains a complex industry where regulatory structure is critical to final outcome. Over the last two decades, the England and Wales electricity generating market has been privatised and deregulated. Between 1990 and 2001 the electricity 'Pool' existed to balance supply and demand. Energy prices were based on the cost of generation at the marginal power station plus a payment for available capacity. In 2001, the 'New Electricity Trading Arrangements' (NETA) were put in place, with a system of bilateral contracts between generators and distributors/consumers.

The United States provides an important example of the potential pitfalls of deregulation. The last few years have seen a number of interruptions, imposing huge costs on consumers, industry and the US economy as a whole. The state-by-state process of deregulation has now ground to a halt, some states having been 'deregulated', others remaining regulated but not nationalised. Whilst excess demand exists mainly in the deregulated states of the eastern seaboard of the US, the building of new electricity capacity has mostly been in regulated states of the mid-west.

One important lesson is that, although deregulation has reduced energy costs for consumers, it may not ensure sufficient capacity in the long term. It is interesting to note that even now the UK imports some electricity from France, the country with the largest nuclear sector and with the lowest electricity prices in Europe. The economics of new build, in particular of baseload plants such as nuclear, are more favourable with the certainty, and lower funding costs, of a more stable, regulated market environment.

The UK has traditionally generated electricity from a variety of fuels – primarily coal, and gas from the North Sea (historically, produced domestically) and uranium (produced by geopolitical allies). This will change if, as currently projected, the UK switches to a reliance on imported natural gas. In addition to being used in industry and the home, natural gas presently supplies about 40% of UK electricity. This is projected (DTI) to rise to 60% by 2020. Future natural gas requirements cannot be met from the remaining North Sea gas reserves alone: the UK, like the rest of Europe, will need to import gas from Russia, Algeria or Central Asia, areas not noted for their geopolitical stability. The potential economic and human costs associated with withdrawal of the major energy source are very significant indeed.

With the current market structure, wholesale electricity prices are subject to the volatility of the price of gas. In recent times, the price of gas has risen significantly, driving up the price of electricity too. Individuals or companies who might be able to use either, in reality have little ability to diversify when energy prices are high. Thus in the deregulated, gas-dominated, scenario, considerable supply and price risk is faced by UK fuel consumers.

In the present regulatory framework, the risks for a potential investor in new gas capacity are low, compared to the risks in baseload power plants, such as coal or nuclear. For any business, risks are minimised if revenue streams are well matched with costs. This is the case with gas, since revenues from wholesale electricity sales on spot markets are volatile but well correlated with the cost of gas. Significantly, due to the nature of limited liability companies operating in rapidly changing markets, the long-term benefits of secure energy supply are not fully captured by free-market mechanisms.

Society as a whole can be fairly sure of its need for reliable carbon-free energy over the next 45 years. Arguably, there is a significant negative externality associated with the dominance of imported gas in the UK electricity supply. The most straightforward way of internalising this cost would be to impose an additional tax on electricity produced by gas relative to that produced from (more securely sourced) coal and nuclear. Since gas emits approximately half as much carbon dioxide as that produced through coal, a simple (but admittedly fairly arbitrary) measure would be to raise the tax per kWh on electricity produced by burning gas to the same level per kWh as that imposed on electricity from coal. A non-carbon obligation expanded to include new nuclear capacity would also have the effect of limiting the dominance of gas.

Issues Specific to Nuclear Energy

A nuclear power station supplies energy reliably, at almost-fixed costs, for its lifetime of four or more decades. With its stability and high energy density (in contrast to say natural gas), many months- or years-worth of unenriched Uranium can be stored safely and easily. Such a strategic reserve can easily be converted to nuclear fuel domestically when required. A nuclear-dominated electricity industry would allow low and stable electricity prices, and provide energy diversity for industrial and domestic consumers. An initial nuclear build should aim to replace the retiring nuclear and coal generation with new nuclear power stations. In the medium term, nuclear energy can cover all baseload electricity demand.

Nuclear energy has in general low fluctuation in its cost of generation. Fuel costs are only a small part of generating costs, and operation and maintenance costs are fairly predictable. Nevertheless, the potential investor faces high risks in a deregulated and short-term market place, because capital costs are high and revenue streams potentially volatile (because the electricity price is potentially volatile). The government is itself also the source of many of the perceived risks associated with new nuclear build and could mitigate such concerns by detailed work with potential investors. The government could also guarantee minimum prices or investigate other ways to encourage very long-term electricity contracts.

Great engineering improvements have been made in recent years in both reactor design and use. Such improvements mean that the nuclear industry is now globally competitive. Reactors of the Westinghouse AP1000 or European pressurised water reactor (EPR) types have already achieved regulatory approval in countries such as the US and Finland. They have a modular design and include 'passive' safety features, reducing both cost and complexity. The UK should set in train the regulatory approval of these reactors to avoid late modifications to design. Typically, any first-of-series new reactor will be significantly more expensive than nth-of-kind. The removal of these uncertainties justifies significant government help for the first-mover, perhaps in the form of a production tax credit payable by the government over the first few years of generation. (Ansolabehere et al. 2003)

The costs of decommissioning are becoming clearer with the experience gained from the decommissioning of the Magnox generation of nuclear reactors. Future decommissioning costs are likely to fall, with efficiency gains coming with experience and those for new reactors much lower, because of the simplifications of 'passive safety' designs.

The management of nuclear waste is the responsibility of the government. At present a long-term solution has not yet been found to the problem of high- and intermediate-level nuclear waste. Nevertheless, political decisions, costs, and security requirements for this solution are mostly independent of decisions regarding renewed nuclear power plant construction. The variable costs and financial risks of storing additional nuclear wastes in a repository are small compared to the fixed and (effectively) already sunk costs and finanial risks of having to set up such a repository.

Great Britain already has a network of nuclear sites (where future reactors would be built) and an existing infrastructure for transporting and storing nuclear material. British Energy now runs some of these nuclear sites; others remain in government hands. The government should set up a 'bank' of approved sites for potential new investors in nuclear power stations.

In order for a 'nuclear renaissance' to take place, a large number of nuclear engineers (more than 20,000) must be trained. This requires university and on-the job training. Skills could prove the main constraint to nuclear expansion. The government should immediately put in place a system of university ‘sponsorship’ of young engineers, similar to that used to train engineers for the armed forces. A clear statement of intent would allow universities and the nuclear industry sufficient time to act to avoid bottlenecks.

Nuclear power has traditionally suffered from a negative public perception due to its association with the awesome destructive power of the atom bomb. Yet the civil nuclear industry has an enviable safety record in this country, with no major incidents in its history.

The strong and well-engineered containment buildings of the current generation of reactors (metres-thick reinforced concrete), along with the small size of the reactor building and other security measures, provide very solid protection against terrorism. The transport of nuclear materials similarly takes place in very secure containers.

An average air hostess receives a higher level of radiation than her colleague in the nuclear industry. The nuclear industry implicitly values human life more highly than almost any other industry. It is important that the government ensures that public is well informed on these issues.

Other Low Carbon Technologies

There are a number of other potential technologies (apart from nuclear) that provide energy while emitting little if any carbon dioxide. These include renewable energy and technologies for storing carbon dioxide underground (sequestration).

Given the geography of Britain and the present costs of the various renewable technologies, wind is seen as the main alternative to fossil fuels and nuclear. Yet wind turbines produce energy only when weather conditions are in its favour. The overall costs of generating electricity through wind are high, because the vicissitudes of the weather necessitate a large amount of 'back-up' capacity (gas). However, an electric generator cannot be turned on with a snap of the fingers. It must be brought up to speed and synchronized with the grid before it can be thrown on-line. This takes time. In order to meet the back-up requirements of a field of wind turbines, the back-up generator must already be turning and synchronized. This is sometimes called a "spinning reserve". Under NETA the costs of intermittency are explicitly considered and the government now pays a substantial subsidy towards wind energy.

Wind projects capable of generating only a relatively small amount of electricity have encountered massive local resistance. Offshore wind, whilst preserving the natural aesthetic, is even more expensive than onshore wind, and interferes with the UK's coastal radar. Even on the most optimistic projections, wind will account for less than 10% of total energy usage by 2020.

Other renewable sources of energy include hydroelectricity; wave power; (conventional) solar thermal (e.g. for water heating) and solar photovoltaic cells (PV); tidal power and biomass. Hydroelectricity is not a serious option except in Scotland where it is already used. Wave energy is also a presently undeveloped technology, currently not at a level where it could be used in a widespread fashion. Solar electricity in general is less suited to the UK, than countries closer to the equator. Photovoltaic cells (PV cells) in particular are an immature technology with costs per kWh far greater than conventional alternatives and require significant amounts of energy in their fabrication.

There is one suitable site for tidal power, the Severn Estuary, which is worthy of serious consideration. Such a project faces similar issues to renewed nuclear build (financing costs, regulatory framework and uncertainty over future electricity prices). However, since the planning and construction issues are different, and the electricity supply changes periodically with the tides, this project would not be a direct competitor to renewed nuclear build.

Vegetable oil could help at the margins as a fuel for transport, and wood could potentially be burnt to generate electricity. (Trees at the edges of motorways would also reduce noise.) However, there are energy costs in growing, harvesting, transporting, and extracting such fuels, as well as pollution of other forms. This subtracts from their environmental attractiveness. Cost and, ultimately, land constraints will prevent biomass from being the major source of energy in this country, although it could be deployed elsewhere where conditions are suitable.

In general renewable sources are presently incapable of providing significant electricity supply to allow us to fulfil our CO2 emission targets in the UK.

In the short-to-medium term, electricity produced by gas and coal will remain an important part of the UK energy mix. Technologies are currently being developed to store CO2 underground, in porous rocks with non-porous caps such as those previously containing natural gas. Such technologies will only become economic, if at all, when generators of electricity pay the costs of emissions. There should be a level playing field for all non-carbon generators. If, and when, it can be demonstrated that carbon capture is permanent and that CO2 will remain underground for the next few centuries, then electricity produced with CO2 captured, should attract no carbon tax. Additional help on regulatory issues and first-time costs would also be justified.

Globally, it makes economic sense to invest in improving technologies early, so as to reap the technological improvements possible as technologies mature. Furthermore it is sometimes possible for a country to develop particular expertise and competitive advantages in certain industries. Nevertheless, it is important to keep in sight the definite goals the UK has set itself. Renewable subsidies could potentially be huge in the current decade, without having a serious role in avoiding dangerous climate change. Nuclear energy, with very low life-cycle carbon emissions, could single-handedly generate most of our electricity by 2020-25. With the lower costs of established reactor designs, it could subsequently start to replace fossil fuels in other sectors.

Domestic Heating

It is important that each house is adequately heated, and that the vulnerable in society are protected, especially in winter. Yet this need not conflict with a general rise in carbon-based energy prices. Efficiency improvements are likely to be 'spent' on further energy use unless they are accompanied by price rises (see below). Government income transfers to the needy can help cushion the pain of higher carbon-based energy prices.

For domestic users, there has been a political need to assuage concerns over fuel poverty. Fuel prices have been kept low, with domestic energy supplies falling under a reduced rate of Value Added Tax (VAT). It would be natural that some or all of the money raised by the increase in energy taxes be used to mitigate poverty particularly for pensioners. Any such assistance should be made in terms of a general increase in payments to all poor pensioners (such as an increase in pensions or in the ‘cold weather’ winter payment), rather than a rebate on energy bills. Further tax concessions could be offered on energy-efficient devices and home insulation and regulations improved on new and existing houses. The government and local authorities should ensure each house is as well insulated as possible.

Every citizen should be careful not to overheat his home. A 1°C increase in temperature corresponds to a 7% increase in heat consumption, a fact that could be conveyed to the public in information campaigns. The government should ensure current building regulations are enforced and provide clear guidelines over the optimal temperature for domestic heating.

Energy Efficiency

There is clearly great potential to improve energy efficiency in UK and other countries. Energy efficiency may be a relatively inexpensive way of reducing emissions. Yet the most effective way to encourage efficiency in a market-based strategy is a general rise in the price of CO2-emitting energy. In the industrial and domestic sectors, subsidies for energy efficiency may also be required.

Measures to improve efficiency are likely to be ineffective without price rises, as technological efficiency improvements may 'rebound' or even 'backfire'. Some or all of energy savings from better efficiency are often spent in increased energy use. ("It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth… Every…improvement of the [steam] engine, when effected, does but accelerate anew the consumption of coal". (Jevons 1879)) Transport provides an important example of this principle. Improvements in the fuel efficiency of aeroplanes may lead to a reduction in the price of aviation and therefore more people flying. Large-scale reductions in emissions are therefore impossible without higher taxation or permitting using the ETS.

There has been a wish to keep large carbon-emitters such as heavy industry in the EU, rather than to see these industries migrate to countries in the developing world with much less stringent environmental considerations. Current environmental obligations are not thought to cause significant 'leakage'. However, if the rate at carbon taxation were to rise significantly (e.g. to, say, £160/tC = £20/bbl in order to reach the UK's CO2 goals), this might become a concern for industry. The effect of higher energy prices could be mitigated in the following ways:

(a) Taxation would occur only on CO2 emitting energy sources. Industrial consumers would have an alternative to fossil fuels in nuclear-generated electricity and might be able to negotiate favourable long-term contracts for such energy. Carbon taxation would likely rise over time, but industrial consumers would have sufficient time to migrate; (b) 'Grandfathering' (compensating individuals and companies for additional cost of permits, according to historical use) and other similar approaches to emissions permitting, would encourage people to make reductions in emissions while avoiding large scale net financial transfers; (c) Experience in the Nordic states suggests it is possible to employ different taxation rates for industrial and service sectors.

Typically, energy is not a large part of costs in service industries. However, companies would be encouraged to improve energy efficiency by an increase in the costs of energy, as well as by information campaigns. The government could introduce certain standards (including turning off electronic equipment overnight) implemented alongside health and safety regulations. An energy-efficient company might consider it good public relations to be recognised as such.

Finally, very long-term electricity contracts for the public sector's requirements may be a way to guarantee price stability, as well as helping the electricity industry develop. Schools, hospitals, prisons, civil service offices each have a responsibility to ensure that they are as efficient as possible in their use of energy.

Transmission & Distribution

New nuclear plants would be built at existing sites in first instance. These are well distributed across the UK, although they tend to be on the coast (for cooling water) and away from major centres of population. Existing transmission networks would need to be maintained and improved. Upgrading the distribution grid is an essential consideration in planning future energy supply.

International Linkages

Avoiding dangerous levels of climate change will require huge and concerted global action on a number of fronts simultaneously. One way of looking at the required change in behaviour is the concept of a 'stabilization wedge' (Schnellnhuber & Cramer 2006). Each 'wedge' represents 1 Gigatonne (billion tonnes) less Carbon emitted per year by 2055. It requires seven such wedges (in addition to present trends) to keep CO2 emissions at current levels and thus stabilise atmospheric CO2 concentrations at the 'safe' level of 500 ppm. Socolow and Pacala provide 15 such 'wedges', all technically feasible. For example: a) stopping deforestation, and doubling the rate of new tree plantation; b) halving car use; c) adding 50 times the current capacity of wind turbine. One 'wedge' would be provided by merely doubling nuclear energy world-wide (an additional 700GW of capacity).

There should be a much greater use of nuclear power, so that it provides the majority of the electricity supply in the major economies (G8 + China and India) over the next 50 years.

The main stumbling block to international agreement on climate change has been the US's US' reluctance to engage in international agreements that it cannot easily keep. If there were significant investment in nuclear power plants, it might find easier to agree to a successor to the Kyoto protocol. The US has an aversion to central environmental taxes. However, it has a long history of industrial innovation and appropriate regulation of free market activities. Parts of the deregulated US market have been based on the UK model.

In the absence of American leadership on climate change, it falls to the others to take the lead on this issue. The UK has a key role to play to show that it can be in the self-interest of a nation to facilitate new nuclear power plants and in the interest of market investors to build them, even in the absence of new international agreements. By ordering one of the new reactor designs (such as the Westinghouse AP1000) this would reduce uncertainties for future investors in nuclear energy in the UK and US, and therefore potentially make a big difference to the final extent of global warming.

China will require a vast amount of electricity (perhaps 1000GW of capacity) over the next decade. At present, China has 4GW of nuclear on order, but is desperate to secure further energy supplies to further its expansion needs. India is also building a small number of new reactors. Given global concerns over climate change and proliferation, it is important that the US and EU maintains strong relations with China and India and that the technology used is of the most up-to date design.

The European Union has recently begun an energy review of its own. Recently, Finland has become the first Western country to begin a new nuclear reactor. France provides a good example of a clean, safe, and efficient nuclear industry providing the majority of electricity needs, and also has plans to build the European Pressurized water Reactor (EPR). If the UK were to support this new reactor, then this might lead to an overall change in behaviour across Europe. (For example, Sweden too has recently adopted a reduction of 60% in CO_2 emissions by 2050. These targets are to be commended but are probably insufficient to stop climate change.)

A well-funded domestic nuclear energy industry would be on balance more secure and more likely to contribute positively to international stability than either a declining sector or the absence of a nuclear industry in this country. In terms of international linkages it is important to develop technologies that can be exported safely to the other major world economies, and to consult on such matters with our partners in continental Europe and America. Reactor regulation could be done on a Trans-Atlantic and/or pan-European basis. The UK should be relaxed towards civil nuclear technology transfer within the major economies.

The UK has a strong internationalist outlook and has consciously taken on this issue in recent residencies of the G8 and EU. By re-embracing nuclear power now, the UK could both meet its long-term targets and send out an influential and timely message to the leaders of the other major economies.

New Technologies in Transport and Heat Generation

Electricity production is currently only 35% of total carbon dioxide emission. In order to reach our target of a more than 60% reduction in overall CO_2 emission, we also need to consider the other parts of the economy. Given that there exist sectors with little prospect of becoming carbon-free (e.g. aviation, some heavy freight without rail connection. and some parts of industry), electricity generation needs to emit almost no carbon dioxide, and other sectors should, where possible, be largely carbon-free.

Aeroplanes, cars and heavy goods vehicles impose further significant external effects on other users of both urban and rural areas. In particular, these forms of transport cause noise, congestion, local air pollution, and require infrastructure that is often unsightly. A shift to low-carbon forms of transport (new high-speed rail lines for intercity and long distance travel, enhanced mass transit systems for suburban and commuter lines, and electric cars for rural and other travel) would also mitigate these other problems., if the electricity comes from low-carbon sources. Electric cars rather than carbon-fuel cars could be encouraged by tax credits on electric cars and by waiving urban parking fees and congestion charges (and increasing the cost for non-electric cars, so that the net financial balance with the government is zero).

In general, the domestic transport sector (cars, buses and trains) should be run using carbon-free energy, where possible. Trains should be almost completely electrified, buses replaced by trams where possible. It is more likely that cars will be powered by batteries rather than hydrogen fuel cells, especially for short distances of up to 200 km per day. Batteries can be recharged by nuclear electricity overnight, when there is little other demand. To the extent that hydrogen fuel cell cars are developed at all, the hydrogen will be produced by nuclear energy using electrolysis or thermo-chemistry.

'Heat pumps' are an important way of heating homes and other buildings. These devices move heat from outside to inside a building. This process requires between 50 and 80% less energy than direct heating. Of course if electricity is produced using nuclear, then the CO_2 emissions are reduced further still. Financial incentives could be used to encourage the wide-scale transfer to heat pump technology.

The conversion of electricity production to nuclear is the single most important step to reaching our CO_2 targets. Without this, both electric cars and heat pumps would still contribute to global warming. It will take at least 10 years before new nuclear plants are complete (due to planning and construction delays). Nevertheless, moves to convert heating and transport should be started immediately, in order that the technology and infrastructure are mature and pervasive once new nuclear capacity comes on line.

The transfer to a near zero-carbon economy can be relatively costless. It does, however, require a large transfer of resources towards domestic capital investment and away from the import of scarce supplies of oil and natural gas.

Conclusions

Climate change is perhaps the biggest and most intractable problem humanity has yet faced. Scientists predict severe consequences unless immediate and sustained action is taken to limit and reduce carbon dioxide emissions. Solving this problem will require a massive and immediate expansion in the nuclear industry in the densely populated, predominantly urban, major economies. The UK has adopted a leadership role on climate change. In order to fulfil this role and have a chance of preventing dangerous climate change the UK should immediately make plans for a conversion to a 'zero carbon economy', with completion of this goal by 2020-2025. Nuclear is the only fuel source, which can provide the large part of our requirements. The reduction in price of the technology (due to 'learning by doing') would compensate for any increase in the resource prices and potentially could encourage nuclear to be adopted in the other large economies such as US and China. This course of action can prevent massive climate disruption and the resulting human and ecological damage.

Action Points

1. Climate scientists predict significant and irreversible environmental consequences unless immediate, sustained, and significant action is taken to curtail the global emission of greenhouse gases (GHGs) such as carbon dioxide (CO2). These consequences include the shutting down of the North Atlantic thermohaline circulation (Gulf Stream), the collapse of the Amazon rainforest and the irreversible melting of the Greenland ice sheet (Schnellnhuber & Cramer 2006). All environmental non-governmental organisations, and all three major British political parties, accept the importance of the warnings of climate scientists and the relatively short window of opportunity (perhaps one decade) to turn around global habits and avoid 'dangerous' climate change. Such global action should be consistent with, but not limited by, the 1997 Kyoto agreement on climate change.
2. The Kyoto Protocol commits the EU to average emissions in the period 2008-2012 of 92% of 1990 levels (the UK's target is a reduction of 12.5% on 1990 levels). The UK will meet its Kyoto commitments due to the large-scale switch in the 1990s from coal to gas-fuelled electricity generation. Further reductions must involve both using less energy and a large-scale switch to carbon-free sources of electricity. Effective action to slow down climate change to 'safe' levels is impossible without a significant expansion in the nuclear industry. In Britain, renewable sources are too intermittent, uneconomic, or are inappropriate to our geographic conditions, and so cannot generate a large part of our energy needs.
3. Electricity generation and aviation should be part of the EU carbon trading scheme. There should be a preference for non-carbon emitting sources of energy (rather than simply renewable), enacted in a 'Non-carbon obligation'. Energy savings should be made in the home and wind turbine generation encouraged in windy areas. Energy efficiency could be encouraged by reductions in tax on highly efficient appliances.
4. The UK government has indicated that any new nuclear build will take place within the private sector. The England and Wales electricity generation and supply industry was one of the first to be deregulated and is one of the places where deregulation has developed the furthest. The decision over nuclear is therefore not one of command and control; rather it is one of appropriate regulatory framework. Such a framework should properly account for society's concerns over emissions and security of supply and should aim to minimise price risk to both consumers and producers of electricity. Important measures to limit such risk may include long-term price guarantees, forward-looking carbon taxes, and the reintroduction of so-called 'capacity payments' within the electricity market.
5. The UK should ensure that the regulatory hurdles and financial risks for first-of-series build are minimised. It should ensure the safety regulation process is efficient, and should liaise with European and US licensing authorities to ensure consistency. It should set in process the planning procedures to provide a 'bank' of suitable nuclear sites (mostly where there are existing nuclear facilities), for both EDF and other potential investors. It should provide financial help to pay for the costs of 'first of series' build, perhaps in the form of tax credits payable in the first few years of generation. The UK should take a full role in the research of a next generation of nuclear fission reactors including fast breeder reactors and high temperature reactors. Universities and the nuclear industry should be given a clear statement of intent to massively increase the number of nuclear engineers and so to avoid skills bottlenecks.

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THE COST OF ELECTRICITY GENERATION[5]

A consistent methodology is outlined for calculating the cost of 26 electricity generation technologies globally.

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Overview

Summary

This document describes the estimation of the parameter values of the Energy Technology subModel (ETM), in particular the matrix “Technical Characteristics of Energy Technologies” (TCET). The cost and other technological characteristics of 28 electricity generation and other technologies were estimated.

Functions indexing and adjusting the cost of generating electricity by region and time, and calculating the levelised cost of generating electricity are defined and implemented in an Excel spreadsheet *TCET-New.xl*s.

This paper updates and expands on the work of Anderson & Winne (2003; 2004) and Barker (2007).

Report Topic

This report concerns the parameter values of the *Technical Characteristics of Energy Technologies* (TCET) matrix, used in the *Energy Technology subModel* (ETM) of the sectoral model E3MG. This report will focus on the *capital (investment)* costs, *operation and maintenance, fuel* costs and *learning rates*.

Report Audience

This report is intended, in the first instance, to be internal to members of 4CMR and Cambridge Econometrics (CE).

Report Purpose

This report will describe the data collection process in estimating the TCET matrix, the data sources used, and the final results of that process. This report has been put together specifically because the TCET matrix is being updated in the other models, namely E3ME and MDM. To avoid duplication of effort and inconsistency, this report present the data collection work already completed.

Report Type

This is a technical report providing background on the data used, estimation methodology and the justification for the values adopted. This material is a working paper and is not intended in the first instance for journal publication.

What Technologies are covered in the ETM?

There are 26 different energy technologies covered[6]. ETM is primarily a model of *electricity generation technologies*. Each technology is defined in technological terms (rather than by fuel). These technologies do in general have a single input fuel; however, this could vary by region.

In addition to pure electricity generation technologies, there are various technologies which have a component of electricity generation, but also another function or are associated with electricity generation in some way. These are as follows:

- It also considers low grade *heat* associated with thermal electricity generation (as could be used in CHP, industry or desalination) and *distributed fuel cells* but not domestic gas boilers and heat-pumps (these are considered in the domestic sub-model).
- It includes electricity *storage* (electric flow batteries, pumped storage) and hydrogen production but not *transport*. Electric cars, including plug-in hybrids, are dealt with in the transport sub-model.
- It includes Carbon Capture and Storage, including *negative carbon* technologies such as Biomass with CCS (BECS), which produces electricity and Air Capture, which does not.
- It deals with *transmission*.

Use of Technical Characteristics of Energy Technologies in The Model

There are two major matrices which define the cost of technology within ETM. Firstly, the two dimensional matrix Technical Characteristics of Energy Technologies (mTCET): this matrix includes the median estimates of each parameter value in our model. Secondly, the TCET matrix is transformed into a three dimensional array, BEWK, which includes variations across regions.[7]

6 These are outlined in detail in appendix 1.

7 The matrices have the following specification:

```
!TCET NTCxNET:technicalcharacteristics(region-independent),variousunits,
!BEWK NETxNWRxNTC:ETcharacteristics,variousunits,yearandyear-end
```

Where the dimensions of the matrices are:

```
!NTC:numberoftechnicalcharacteristics(TC)fornewenergytechnologies(ET)
!NET:numberofenergytechnologies(ET)
!NWR:numberofworldregions
```

Data Sources & Methodology

There are 23 primary technical characteristics in the new TCET matrix. An additional 17 characteristics (making 40 in total) have been also been estimated for clarification and further information; these are not used directly in E3MG.[8]

Methodology By Technical Characteristic

The methodology adopted for estimating each of the parameter values differs according to the data availability.

Parameter	Data Availability	Methodology
Capital Cost	Excellent	Simple Average Across Studies[9] [10]; Adjusted for Time and Country
O&M	Moderate	Expert Estimate based on comparing a small number of studies
Learning Rate	Good	Expert Estimate of capital cost curve based on comparing a small number of studies and integration of time and capacity information
Efficiencies	Moderate	Expert Estimate based on comparing a small number of studies
CO2 Emissions	Excellent	Implicit from the carbon content of fuels (elsewhere specified) and the efficiencies of the energy technologies
Non-CO2 Emissions (SOx, NOx etc)	Poor	Old data used
Full Lifecycle Greenhouse Gas Emissions	Good	Parliamentary Office of Science and Technology (POST)

Data

There are four main classes of information sources.

1. Survey data from the International Energy Agency document "The Cost of Electricity Generation" (IEA 2005) (base year 1st July 2003).
2. Data from Energy Technology Perspectives (IEA 2006), from the US NEMS model (EIA 2007b; EIA 2007a)and from a recent EU (Strategic Energy Technology Plan) study (EU 2007).
3. Other recently published peer-reviewed articles.
4. Estimates used in the Markal model.
5. The studies that were used as input to the UK Markal team.

All the data was compiled into a master database, with information on the costs of all the generating technologies. Each of the studies was treated as one datapoint, except the IEA (2005) data, where each of the input estimates is treated as a single data point.

8 For details of these characteristics, please see Appendix 3.
9 We assume the logarithm of the costs are drawn from a normal distribution with unknown variance. Under common Bayesian assumptions, the posterior distribution of log(costs) is a t-distribution with n-1 degrees of freedom, where n is the sample size. The mid points quoted are the anti-log of the mean of this distribution (ie e^{μ} where μ is the mean of the posterior distribution of Ln(Capital Cost)).
10 For a discussion of how uncertainty from all sources is implemented in the model please see appendix 1.

Primary Data Sources *(IEA 2005; IEA 2006; IEA 2008; EU 2007; EIA 2007a; EIA 2007b)*

Source	Reviewed	Data used	Summarized	Document title	Author	Date of publication
IEA (2005)	Yes	Yes	Yes	Projected Costs of Generating Electricity, a 2005 update	IEA	2005
IEA (2006)	Yes	Yes	Yes	Energy technology perspectives (2006)	IEA	2006
IEA (2008)	Yes	Yes	Yes	Energy technology perspectives (2008)	IEA	2008
EU (2007)	Yes	Yes	Yes	A European strategic energy technology plan	EU	2007
EIA	Yes	Yes	Yes	NEMS Model Documentation - Presentation from IEA/DBerr CCS Workshop	EIA	2007

Minor Studies (El-Kordy et al. 2002; Harding 2007; Winters 2007; Gibbins & Chalmers; Sims et al. 2003)

Source	Reviewed	Data used	Summarized	Document title	Author	Date of publication
DBerr/IEA CCS Workshop	Yes	Yes	Yes	Feedback from CCS workshop held late 2007	Various	2007
Harding	Yes	Yes	Yes	Economics of nuclear power and proliferation risks in a carbon-constrained world	Harding	2007
El-Kordy et al	Yes	Yes	Yes	Economical evaluation of electricity generation considering externalities.	El-Kordy et al.	2002
Winters	Yes	Yes	Yes	Electric Supply Options in a World Driven by CO2 Emission Policies	Winters	2007
Gibbins and Chalmers	Yes	Yes	Yes	Carbon capture and storage, Foresight Document	Gibbins and Chalmers	2004
Andersol	Yes	Yes	Yes	Concentrated Solar Power Data for the Andersol 1 Plant	Andersol	2006
Sims	Yes	Yes	Yes	Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity	Sims	2002

Source	Reviewed	Data used	Summarized	Document title	Author	Date of publication
				generation		

UK (Markal Team) Data Sources (full reference provided in Markal team documentation)

Primary sources	**Reviewed**	**Data used**	**Summarized**	**Document title**	**Author**	**Date of publication**
RAE	Yes	Yes	Yes	The Costs of Generating Electricity: A study carried out for the Royal Academy of Engineering	PB Power (for RAE)	2004
WNA	Yes	Yes	Yes	The New Economics of Nuclear Power	World Nuclear Association	2005
OXERA	Yes	Yes	No	Results of Renewables Market Modelling	OXERA	2004
ECN	Yes	Yes	No	Characterisation of Power Generation Options for the 21st century	ECN Policy Studies (Lako and Seebregts)	1998
ICEPT	Yes	No	Yes	Alternative fuels for transport and low carbon electricity generation: A technical note	Robert Gross and Ausilio Bauen	2005
SDC	Yes	Yes	Yes	Economics of Nuclear Power: A report to the Sustainable Development Commission	University of Sussex and NERA	2005
WADE	Yes	Yes	Yes	Decentralising UK energy: Cleaner, cheaper, more secure energy for the 21st century: application of the WADE economic model to the UK economy.	World Alliance for Decentralized Energy (on behalf of Greenpeace)	2006
Carbon Trust	Yes	Yes	Yes	Future Marine Energy: Results of the Marine Energy challenge: cost competitiveness and growth of wave and tidal stream energy	Carbon Trust	2006
RCEP	Yes	No	No	Biomass as a renewable energy source	Royal Commission on Environmental Pollution	2004
Enviros	Yes	No	Yes	The costs of supplying renewable energy	Enviros Consulting Ltd (for DTI)	2005
IEA	Yes	No	No	National Survey report of PV power applications in the United Kingdom	International Energy Agency	2004

UKERC	Yes	No	No	The Costs and Impacts of Intermittency	UK Energy Research Centre	2006
AEA	Yes	Yes	No	Options for a Low carbon future: appendix E (energy white paper modelling)	AEA Technology	
PSIRU	Yes	No	Yes	The Economics of Nuclear Power: analysis of recent studies	Steve Thomas (PSIRU)	2005
Secondary sources *	** Secondary sources are those referred to in primary sources.*					
Chicago		Yes	Yes	The Economic Future of Nuclear Power	University of Chicago	2004
MIT		Yes		The Future of Nuclear Power: an interdisciplinary MIT study	Massachusetts Institute of Technology	2003
DGEMP		Yes		Energy Baseline Scenario for France to 2030	General Directorate for Energy & Raw Materials (France)	2004
T&R		Yes			Tarjanne and Rissanen	
T&L		Yes		Research report: Competitiveness comparisons of electricity production alternatives	Tarjanne and Luostarinen (in Finnish)	2003
CERI		Yes			Canadian Energy Research Institute	2004
Scully		Yes		Business case for new nuclear power plants: bringing public and private resources together for nuclear power	Scully Capital (for the US Department of Energy)	2002
Areva		Yes		EPR Background and its role in Continental Europe	AREVA	2005

Basis

In order for the parameters to be fully defined, we need to choose a convenient monetary, time, geographical and energy basis.

Nominal/Currency Base

The initial calculation estimates costs and other financial quantities in US Dollars of 1st Jan 2000.

Reference Cost Year

The cost of capital equipment varies over time, depending on supply and demand for raw materials and labour, and technological learning. Our costs are estimated to be correct for a reference year of 1st Jan 2000.

Reference Capacities

Future costs of an energy technology are a function of the cumulative investment in that technology. The initial cost C at our base year t_{base} is a function of the cumulative investment in energy capacity at our base year: $C= C(I_{t_{base}})$.

Energy Basis

All energy is measured according to the Net Calorific Value, NCV (Also known as: Lower Heating Value (LHV)), consistently with the energy data (Enerdata) used in the model.

The net calorific value energy content of a given mass of fuel will be numerically less than its gross calorific value equivalent.

NCV electrical efficiencies will be correspondingly higher than GCV efficiencies. For example, a supercritical coal plant might have a Lower Heating Value (LHV) efficiency of 45%; an equivalent gross heating value efficiency would be 40%.

Time and Geographical Indexation

Time Indexation Methodology

The IEA study presents information approximately consistent with capital costs in 1st Jan 2000, in 1st Jan 2000US$. Cost estimates are indexed to the present using the Chemical Engineering Plant Cost Index (CEPCI) (CECPI 2007; Chemical-Engineering 2007a) (Consistent with the Marshall and Swift Index for used equipment (Chemical-Engineering 2007b)). More recent electricity cost data (Sims et al. 2003) was also used. (*Reference dates for compared studies vary).

By indexing with the CEPCI and US CPI, the spreadsheet also has the functionality to refer to any Nominal Currency year and any Cost Year.

Regional Effects

In order to adjust for relative costs, relative cost information and exchange rates were used. This information was recovered from the World Bank (World-Bank 2005).
The relative cost numbers used were an average of the cost for capital goods and those of construction goods. A weighting of 50% for equipment and 50% for construction was estimated for . Further work would integrate this with the exchange rates

Implementation in the TCET Spreadsheet

The front page allows one to choose the characteristics for any currency and any country and any year 2000-2008.

Net Present Value & Levelised Cost Calculation

This section goes beyond what is required for the ETM. It describes an analytical method for calculating the levelised cost of electricity production.

Cost Components

We assume that there are the following sources of costs:

- I: Unit Investment Costs
- I*: Infrastructure or Back-end or Other System Costs
- O_F: Non-fuel Operation and Maintenance (Fixed)
- O_V: Non-fuel Operation and Maintenance (Variable)
- F: Fuel Costs
- CT: Costs of Carbon internalised by an additional tax or cost of permits

There is a single source of revenue

- R: Revenue from Output Electricity

Discount Rates

Discount Rates are given exogenously in the model. We replicate the model assumption in the spreadsheet.
For example, the UKERC runs use a real discount rate of 10%, (Pathways to a low carbon economy, p18).

However, it is sometimes useful to assume an exogenous value of discount rates. For example the international Energy Agency uses a real discount rate of 5% or 10%. (IEA 2005).

Real or Nominal?

Cost calculations are carried out in constant money (ie. real terms). Our initial calculations consider the elements to be constant in real terms.

We use a real interest rate r in the calculation below.

Net Present Value

The net present value is calculated as the discounted sum of cash flows (CF) i.e. revenue minus costs, where revenue accrues from the sale of electricity and costs include: investment, operation and maintenance, fuel and other costs. Time t is measured in years:

$$\Rightarrow NPV = \sum CF_t \, e^{-r.t}$$

$$\Rightarrow NPV = \sum (R_t - I_t - I^*_t - O_{Ft} - O_{Vt} - F_t - CT_t) \, e^{-r.t}$$

t

Continuous Time Approximation

For any cashflow CF_t we approximate the sum:

$$NPV = \sum_t CF_t e^{-r.t}$$

by the integral

$$NPV = \int_{T_0}^{T} CF_t e^{-r.t} dt$$

If the cash flow CF_t is constant in real terms, $CF_t = CF$, then we can integrate trivially:

$$NPV = \int_{T_0}^{T} CF e^{-r.t} dt = CF \frac{e^{-rT_0} - e^{-rT}}{r}$$

In the case of a constant real escalation s

$$NPV = \int_{T_0}^{T} CF e^{s.t} e^{-r.t} dt = \frac{e^{-(r-s)T_0} - e^{-(r-s)T}}{r-s}$$

$$\text{So: } NPV = CF \frac{e^{-(r-s)T_0} - e^{-(r-s)T}}{r-s}$$

Levelised Cost

The Levelised Cost of Electricity (LCE) is calculated as the discounted sum of costs (C) divided by the discounted electricity produced (EP) . EP = LF*365*24 where LF is the load factor. It is the electricity price required to give a net present value of zero for a required rate of return equal to the discount rate.

$$LCE = \sum_t (I_t + I^*_t + OF_t + OV_t + F_t + CT_t) e^{-r.t}$$

In general we calculate the levelised cost of each component i as follows:

$$LCE^i = EP_t e^{-rt}$$

Employing the continuous time approximation we have

$$LCE^i = \frac{NPVi(C^i, r-s^i, T_0{}^i, T^i)}{NPVi(EP, r, T_0{}^e, T^e)}$$

(note the denominator is not a NPV calculation, but uses the same function giving 'discounted electricity produced')

Where

$$NPV^i = \frac{C_i * [e^{-(r-s)T_0{}^i} - e^{-(r-s)Ti}]}{r - s}$$

NPV can be interpreted as the net present value of cash flow CF at interest rate r-s obtained between $T_0{}^i$ and T^i.

The following page gives a summary of the parameters needed for this relation:

Summary of Parameters

Item	Cost/year	Start	End	Real Cost Esc	Uncertainty
^{i}	C^{i}	$T_0^{\,i}$	T^{i}	s^{i}	σ^{i}
Investment	I/T_{con}	0	T_{con}	0	σ_I
Infrastructure	I*	0	0	0	0
O & M Fix	O_F	T_{con}	$T_{con} + T_{life}$	0	0
O & M Var	O_V*EP	T_{con}	$T_{con} + T_{life}$	0	0
Fuel Cost	FC_f.[EP/(η)]	T_{con}	$T_{con} + T_{life}$	s^{f}	σ_f*[EP/(η)]
Carbon Cost	CT.CC_f.[EP/(η)]	T_{con}	$T_{con} + T_{life}$	s^{ct}	σ_{CT}*CC_f*[EP/(η)]

- I: Overnight Investment Costs per kW
- I*: Infrastructure or Back-end or Other System Costs cost per kW
- O_F: Non-fuel Operation and Maintenance (Fixed) cost per kW
- O_V: Non-fuel Operation and Maintenance (Variable) cost per kWh
- FC_f: Fuel Costs per kWh_{th}
- CT: Costs of Carbon internalised by an additional tax etc
- T_{con}: Construction Time
- T_{life}: Design Life
- EP: Electricity produced per year; EP = 365*24*LF
- LF: Expected Load Factor
- η: Electrical Efficiency %(LHV)
- s^{f}: Real escalation in Fuel cost
- s^{ct}: Real escalation in Carbon Price
- CC_f: Carbon Content of Fuel [$(tCO_2)/(kWh_{th})$]
- CT: Carbon Price $/$tCO_2$
- σ_I: Prior uncertainty in Construction Cost
- σ_f: Uncertainty in Fuel Cost
- σ_{ct}: Uncertainty in Carbon Price

Results - Capital Cost

Technology	*Median of Published Studies*	*Variability*	*Data points*	*Old Estimates*	*US Data*	*EU Data*	*Markal*	*Capital Cost Mid-Range*	*High (1sd)*	*Low (1sd)*	*Modelled Uncertainty*	*Lear ning Rate*
Coal - IGCC	1496	0.29	32	1200	1491		1431	**1431**	1844	1111	0.4	0.1
Coal - PC	1198	0.21	15	1000	1290		1257	**1257**	1620	1037	0.45	0.1
Oil	895	0.39	3	1340	594		800	**800**	1031	574	0.46	0.1
Gas	591	0.31	36	450	420		540	**540**	696	413	0.4	0.1
Gas CHP	1095	0.31	23	2200			1094	**1094**	1410	838	0.37	0.1
Fuel Cell	4465	0.17	8	4500	4520		4520	**4520**	5824	3855	0.51	0.16
Nuclear LWR	2001	0.36	23	2200	2081	2175	2080	**2080**	2680	1532	0.83	0.1
Nuclear Adv	3216						3216	**3216**	4144	1757	0.83	0.12
Hydro	2587	0.66	14	1500	1500	3263	2586	**2586**	3332	1553	0.57	0.06
Biomass	2278	0.16	11	1800	1869		2300	**2300**	2964	1976	0.44	0.12
Biomass CHP	2962	0.6	4				2385	**2385**	3073	1489	0.44	0.12
Onshore Wind	1179	0.38	55	1200	1208	1595	1378	**1378**	1776	999	0.4	0.14
Offshore Wind	2042	0.28	11			2465	2200	**2200**	2835	1717	0.26	0.14
PV Flat	5695	0.49	27	4160	4751	5075	6000	**6000**	7731	4018	0.51	0.16
CPV							5000	**5000**	6443	3788	0.32	0.16
CSP	4259	0.37	6		3149	4785	3500	**3500**	4510	2550	0.4	0.14
Tidal							2951	**2951**	3803	2236	0.32	0.14
Wave	3413	0.77	11	2800		14460	4927	**4927**	6349	2783	0.32	0.14
Geothermal							2000	**2000**	2577	1515	0.32	0.14
CCS Retrofit	770	0.3	3				1000	**1000**	1289	771	1.53	0.12
Biomass CCS	1997	0.09	4	2000	1880	2175	2500	**2500**	3221	2300	0.77	0.12
Gas CCS	1101	0.43	7	800	1185	1885	1100	**1101**	1418	770	0.83	0.12
Coal CCS	2246	0.12	11	2000	2134	2465	2246	**2246**	2895	2006	0.83	0.12
H2	2962		1				6120	**6120**	7886	3511	0.74	0.12
Air Capture				800			3500	**3500**	4510	2652	0.32	0.1
Pumped Storage							2905	**2905**	3743	2201	0.32	0.12
Batteries							3000	**3000**	3866	1882	0.59	0.1
Transmission							500	**500**	644	379	0.32	0.1

Results – All Parameters

The following tables show the final assumptions adopted by technology group. The first 23 characteristics are 'core'; the others are included for purposes of completeness.

Fossil Fuels

New data for new TC, new ET	1 Coal - IGCC	2 Coal - PC	3 Oil - Peaking	4 Gas - CCGT	5 Gas -CHP DH	6 Gas - Fuel Cell Dist
1 Invest cost USD/kWe	1431	1257	800	540	1094	4520
2 OM Var costs USc/kWh	0.33	0.30	0.19	0.36	0.67	4.51
3 OM Fix costs USD/kWe	39	25	12	11	15	5
4 Elec Eff kwhe/kwh	0.45	0.40	0.25	0.55	0.40	0.48
5 Exp Load factor %	80	80	50	80	50	50
6 Heat produced %	0.0	0.0	0.0	0.0	0.4	0.0
7 CO2 Captured % of fuel	0.0	0.0	0.0	0.0	0.0	0.0
8 NOx emissions: g/kWh	0.9	9.0	0.1	0.1	0.1	0.1
9 SO2 emissions g/kWh	0.5	10.0	0.0	0.0	0.0	0.0
10 PM10 emissions g/kWh	0.2	16.0	0.0	0.0	0.0	0.0
11 Lifetime of plant, yr	30	30	30	25	25	25
12 Investment lag, yrs	4.00	3.50	3.00	2.00	2.50	2.00
13 Development lag, yrs	1.00	1.00	1.00	1.00	10.00	15.00
14 Energy Density (W/m2)	1000	1000	1000	1000	1000	1000
15 Subn parameter ‘a’	10	10	10	10	6	3
16 Learning Parameter b	0.15	0.15	0.15	0.15	0.15	0.25
17 Min. cost: US$/kWhe	3.00	2.70	5.00	3.00	2.50	4.00
18 Rel tech limit % elec	1.00	1.00	1.00	1.00	1.00	0.10
19 Initial mkt sh. S0, %	24	20	1	18	0	0
20 Infrastr. cost US$/kW	0	0	0	0	500	0
21 Resource endow (var.)	0.00	0.00	0.00	0.00	0.00	0.00
22 Waste used % input	0.00	0.00	0.00	0.00	0.30	0.00
23 Average Cost (c/kWh) incl fuel	4.64	4.17	18.69	5.09	10.52	8.12
24 Availability Factor	*0.8333*	*0.8333*	*0.412*	*0.8333*	*0.6871*	*0.5*
25 Flexibility (y/n)	*Yes*	*Yes*	*Yes*	*Yes*	*No*	*Yes*
26 Intermittency (y/n)	*No*	*No*	*No*	*No*	*No*	*No*
27 Contr to peak load	*0.90*	*0.90*	*0.90*	*0.90*	*0.50*	*0.90*
28 Decomm Cost ($/kWe)	*0*	*0*	*0*	*0*	*0*	*0*
29 Waste Cost (c/kWhe)	*0*	*0*	*0*	*0*	*0*	*0*
30 Real Esc rate: Invest	*0*	*0*	*0*	*0*	*0*	*0*
31 Real Ec rate: OM	*0*	*0*	*0*	*0*	*0*	*0*
32 Real Esc rate: Decom	*0*	*0*	*0*	*0*	*0*	*0*
33 Abs tech pot Gwe	*0*	*0*	*0*	*0*	*0*	*0*
34 Base Year	*2000*	*2000*	*2000*	*2000*	*2000*	*2000*
35 Global Capacity Base						
36 Unit Size (MW)	*500*	*500*	*500*	*500*	*100*	*0.01*
37 Learning Rate R	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.16*
38 LCA CO2 (g/kWh)	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
39 Other GHG gCO2e/kWh						
40 NonGHG External Cost	*0*	*0*	*0*	*0*	*0*	*0*

Nuclear, Hydro & Biomass

New data for new TC, new ET	7 Nuclear LWR	8 Nuclear - advanced	9 Hydro Large	10 Biomass	11 Biomass/Coal CHP
1 Invest cost USD/kWe	2080	3216	2586	2300	2385
2 OM Var costs USc/kWh	0.04	0.25	0.33	0.20	0.58
3 OM Fix costs USD/kWe	63	63	13	59	13
4 Elec Eff kwhe/kwh	0.30	0.35	1.00	0.34	0.30
5 Exp Load factor %	90	90	34	80	70
6 Heat produced %	0.0	0.0	0.0	0.5	0.4
7 CO2 Captured % of fuel	0.0	0.0	0.0	0.0	0.0
8 NOx emissions: g/kWh	0.0	0.0	0.0	0.9	0.9
9 SO2 emissions g/kWh	0.0	0.0	0.0	0.5	0.5
10 PM10 emissions g/kWh	0.0	0.0	0.0	0.2	0.2
11 Lifetime of plant, yr	60	50	60	25	25
12 Investment lag, yrs	7.00	10.00	6.00	4.00	4.00
13 Development lag, yrs	1.00	20.00	1.00	1.00	1.00
14 Energy Density (W/m2)	1000	1000	0	0	0
15 Subn parameter ‘a’	10	10	4	6	6
16 Learning Parameter b	0.25	0.25	0.09	0.18	0.18
17 Min. cost: US$/kWhe	3.50	3.50	3.50	3.50	1.80
18 Rel tech limit % elec	0.80	0.80	0.10	0.10	0.10
19 Initial mkt sh. S0, %	17	0	17	1	0
20 Infrastr. cost US$/kW	0	0	0	0	0
21 Resource endow (var.)	0.00	0.00	0.00	0.00	0.00
22 Waste used % input	0.00	0.00	0.00	0.00	0.40
23 Average Cost (c/kWh) incl fuel	5.9	8.4	12.70	9.85	11.00
24 Availability Factor	*0.8333*	*0.8333*	*0.372*	*0.8333*	*0.5469*
25 Flexibility (y/n)	*No*	*No*	*Yes*	*Yes*	*Yes*
26 Intermittency (y/n)	*No*	*No*	*No*	*No*	*No*
27 Contr to peak load	*0.90*	*0.90*	*0.70*	*0.90*	*0.00*
28 Decomm Cost ($/kWe)	*1000*	*0*	*0*	*0*	*0*
29 Waste Cost (c/kWhe)	*0.15*	*0.15*	*0*	*0*	*0*
30 Real Esc rate: Invest	*0*	*0*	*0*	*0*	*0*
31 Real Ec rate: OM	*0.00*	*0*	*0*	*0*	*0*
32 Real Esc rate: Decom	*0.02*	*0.02*	*0*	*0*	*0*
33 Abs tech pot Gwe	*0*	*0*	*0*	*0*	*0*
34 Base Year	*2000*	*2000*	*2000*	*2000*	*2000*
35 Global Capacity Base					
36 Unit Size (MW)	*1000*	*100*	*1000*	*50*	*50*
37 Learning Rate R	*0.16*	*0.16*	*0.06*	*0.12*	*0.12*
38 LCA CO2 (g/kWh)	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
39 Other GHG gCO2e/kWh					
40 NonGHG External Cost	*0*	*0*	*0*	*0*	*0*

Wind and Photovoltaic

New data for new TC, new ET	12 Wind onshore	13 Wind offshore	14 Solar PV Flat Panel	15 Solar Conc PV
1 Invest cost USD/kWe	1378	2200	6000	5000
2 OM Var costs USc/kWh	0.00	0.00	0.00	0.00
3 OM Fix costs USD/kWe	40	63	50	50
4 Elec Eff kwhe/kwh	1.00	1.00	1.00	1.00
5 Exp Load factor %	26	30	20	20
6 Heat produced %	0.0	0.0	0.0	0.0
7 CO2 Captured % of fuel	0.0	0.0	0.0	0.0
8 NOx emissions: g/kWh	0.0	0.0	0.0	0.0
9 SO2 emissions g/kWh	0.0	0.0	0.0	0.0
10 PM10 emissions g/kWh	0.0	0.0	0.0	0.0
11 Lifetime of plant, yr	25	20	30	30
12 Investment lag, yrs	2.00	3.00	2.00	2.00
13 Development lag, yrs	1.00	1.00	1.00	1.00
14 Energy Density (W/m2)	2	3	12	12
15 Subn parameter ‘a’	6	6	3	3
16 Learning Parameter b	0.22	0.22	0.25	0.25
17 Min. cost: US$/kWhe	2.50	2.50	4.00	4.00
18 Rel tech limit % elec	0.20	0.20	0.20	0.20
19 Initial mkt sh. S0, %	1	0	0	0
20 Infrastr. cost US$/kW	100	200	0	0
21 Resource endow (var.)	0.00	0.00	0.00	0.00
22 Waste used % input	0.00	0.00	0.00	0.00
23 Average Cost (c/kWh) incl fuel	9.58	14.7	42.75	36.10
24 Availability Factor	*0.2675*	*0.3*	*0*	*0*
25 Flexibility (y/n)	*No*	*No*	*No*	*No*
26 Intermittency (y/n)	*Yes*	*Yes*	*Yes*	*Yes*
27 Contr to peak load	*0.43*	*0.43*	*0.00*	*0.00*
28 Decomm Cost ($/kWe)	*0*	*0*	*0*	*0*
29 Waste Cost (c/kWhe)	*0*	*0*	*0*	*0*
30 Real Esc rate: Invest	*0*	*0*	*0*	*0*
31 Real Ec rate: OM	*0*	*0*	*0*	*0*
32 Real Esc rate: Decom	*0*	*0*	*0*	*0*
33 Abs tech pot Gwe	*0*	*0*	*0*	*0*
34 Base Year	*2000*	*2000*	*2000*	*2000*
35 Global Capacity Base				
36 Unit Size (MW)	*3*	*3*	*0.01*	*1*
37 Learning Rate R	*0.14*	*0.14*	*0.16*	*0.16*
38 LCA CO2 (g/kWh)	*0.0*	*0.0*	*0.0*	*0.0*
39 Other GHG gCO2e/kWh				
40 NonGHG External Cost	*0*	*0*	*0*	*0*

Solar, Marine and Geothermal

New data for new TC, new ET	16 Conc Sol Thermal CSP	17 Tidal	18 Wave	19 Geothermal
1 Invest cost USD/kWe	3500	2951	4927	2000
2 OM Var costs USc/kWh	0.00	0.00	0.00	0.00
3 OM Fix costs USD/kWe	53	77	300	155
4 Elec Eff kwhe/kwh	0.33	1.00	1.00	0.09
5 Exp Load factor %	20	39	35	80
6 Heat produced %	0.0	0.0	0.0	0.0
7 CO2 Captured % of fuel	0.0	0.0	0.0	0.0
8 NOx emissions: g/kWh	0.0	0.0	0.0	0.0
9 SO2 emissions g/kWh	0.0	0.0	0.0	0.0
10 PM10 emissions g/kWh	0.0	0.0	0.0	0.0
11 Lifetime of plant, yr	30	50	25	30
12 Investment lag, yrs	3.00	8.00	3.00	3.00
13 Development lag, yrs	3.00	2.00	10.00	1.00
14 Energy Density (W/m2)	12	3	6	1000
15 Subn parameter ‘a’	6	6	6	3
16 Learning Parameter b	0.22	0.22	0.22	0.22
17 Min. cost: US$/kWhe	3.50	4.00	4.00	2.50
18 Rel tech limit % elec	0.10	0.50	0.40	0.10
19 Initial mkt sh. S0, %	0	0	0	0
20 Infrastr. cost US$/kW	0	0	0	0
21 Resource endow (var.)	0.00	0.00	0.00	0.00
22 Waste used % input	0.00	0.00	0.00	0.00
23 Average Cost (c/kWh) incl fuel	27.57	15.59	30.20	5.71
24 Availability Factor	*0*	*0.23*	*0*	*0.635*
25 Flexibility (y/n)	*No*	*No*	*No*	*No*
26 Intermittency (y/n)	*Yes*	*Yes*	*Yes*	*Yes*
27 Contr to peak load	*0.00*	*0.09*	*0.18*	*0.63*
28 Decomm Cost ($/kWe)	*0*	*0*	*0*	*0*
29 Waste Cost (c/kWhe)	*0*	*0*	*0*	*0*
30 Real Esc rate: Invest	*0*	*0*	*0*	*0*
31 Real Ec rate: OM	*0*	*0*	*0*	*0*
32 Real Esc rate: Decom	*0*	*0*	*0*	*0*
33 Abs tech pot Gwe	*0*	*0*	*0*	*0*
34 Base Year	*2000*	*2000*	*2000*	*2000*
35 Global Capacity Base				
36 Unit Size (MW)	*100*	*1*	*0.1*	*1*
37 Learning Rate R	*0.14*	*0.14*	*0.14*	*0.14*
38 LCA CO2 (g/kWh)	*0.0*	*0.0*	*0.0*	*0.0*
39 Other GHG gCO2e/kWh				
40 NonGHG External Cost	*0*	*0*	*0*	*0*

Carbon Capture and Sequestration

New data for new TC, new ET	20 Coal CCS Retrofit	21 Biomass/Coal with CCS	22 Gas with CCS (Post)	23 Coal with CCS (Pre)
1 Invest cost USD/kWe	1000	2500	1101	2246
2 OM Var costs USc/kWh	0.45	0.45	0.30	0.45
3 OM Fix costs USD/kWe	47	47	20	47
4 Elec Eff kwhe/kwh	0.40	0.26	0.35	0.35
5 Exp Load factor %	50	50	80	80
6 Heat produced %	0.0	0.0	0.0	0.0
7 CO2 Captured % of fuel	0.9	0.9	0.9	0.9
8 NOx emissions: g/kWh	0.0	0.0	0.1	0.9
9 SO2 emissions g/kWh	0.0	0.0	0.0	0.5
10 PM10 emissions g/kWh	0.0	0.0	0.0	0.2
11 Lifetime of plant, yr	30	30	30	30
12 Investment lag, yrs	3.00	3.00	4.00	5.00
13 Development lag, yrs	10.00	15.00	10.00	10.00
14 Energy Density (W/m2)	1000	0	1000	1000
15 Subn parameter ‘a’	6	6	6	6
16 Learning Parameter b	0.18	0.18	0.18	0.18
17 Min. cost: US$/kWhe	4.50	4.50	3.50	4.50
18 Rel tech limit % elec	1.00	1.00	1.00	1.00
19 Initial mkt sh. S0, %	0	0	0	0
20 Infrastr. cost US$/kW	0	0	0	0
21 Resource endow (var.)	0.00	0.00	0.00	0.00
22 Waste used % input	0.00	0.00	0.00	0.00
23 Average Cost (c/kWh) incl fuel	5.57	14.29	8.33	6.92
24 Availability Factor	*0*	*0*	*0.8333*	*0.8333*
25 Flexibility (y/n)	*Yes*	*Yes*	*Yes*	*Yes*
26 Intermittency (y/n)	*No*	*No*	*No*	*No*
27 Contr to peak load	*0.00*	*0.00*	*0.90*	*0.90*
28 Decomm Cost ($/kWe)	*0*	*0*	*0*	*0*
29 Waste Cost (c/kWhe)	*0*	*0*	*0*	*0*
30 Real Esc rate: Invest	*0*	*0*	*0*	*0*
31 Real Ec rate: OM	*0*	*0*	*0*	*0*
32 Real Esc rate: Decom	*0*	*0*	*0*	*0*
33 Abs tech pot Gwe	*0*	*0*	*0*	*0*
34 Base Year	*2000*	*2000*	*2000*	*2000*
35 Global Capacity Base				
36 Unit Size (MW)	*500*	*500*	*500*	*500*
37 Learning Rate R	*0.12*	*0.12*	*0.12*	*0.12*
38 LCA CO2 (g/kWh)	*0.9*	*0.9*	*0.9*	*0.9*
39 Other GHG gCO2e/kWh				
40 NonGHG External Cost	*0*	*0*	*0*	*0*

Related Non-Electricity-Generating Technologies

New data for new TC, new ET	24-Hydrogen	25 Air Capt kw~kgCO2/h	26 Pumped Storage	27 Battery storage	28-Transmission
1 Invest cost USD/kWe	6120	3500	2905	3000	500
2 OM Var costs USc/kWh	6.48	4.00	0.43	0.50	0.00
3 OM Fix costs USD/kWe	265	50	2	100	0
4 Elec Eff kwhe/kwh	0.63	0.25	0.77	0.70	0.99
5 Exp Load factor %	80	100	20	50	50
6 Heat produced %	0.0	0.0	0.0	0.0	0.0
7 CO2 Captured % of fuel	0.0	1.0	0.0	0.0	0.0
8 NOx emissions: g/kWh	0.0	0.0	0.0	0.0	0.0
9 SO2 emissions g/kWh	0.0	0.0	0.0	0.0	0.0
10 PM10 emissions g/kWh	0.0	0.0	0.0	0.0	0.0
11 Lifetime of plant, yr	30	20	50	10	50
12 Investment lag, yrs	5.00	5.00	7.00	2.00	5.00
13 Development lag, yrs	10.00	30.00	3.00	10.00	1.00
14 Energy Density (W/m2)	0	0	100	0	0
15 Subn parameter ‘a’	6	0	3	3	0
16 Learning Parameter b	0.18	0.15	0.18	0.15	0.15
17 Min. cost: US$/kWhe	4.50	0.00	4.00	4.00	0.00
18 Rel tech limit % elec	1.00	0.00	1.00	1.00	1.00
19 Initial mkt sh. S0, %	0	0	0	0	0
20 Infrastr. cost US$/kW	0	0	0	0	0
21 Resource endow (var.)	0.00	0.00	0.00	0.00	0.00
22 Waste used % input	0.00	0.00	0.00	0.00	0.00
23 Average Cost (c/kWh) incl fuel	25.35	18.57	35.13	26.21	9.57
24 Availability Factor	*0*	*0*	*0.65*	*0*	*0*
25 Flexibility (y/n)	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
26 Intermittency (y/n)	*No*	*No*	*No*	*No*	*No*
27 Contr to peak load	*0.00*	*0.00*	*0.95*	*0.00*	*0.00*
28 Decomm Cost ($/kWe)	*0*	*0*	*0*	*0*	*0*
29 Waste Cost (c/kWhe)	*0*	*0*	*0*	*0*	*0*
30 Real Esc rate: Invest	*0*	*0*	*0*	*0*	*0*
31 Real Ec rate: OM	*0*	*0*	*0*	*0*	*0*
32 Real Esc rate: Decom	*0*	*0*	*0*	*0*	*0*
33 Abs tech pot Gwe	*0*	*0*	*0*	*0*	*0*
34 Base Year	*2000*	*2000*	*2000*	*2000*	*2000*
35 Global Capacity Base					
36 Unit Size (MW)	*200*	*100*	*1000*	*1*	*1*
37 Learning Rate R	*0.12*	*0.1*	*0.12*	*0.1*	*0.1*
38 LCA CO2 (g/kWh)	*0.0*	*1.0*	*0.0*	*0.0*	*0.0*
39 Other GHG gCO2e/kWh					
40 NonGHG External Cost	*0*	*0*	*0*	*0*	*0*

Cost of Generating Electricity - Summary

The following table shows the cost of generating electricity in 2008.

Levelised Costs (c/kWh)	Coal (IGCC)	Coal (PC)	Gas	Nuclear	Onshore Wind	Offshore Wind	Coal CCS
Investment Costs	3.7	3.1	1.3	5.3	4.1	6.5	6.1
O&M Costs	1.1	0.8	0.7	1.2	2.2	3	1.4
Fuel Cost	1.5	1.7	7	0.9	-	-	2
Carbon Cost	-	-	-	-	-	-	-
Total Cost	6.3	5.7	9	7.3	6.3	9.5	9.5

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