sustainable development commission

The role of nuclear power in a low carbon economy

Paper 2: Reducing CO_2 emissions - nuclear and the alternatives

An evidence-based report by the Sustainable Development Commission

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1 INTRODUCTION

This evidence-based report looks at the potential contribution of nuclear power to long-term targets for the reduction of carbon dioxide (CO_2) emissions. Section 2 begins by placing nuclear power in context, examining its current contribution to UK electricity and total energy supply and its impact on CO_2 emissions.

Section 3 looks at the research on the alternatives to nuclear power and asks whether there is sufficient practical resource potential for a low carbon energy supply without recourse to nuclear power, and what this might look like.

Section 4 then considers the extent to which nuclear power can be considered a low carbon technology by summarising the evidence on embodied carbon emissions from a wide range of sources.

In Section 5, the potential contribution of nuclear power to electricity supply and carbon reduction targets is assessed using two new-build scenarios: replacement of existing capacity, and an expansion to double current levels.

Finally, Section 6 summarises the potential long-term contribution of nuclear power under these two scenarios and highlights the importance of other measures.

2 NUCLEAR POWER AND UK ELECTRICITY SUPPLY

2.1 Nuclear in context

Currently nuclear power in the UK is only used to make electricity, with no industrial heat or hydrogen outputs. This means that while its percentage contribution to UK electricity supply is relatively large, it makes up a much smaller amount of total energy consumption, which includes transport and heating fuels. However, its impact on CO_2 emissions is significant due to the inherent inefficiency of electricity generation, and the prevalence of a large percentage of coal in the fuel mix.

2.2 Electricity supply

Figures for 2004 show that nuclear power made up 19.3% of UK electricity supply, generating 73.7TWh of a total of 382.5TWh – see Figure 1. This was down from a contribution in 2002 and 2003 of 21.6% due to a series of outages in 2004 that contributed to a lower than average load factor. Total UK nuclear capacity, annual output, the load factors of the combined plant, and the average operating efficiency, are shown in Table 1 for the period 1996-2004.

As this table shows, nuclear capacity has been declining slowly from a peak of almost 13GW, to 11.85GW currently. This is due to the decommissioning of the first Magnox stations, although these represent a minor percentage of total output.

2.3 Energy supply

Of a total energy supply of 235 million tonnes of oil equivalent (mtoe), nuclear power contributed 18.3mtoe in 2004, or 7.8% - see Figure 2. This shows the much smaller role nuclear power plays once energy for transport and heat are included.

Table 1: UK nuclear plants statistics for 1996-2004[1]

Year	1996	1997	1998	1999	2000	2001	2002	2003	2004
Plant capacity (GW)	12.92	12.95	12.96	12.96	12.49	12.49	12.24	11.85	11.85
Nuclear output (TWh)	85.82	89.34	90.59	87.67	78.33	82.99	81.09	81.91	73.68
Load factor (%)	n/a	79.1	80.1	77.5	70.5	76.1	75.1	77.8	71.0
Thermal efficiency (%)	n/a	36.7	36.5	36.8	37.3	37.3	37.6	38.1	37.9

Figure 1: UK electricity supply by fuel source, 2004[2]

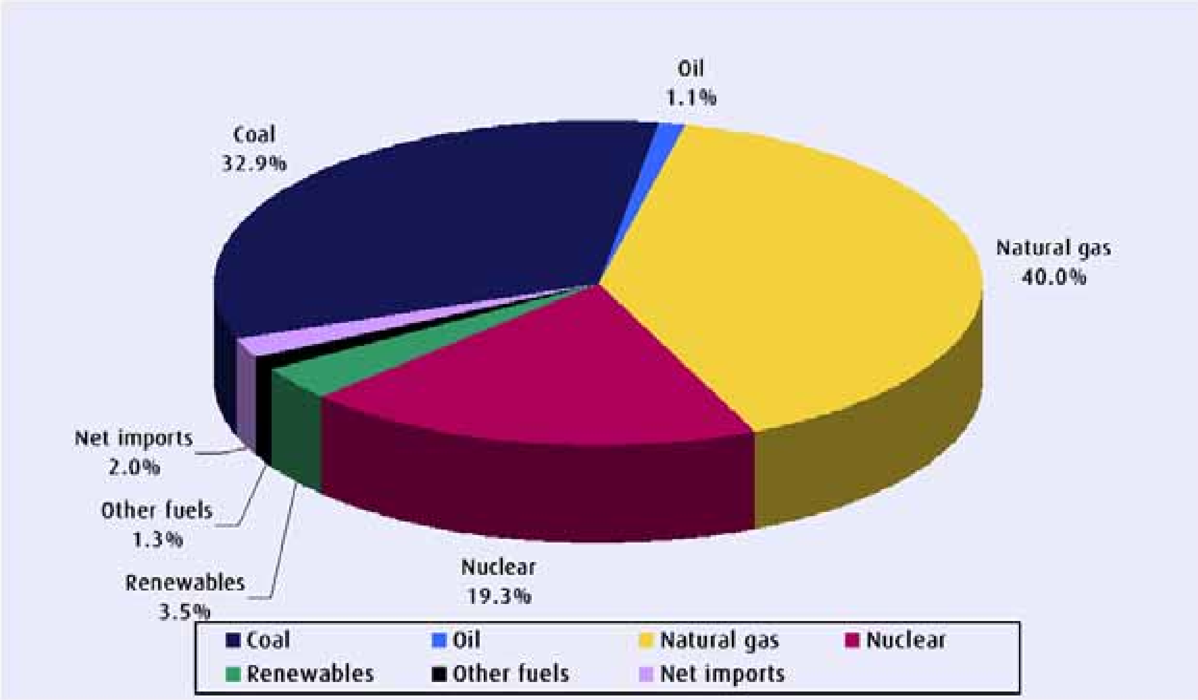
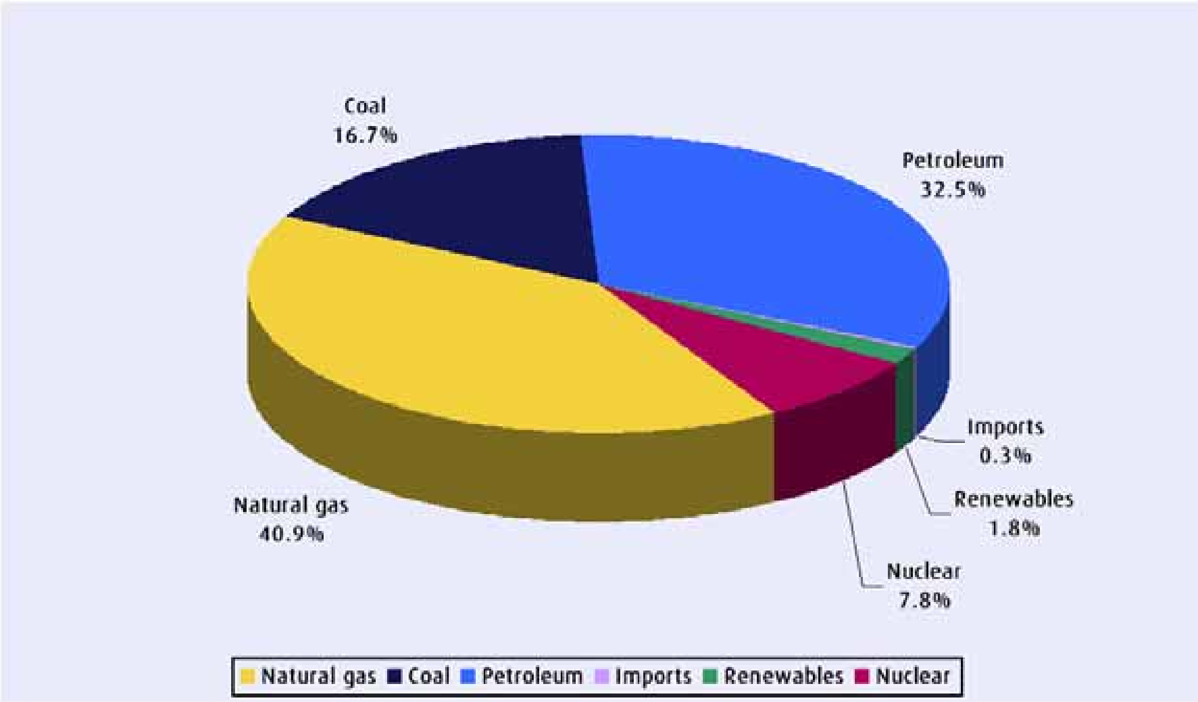


Figure 2: Total UK energy supply by source, 2004



2.4 CO_2 emissions

Power stations in the UK are responsible for 29.7% of total CO_2 emissions. Nuclear power therefore results in a substantial CO_2 saving. However, the calculation of avoided CO_2 emissions resulting from nuclear power is not straightforward and depends on a number of assumptions as to the displaced fuel mix.

As nuclear is used to provide base-load capacity, it would most likely be replaced with large, centralised fossil fuel plant if it were taken out of the current system. If considered on a historical basis, this plant would be primarily coal; however if current nuclear capacity were to be replaced instantaneously, this would most likely be gas CCGT (combined cycle gas turbine) plant.

Currently, coal-fired electricity generation is estimated to result in CO_2 emissions of 243 tonnes per GWh (t/GWh); the figure for existing gas plant (which will include some less efficient non-CCGT plant) is 97t/GWh, falling to around 90t/GWh for new-build CCGT (based on standard assumptions, and assuming average degradation in efficiency). For comparison, combined heat and power (CHP) results in average emissions of 50tC/GWh.

Assuming that current nuclear capacity would be replaced with a historical coal-gas mix, this data can be used to estimate the emissions savings per year from current nuclear output. Figure 3 shows how the emissions savings decrease as the level of replacement by gas grows at the expense of coal (i.e. the chart shows the balance changing from 100% coal and 0% gas, to 100% gas and 0% coal). Emissions savings range from 7.95MtC to 19.9MtC per year. At the mid point, where nuclear displaces a 50/50 coal-gas mix, total displaced emissions are just under 14MtC per year.

This figure represents around 8.8% of total UK CO_2 emissions in 2004, with a range of 5-12.6%[35]. However, it is unlikely that any future capacity would be displaced by anything other than gas CCGT – this is explained further in the next section, and also in Annex B.

2.5 Security of electricity supply

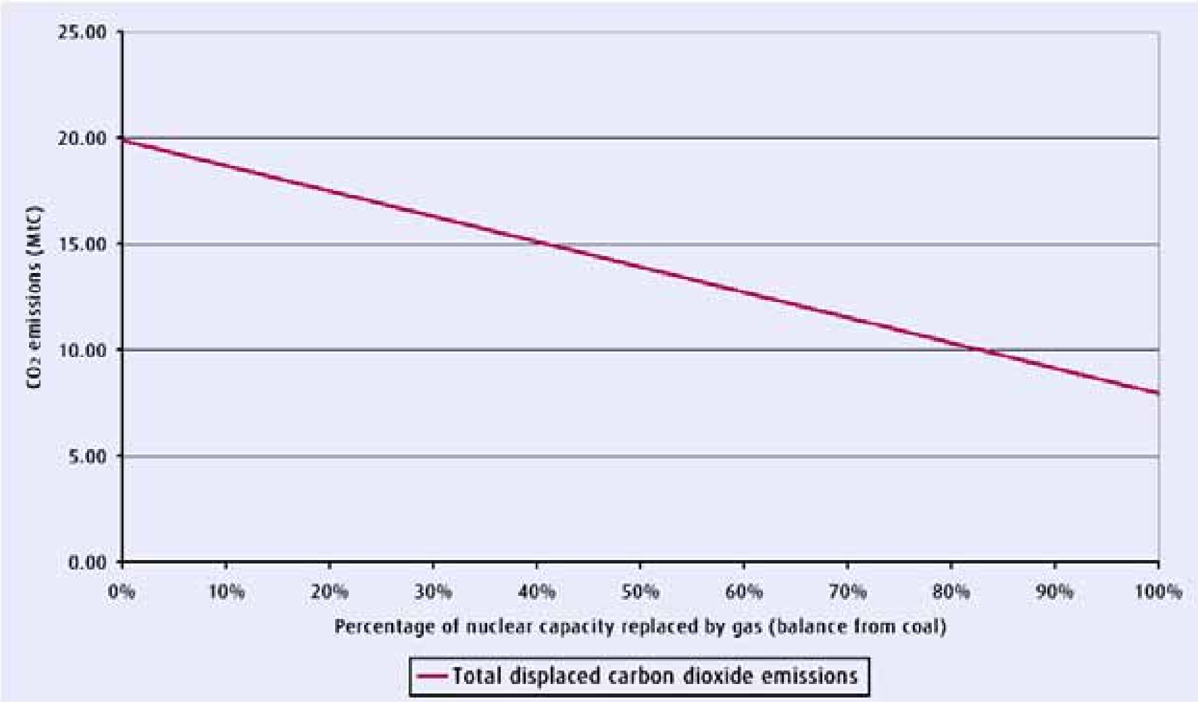
This section will not attempt a full analysis of the contribution of nuclear power to the UK's security of energy supply. However, as a base-load generator, nuclear is often credited with performing a security of electricity supply role for which it receives no premium in the UK's liberalised electricity market.

Nuclear output will always be the primary base-load plant so long as it exists, and its maximum capacity does not exceed minimum demand. The reason for this is that nuclear plants have very low fuel costs, and are difficult to shut down without notice. Therefore, it is always preferable for a nuclear plant operator to supply the maximum available output, and this puts nuclear in the position of a 'price taker', where prices will be set by the marginal cost of fossil-based plant at each time period. The UK's minimum summer-time demand in 2004-5 was around 22GW, meaning nuclear capacity would have to double before curtailment and/or storage becomes necessary.

As a base-load provider, nuclear power does provide a stable source of electricity that is less vulnerable to short term fuel disruption when compared to coal, and especially gas[i]. But as a price-taker, this leaves nuclear power providers vulnerable to decreases in the cost of wholesale electricity prices, and this was a significant factor in the near collapse of British Energy in 2002.

[i] Gas supplies to electricity generators can be disrupted at short notice, with priority given to domestic users when supplies are short. There is limited storage of gas, making it vulnerable to disruptions in the supply network.

Figure 3: Estimated displaced emissions from current UK nuclear capacity, 2003 [1,]



3 LOW CARBON OPTIONS

3.1 The alternatives to nuclear power

There should be no question that it is theoretically possible to achieve a low or zero carbon economy using a wide variety of renewable energy technologies combined with energy efficiency and demand management measures. This fact is clearly shown by the evidence on energy efficiency potential, UK renewable resources, and modelling work done to map low carbon options through to 2050 and beyond.

The UK's 'practical' wind power resource is around half our current electricity consumption[ii], and this is before taking account of future technological advances (which could increase the resource by using larger turbines and moving much further offshore).

We also have huge tidal, wave, biomass and solar resources, and a recent report by the Environmental Change Institute (ECI) shows how we could reduce household CO_2 emissions by 60% using a variety of currently available technologies, particularly energy efficiency[3]. Recent work by the Energy Saving Trust estimates that microgeneration could provide 30-40% of the UK's electricity generating needs by 2050, sooner if the right economic incentives were in place[4].

Theoretically we could choose to deliver a low or zero carbon economy through just one or two technologies or measures, but this would most likely be prohibitively expensive. For example, the UK may be able to source all its electricity from wind power (much of this offshore), but wind would become expensive at high rates of penetration (i.e. if it made up a large percentage of total supply) in the absence of other complementary technologies, due to the need for increased electricity storage.

So it is more likely that a basket of options would be most cost-effective, and the choice then becomes which options should be in the basket. With liberalised energy markets this is unlikely to be an explicit choice, as the market will be free to choose the lowest cost options within whatever carbon constraints are in place, such as emissions trading schemes.

Therefore any choice is more likely to relate to the UK's policy on innovation, or other market or regulatory interventions that are deemed necessary to help stimulate the market for new technologies.

3.2 Energy efficiency

3.2.1 Energy intensity

The UK economy has for many years managed to achieve improvements in energy intensity – the amount of energy consumed per unit of economic output. The UK's energy intensity has improved by around 40% since the early 1970s, largely as a result of energy efficiency improvements, fuel switching, and structural changes in the UK economy[5].

However, such improvements have not been enough to counter the increases in carbon emissions from continuing economic growth. UK carbon emissions have decreased little since 2000. Without further measures they are projected to continue increasing, preventing the UK from reaching its domestic target of a 20% reduction in emissions by 2010.

3.2.2 Energy efficiency potential

There is a wide base of evidence on the potential for energy efficiency savings in the UK. In the 2001 Energy Review, the Policy &

[ii] The theoretical onshore resource is 1,000,000GWh, which is more than double our current electricity consumption.

Innovation Unit reports a technical potential of approximately 30% of final energy demand, equal to around 40MtC/year[6]. As they point out, this is broadly consistent with estimates for other countries.

In 2003, the Interdepartmental Analysts Group (IAG) produced a background note to summarise the work done on energy efficiency for the 2003 Energy White Paper[7]. This points to similar potential emissions savings of 25MtC/year by 2050. The Energy White Paper itself declares that 10MtC of energy efficiency savings could be delivered by 2010[8]. And the subsequent Energy Efficiency Action Plan states that a further 10MtC of savings could be achieved by 2020[9].

More recently, the Energy Efficiency Innovation Review estimated the energy efficiency potential in the domestic, business and public sectors. This identified emissions potential savings to 2020 of 9MtC in the household sector, and 11.2-12.6MtC in the business and public sectors[10]. They also estimated that fuel switching in the power sector as a result of EUETS could deliver an additional 10MtC as a result of improved end-use efficiency.

The Energy Efficiency Innovation Review also looked at the potential for developing new energy saving technologies through research and development activities. The estimated carbon saving from the introduction of key technologies is >4MtC by 2020, and >24MtC by 2050[10].

The updated MARKAL modelling conducted for the DTI's report on carbon abatement technologies (see section 3.4.7; Figure 3) highlights the leading role that energy efficiency is expected to make to meeting the UK's long-term target to reduce carbon emissions by 60% by 2050.

3.2.3 Standby savings

The wastage of electricity as a result of inefficient appliances left on standby is a good example of some of the 'low hanging fruit' that exists for reducing carbon emissions.

The Energy Saving Trust (EST) estimates that we currently waste over 1.11 million tonnes of carbon (4.06 million tonnes of CO_2) from appliances on standby[11]. This is equivalent to the output of a 1500MW conventional power station[iii].

3.3 Renewable resources

The UK has some of the best renewable energy resources anywhere in the world. This is particularly the case offshore, where the theoretical potential of marine renewables and offshore wind power is very large.

Renewable energy resources are usually presented in several ways. The 'theoretical resource' is the term used to describe the maximum available resource before consideration of spatial, environmental, infrastructural and economic limitations.

This leads to the calculation of a maximum 'practicable resource', which takes into account the first three factors, although excludes economics. However, there is some degree of overlap between these terms, particularly when comparing different studies, and so caution should be exercised in their interpretation.

Also, all figures are liable to revision in either direction over time due to increased scientific knowledge and technological development.

The results from three studies on the potential of renewables in the UK are presented below. The first two deal with theoretical and practicable potentials. The latter is taken from work done as part of the 2003 Energy White Paper and looks at the practicable resource by 2025 at different electricity price levels, thus including economic considerations.

[iii] Gas CCGT; 85% load factor.

3.3.1 IEE – renewable energy in the UK

The Institute of Electrical Engineers published a report on renewable energy in 2002[12]. It shows the 'technical potential' of a variety of renewable technologies for UK electricity generation – this is defined as "an upper limit that is unlikely ever to be exceeded even with quite dramatic changes in the structure of our society and economy".

Table 2: Summary of possible contributions from renewables in the UK

Technology		Technical potential (TWh/year)
Onshore wind power		45
Offshore wind power		140
Tidal power		54
Geothermal (hot dry rocks)		210
Wave power		50
Small-scale hydro		2
Biofuels	- Wet and dry wastes	44
	- Forestry	At least 40
TOTAL		585

The IEE's definition of technical potential would seem to coincide closely with the DTI's 'practicable resource' in that it is a calculation of what would be feasible without major structural change. With the exception of geothermal (which is not included in the Tyndall Centre report below), the figures show some degree of correlation.

As can be seen, this analysis does not include microgeneration technologies specifically or solar photovoltaics at all. It is unclear whether microgeneration applications are included in the technical potential of technologies such as wind power and biomass.

3.3.2 Tyndall Centre – renewable energy and CHP resources

This report draws heavily on DTI-commissioned work by ETSU from 2000[13]. The definition of the data provided for each technology differs to some degree, in part because a number of different sources were used. However, it gives a good indication of the very large theoretical potentials of some technologies, despite the fact that the practicable resource is much smaller.

This data suggests that the UK's practicable resource is roughly equal to around 87% of current electricity production of 382TWh/year.

Table 3: Tyndall Centre - renewable energy resource estimates in the UK

Technology		Theoretical potential (TWh/year)	Practicable resource (TWh/year)
Municipal solid waste combustion			13.5
Hydro power		40	1.9*
Onshore wind power		318	58
Offshore wind power		3,000	100
Energy crops		190**	17*
Forestry and agricultural wastes			14*
Wave power	- Shoreline	2	0.4
	- Near-shore	140	2
	- Offshore	700	50
Tidal	- Tidal stream		36
	- Barrage		50***
Solar photovoltaics****		267	7.2
TOTAL			334

* No data is given for the practicable resource, so the cost effective resource for 2010/2025 is presented.
** Figure derived from RCEP data.
*** Figure derived from EU study.
**** The theoretical potential assumes the use of all suitable buildings in the UK; the practicable resource assumes that solar PV is installed only on new-build projects.

Table 4: IAG - maximum practicable resource in 2025 (8% discount rate)

	Electricity generated (TWh/year) at price under:			
Technologies	2.5p/kWh	3p/kWh	5p/kWh	7p/kWh
Agricultural and forestry residues	1	3	19	19
Energy crops (SRC)	0	5	33	33
Landfill gas	2	7	7	7
Municipal solid waste	3	4	6	7
Solar photovoltaics	0	0	0	0.5
Tidal power	<1	1	1.4	2
Wave power	0	0	33	33
Onshore wind power	10	45	57	57
Offshore wind power	35	98	100	100
TOTAL	51	163	257	258

3.3.3 IAG – Supporting work for the 2003 Energy White Paper

This report by the Government's Interdepartmental Analysts Group was published as supporting work to the 2003 Energy White Paper[14]. Using data on practicable resources and combining it with estimated cost curve data, the IAG produced a summary of the maximum practicable resource that could be expected from a range of renewable technologies by 2025 under four different price scenarios[iv] - see Table 4. This gives an indication of the level of renewable electricity generation that would be possible depending on the costs that society is willing to bear[v].

As this data shows, the inclusion of economic considerations related to a set time period (2025) reduces the maximum potential of renewables to 258TWh / year if costs of 5-7p / kWh are accepted. This represents around 68% of current UK electricity production.

3.3.4 Carbon Trust – UK renewables

In 2003 the Carbon Trust published a report looking at the long-term potential of renewables in the UK[15]. This has a brief summary of the global 'natural' and the global 'potential' resources of selected renewables – solar PV, onshore and offshore wind, wave, and tidal.

This shows that even the global 'practical' resource (which includes siting and economic constraints) is large enough to supply current world electricity demand (~15,000TWh) several times over. The total practical resource from these five renewables is estimated to be between 54,800TWh and 117,800TWh.

3.3.5 Energy Saving Trust – potential for microgeneration

As part of developing its Microgeneration Strategy, the DTI commissioned the Energy Saving Trust (EST) to look at the long-term potential of microgeneration technologies in the UK[16].

Their report, published in 2005, covers all microgeneration technologies including micro CHP. It finds that by 2050, microgeneration could potentially provide 30-40% of the UK's total electricity needs and could help to reduce CO_2 emissions by up to 15%. In energy terms, microgeneration could supply just over 300TWh of energy by 2050, most of this from micro CHP and fuel cells.

3.3.6 Carbon Trust – marine renewables

A recent report by the Carbon Trust looked at the potential for marine renewables (tidal and wave power) in the UK[17]. The report estimates that there is enough practical resources from these sources to supply between 15% and 20% of current UK electricity consumption.

The Carbon Trust highlight the large role that offshore wave energy could make, with a substantial contribution possible from tidal stream. Near-shore and shoreline wave energy has only niche potential.

3.4 Modelling low carbon pathways

A number of studies over the past five years have looked at pathways to a low carbon economy. These generally look at possible combinations of technologies and measures that would deliver desired carbon emission reductions by 2050 or some other date. An overview of these studies is given below.

[iv] Calculations were given for two different discount rates – 8% and 15%. Only the lower rate is shown here (leading to a higher estimate of maximum resource), although at the higher end of electricity prices changing the rate to 15% has only a limited effect.

[v] It should be noted that the costs presented are for generated electricity. The cost to the consumer would be higher once network and suppliers costs are included.

3.4.1 Royal Commission on Environmental Pollution

The 22nd report of the Royal Commission on Environmental Pollution (RCEP)[18] was completed in 2000 and led to the adoption by the Government of the 60% carbon reduction target by 2050. RCEP presented four scenarios for how the UK might achieve the 60% target, which were[vi]:

- scenario 1: no increase on 1998 demand, combination of renewables and *either* nuclear power station *or* large fossil fuel power stations at which carbon dioxide is recovered and disposed of
- scenario 2: demand reductions, renewables (no nuclear power station or routine use of large fossil fuel power stations)
- scenario 3: demand reductions, combination of renewables and *either* nuclear power station *or* large fossil fuel power stations at which carbon dioxide is recovered and disposed of
- scenario 4: very large demand reductions, renewables (no nuclear power stations or routine use of large fossil fuel power stations.

These scenarios are explained in detail in the report, but it is worth noting that three of them would require demand reductions (from 1998 levels) of between 36 and 47% by 2050. This would be delivered by a mix of measures, including more efficient use of heat, and increases in the efficiency of electricity generation and transport.

3.4.2 PIU Energy Review

The Performance and Innovation Unit of the Cabinet Office conducted a review of energy policy in 2001, which contributed to the development of the Energy White Paper in 2003[6]. Their report presents five scenarios to cover a spectrum of possibilities for how a 60% cut in carbon emissions by 2050 might be achieved. The scenarios are:

- Business As Usual (BAU): continuation of current trends, high rate of GDP growth
- World Markets (WM): core value is consumerism, high growth, low sustainability
- Provincial Enterprise (PE): core value is individualistic, low growth, low innovation, low sustainability
- Global Sustainability (GS): core value is sustainable development, medium growth, strong carbon incentive promotes innovation, high sustainability
- Local Stewardship (LS): core value is conservation, low growth, low innovation, high sustainability through local action

Of the five scenarios, only the last two result in a carbon emissions reduction of 60% by 2050. Both of these rely on an energy mix that consists of differing proportions of renewables, oil and gas, combined with much greater energy efficiency. New electricity generation under these two scenarios is provided by just CHP and renewables, and does not include nuclear. The only scenario that does include new nuclear build is PE.

3.4.3 Energy White Paper modelling

A detailed modelling exercise was carried out by a team from Imperial College London and Future Energy Solutions in 2003[19]. They looked at three scenarios for possible future development of the UK economy, and its impact on energy demand and delivery. Following on from the 2001 Energy Review, these were:

- Baseline
- World Markets
- Global Sustainability

[vi] Scenarios have been presented as shown in the RCEP report, with italics preserved.

Taking the conservative Baseline scenario, they presented a variety of pathways for electricity generation that would be consistent with a 60% reduction in CO_2 emissions by 2050, but through different means. Of the eight model runs presented, the contribution of nuclear power in three projections was zero or close to zero. In these three projections, electricity supply was provided by a varying combination of gas (with and without carbon capture and storage), wind and tidal power, biomass, combined heat & power (CHP), and other renewables. In the non-electricity sectors, carbon savings were delivered by mainly hydrogen use in transport, and much greater energy efficiency across the economy.

This research also conducted sensitivity analysis on the exclusion of nuclear power and carbon capture & storage from the options available to the model. When both were simultaneously removed the 60% abatement target could still be obtained, through greater deployment of energy efficiency and renewable energy measures. However, this was shown to increase abatement costs by around 250%, reinforcing the need for a strong innovation policy.

3.4.4 Pacala and Socolow – Stabilisation Wedges

A paper by S. Pacala and R. Socolow published in 2004 developed the concept of 'stabilisation wedges', which are 1Gt increments of carbon reductions that could be delivered over the next 50 years. Their suggestion was that seven such 'wedges' would be needed globally to deliver the 7Gt of carbon beyond business as usual that would be required to stabilise atmospheric concentrations of CO_2 at 500 parts per million (ppm) by 2050.

The wedges concept is intended to show that by massively scaling up existing, proven technologies, humanity could achieve carbon stabilisation without the need for radical technological advances.

Fifteen wedges were identified over the following five categories: energy efficiency and conservation (4), fuel shift (4), nuclear fission (1), renewable electricity and fuels (4), and forests and agricultural soils (2). Not all of these options are required for CO_2 stabilisation at 500ppm, but as the analysis does not account for cost – just technical potential – the options are not viewed in terms of practicality, or compared against each other.

The authors acknowledge that some wedges could be delivered twice (i.e. double the effort on nuclear fission), while others will inevitably have some carbon saving overlap. However, it is clear that taken together, substantial carbon reductions are possible (enough to deliver a zero carbon economy), even if some options do not deliver or are excluded.

3.4.5 Stanford Energy Modelling Forum

This study, published in 2004, compared global energy supply projections from eight major models for the year 2100[20]. It is a 'top down' study, meaning the models took a macro-economic resource allocation perspective. The results from two scenarios – a world with no carbon constraints and a world where carbon concentrations were limited to 550ppm – are presented side-by-side for comparison.

Of the eight models, three project no role for nuclear under the reference scenario, but all of them project some role in the carbon constrained scenario. However, the nuclear contribution is small in two of the scenarios, and is combined with a very large reduction in overall energy usage; in one of these, both solar energy and biomass contribute more to energy demand than nuclear.

3.4.6 Tyndall Centre

A recent report by the Tyndall Centre presents five scenarios for how the UK could meet at 60% reduction in CO_2 emissions by 2050 using a variety of options[21]. Based on a wide range of Tyndall Centre research in this area, the report looks at both the demand

and supply of energy, and for the first time includes all aviation and shipping emissions in its calculations.

Of the five scenarios, one (the 'red' scenario: high GDP growth, low energy demand) does not include nuclear, and instead relies on a combination of reduction in household energy demand (from energy efficiency measures), a strong innovation policy, low growth in transport emissions (including aviation), and big increases in renewables, CHP, carbon capture & storage, and biofuels, combined with the use of hydrogen.

All the other scenarios allow for a larger growth in aviation and energy demand more generally, which increases the need for carbon reductions on the supply side. In all but one of these scenarios, hydrogen (generated from a low carbon electricity fuel mix) plays a key role in helping to satisfy increases in energy demand in the non-electricity sector.

3.4.7 DTI Carbon Abatement Strategy modelling

The DTI published their strategy for the development of carbon abatement technologies in June 2005[22]. This included modelling work (using the MARKAL model) that looked at the long-term potential of carbon capture and storage (CCS). This updated the model used for the 2003 Energy White Paper to take account of a broader range of CCS technologies and improvements in the knowledge base. However, no updates were made to the assumptions behind other technologies. The SDC anticipates that a fully updated model will be developed for the 2006 Energy Review.

The overall purpose of the modelling for this study was to demonstrate the potential role of CCS and other Carbon Abatement Technologies in a low carbon energy system. MARKAL is a cost optimisation programme and consequently may differentiate strongly between technologies with very similar costs. In the database the following cost assumptions are made:

nuclear	3p/kWh
coal with CCS (retrofitted)	3.2p/kWh
new gas plant with CCS	3.6p/kWh
new coal with CCS	3.8p/kWh

Consequently, MARKAL adopts nuclear almost exclusively for baseload, unless it is constrained to prevent the deployment of new nuclear capacity.

Firstly, the analysis looks at the potential contribution needed from different energy policy areas to meet the UK's 60% target for reducing CO_2 (see Figure 4 below). This shows the increase in CO_2 emissions that would occur if the UK economy were to grow at an average rate of 2.25% per year while carbon intensity improves by 1.6% per year (the rate achieved between 1990-2000). The lower lines show the potential reductions in CO_2 emissions that can be delivered through energy efficiency, fuel switching (excluding power generation), and action to reduce the emissions of power generation.

This illustrates the importance of both energy efficiency (which would need to achieve reductions in energy intensity of 2.7% per year –much higher than historical trends) and the electricity sector. Without contributions from *both*, the target will be very difficult to achieve.

Based on this analysis, the report presents a series of scenario projections to 2050 looking at the electricity output required from different technologies (energy efficiency, renewables and different forms of CCS) consistent with delivering the emissions reductions required from the electricity sector. Ten model runs are summarised, six of which assume that there is no new nuclear build. The Baseline scenario with no nuclear new build (termed BL-60NN in the report) is shown in Figure 5 below.

This clearly shows how increases in CHP and renewables would be the sole contributors to reducing emissions up to 2020. After this point, rapid and sustained increases in output from renewables will need to be accompanied firstly by coal with CCS (Coal CCS), and then from around 2030 by gas with CCS (Gas CCS). By 2050, the scenario shows Coal CCS providing around 25% of output, Gas CCS also at 25%, renewables at around 40%, and CHP providing the remaining 10%.

This would allow the UK to restrict gas dependence in the electricity sector to around 35% of output, with coal and renewables making up the remaining 65%.

It is important to realise that such projections are highly sensitive to changes in the input parameters, and these are explained in the original report. However, this study makes a clear case for the potential of carbon capture and storage, and how when combined with renewables and CHP it could enable the electricity generating sector to make its required contribution to CO_2 reduction targets when combined with an even greater contribution from energy efficiency.

3.5 Summary

The potential for energy efficiency savings is very large. It is estimated we could save over 20MtC of carbon emissions by 2020 using existing technologies, with further cuts possible by 2050.

If new energy saving technologies are successfully developed, the long-term potential of energy efficiency is greatly increased. To put this in perspective, 20MtC is equivalent to the output of around 27 standard power plants[vii].

The data on UK renewable resources suggests that the total practicable resource is at least 334TWh/year, or 87% of current electricity production. Introducing price restrictions reduces this total somewhat, but at 258TWh/year it is still considerable. Such calculations assume either a low, or no, role for solar photovoltaics based on the assumption that costs will remain comparatively high. However, a technological breakthrough could change this situation and help capture some of the huge theoretical potential of this resource.

Practicable resource calculations are highly dependent on the underlying assumptions, and therefore could be expected to change over time. Significant technological progress in renewables and infrastructure could push the practicable resource further towards the theoretical resource estimates. It is therefore reasonable to state that it is theoretically possible to supply all of the UK's electricity from renewable sources in the long-term, especially when combined with energy efficiency. The main constraint is likely to be economic rather than technical.

The low carbon pathway studies all show that it is theoretically possible to achieve substantial cuts in CO_2 emissions with or without nuclear power. Therefore, the UK may want to consider nuclear power for its basket of measures, but rejecting it does not mean that CO_2 reduction targets will be impossible to meet.

However, several scenarios also show that without nuclear power, greater effort is required on other fronts, and a strong role is needed for innovation policy to help support new low carbon technologies. In the electricity generating sector, the exclusion of nuclear power requires substantial investments in renewables, carbon capture & storage, and CHP to enable a scenario whereby all the UK's electricity could be obtained from these technologies alone by around 2040.

[vii] Assuming 1,000MW capacity gas-fired CCGT and an 85% load factor.

Figure 4: Potential contribution of different energy area to the attainment of the UK's 60% reduction in CO_2 emissions by 2050.

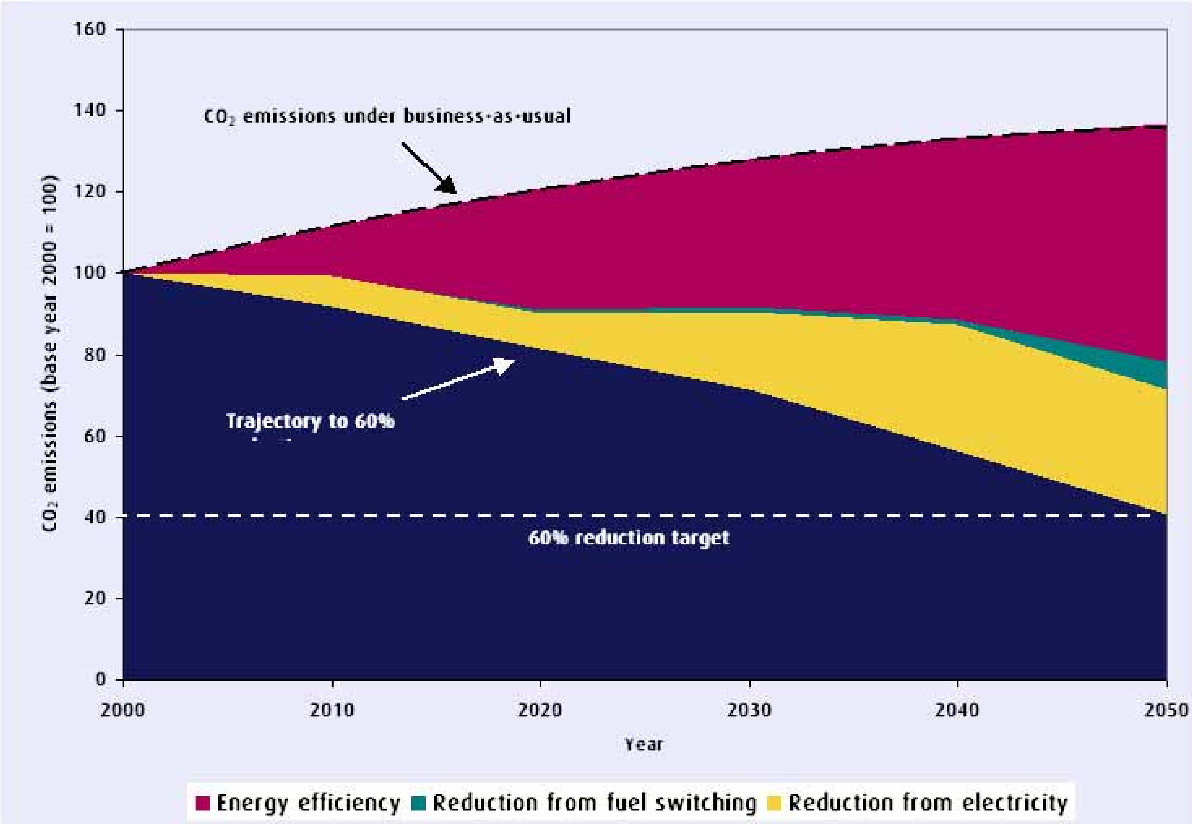
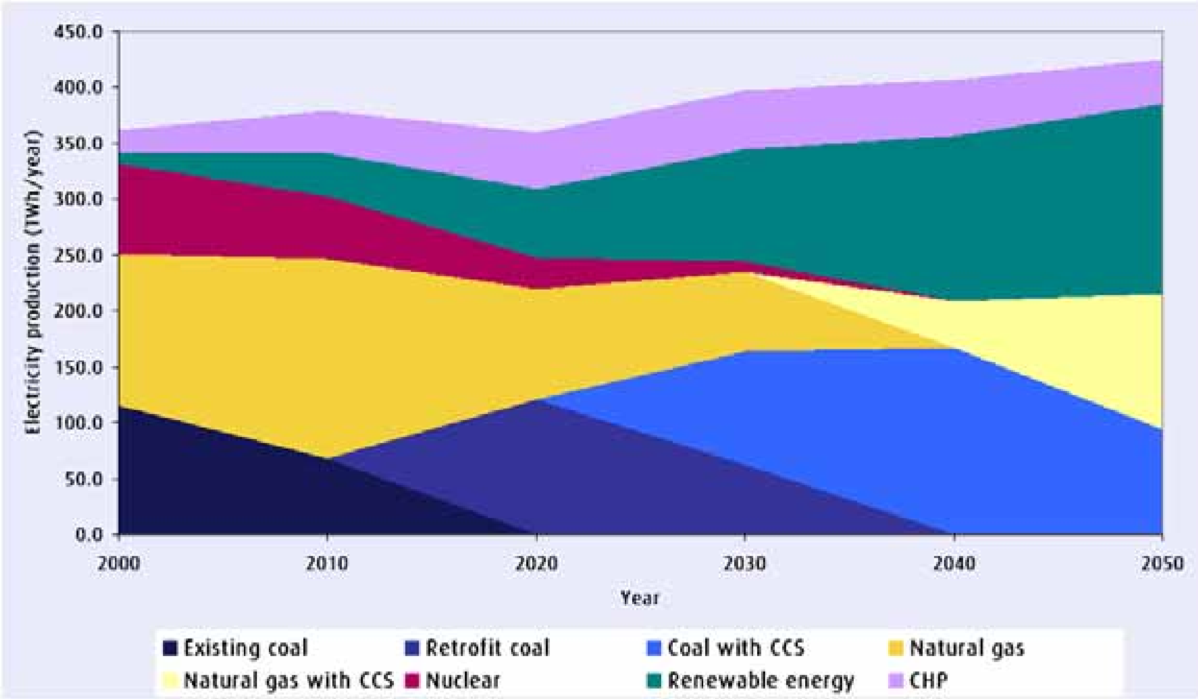


Figure 5: Results from the MARKAL model for the Baseline scenario with no new nuclear build showing the mix of fuels used for electricity generation.



4 CO_2 EMISSIONS FROM NUCLEAR POWER

4.1 Background

Nuclear power plants do not produce emissions directly from electricity generation, although the processes involved with the construction and operation of the plants do.

Lifecycle emissions include those associated with the mining and processing of the fuel, construction and operation of the plant, the disposal of used fuel and by-products, and waste & decommissioning activities. These emissions result from the use of transport fuel and conventional electricity to conduct these processes. If this energy were obtained from zero carbon sources, then nuclear power might be considered a source of energy with near zero emissions, with only the emissions from cement manufacture to consider.

Following the literature on this subject, this section deals with emissions in carbon dioxide (CO_2) equivalent, and care should be taken when comparing to data in other sections, where tonnes of carbon (tC) are used. CO_2 can be converted into its carbon equivalent by multiplying by a factor of 12/44.

4.2 Sources of CO_2 emissions

Nuclear power indirectly results in emissions of CO_2 and these fall into two broad categories: construction activities, and the fuel cycle. The electricity required for the operation of a nuclear power plant can be considered as self-generated, and should therefore be disregarded.

As with wind power, the production of materials for nuclear plant construction is a carbon intensive process with CO_2 outputs from cement and steel manufacture. Typically one tonne of CO_2 is released for the production of each tonne of Portland cement[23], and with large quantities required for nuclear plant construction this is a significant factor in total lifecycle emissions.

Fuel cycle emissions stem primarily from the energy consumed in mining activities and the electricity required for fuel fabrication. The level of emissions from electricity consumption is related to the energy mix of the country where the process is performed. For instance, coal and gas-fired plants generate 73% of UK electricity whereas in France 76% is provided by nuclear power[24]. The impact of the British fuel mix on CO_2 emissions is therefore significant.

The enrichment of uranium is a major source of CO_2 where the older gas diffusion technology is used. However, centrifuge enrichment is far less energy intensive, and where this is standard, plant construction becomes the significant CO_2 output. The transportation of fuel, materials and waste also represents a significant amount of total CO_2 although emissions for plant operation and fuel reprocessing are generally very low.

4.3 What affects the level of emissions?

Estimates of CO_2 emissions vary widely due to the characteristics of each plant assessed. There are differences in plant type, capacity, efficiency and expected lifetime, alongside the various technologies, enrichment techniques and fuel cycle practices used. Results also differ with respect to location; related to issues of fuel mix, transport infrastructure and national energy policy.

4.3.1 Enrichment technique

Fuel enrichment by gas diffusion is more energy intensive than the centrifuge enrichment process, emitting larger quantities of CO_2. This accounts for some of the variation in CO_2 estimates between countries and plants. For example, US estimates of CO_2 emissions by nuclear power are placed at around 4% of an equivalent coal-fired plant, whereas in Germany the relative figure is only 0.5%. This is due to the predominance of the older gas diffusion techniques in the US[25].

Uranium imported into the UK is enriched by Urenco, using the centrifugal method. Estimates for the diffusion technique are therefore less relevant to the UK context. The development of laser enrichment technology will eventually supersede both methods, lowering emissions further.

4.3.2 Technology

The size and type of reactor clearly influences all inputs to the lifecycle and therefore affects CO_2 emissions. The potential reactor technologies currently available to the UK incorporate smaller, more compact designs with fewer components, higher fuel burn-up and greater efficiency.

Boiling water reactors (BWR) are claimed to be less costly to construct because of their lower pressure characteristics and the Advanced CANDU Reactor (ACR), the European Pressurised Reactor (EPR) and the Advanced Passive Series (AP1000) all have the capacity to use mixed-oxide (MOX) fuel, using low-enriched uranium and requiring less energy.

The choice of technology will ultimately affect CO_2 emissions, and future technological improvements indicate that CO_2 will continue to become less significant as a product of nuclear power, regardless of developments in the fuel mix.

4.3.3 Plant characteristics

- Fuel conversion efficiency
- Thermal efficiency
- Load factor
- Expected Lifetime (yrs)

Table 5: States of the fuel cycle contributing to CO_2 emissions.

Stage	Energy use for	Main source
Fuel Production	Fuel extraction (mining)	Electricity / petroleum
	Conversion (milling)	Electricity
	Uranium enrichment	Electricity
	Transportation	- Of fuel - Of materials
Construction	Construction & the production of materials for plant and waste facilities	Steel, concrete, copper & other materials (direct and indirect)
Operation	Operation	Production of chemicals
Waste Handling	Spent fuel disposal	- Manufacturer of copper canisters - Transport
	Fuel reprocessing	- Electricity - Material inputs - Construction
	Decommissioning	- Electricity - Material inputs

The output of a power plant per unit of fuel is related to the fuel conversion efficiency (often termed as the 'burn-up' rate for nuclear plants), the thermal efficiency of the turbine, and the load factor of the plant[viii]. If overall efficiency is low, more fuel will be required for the same level of output and the additional mining, processing, enrichment and transportation will increase CO_2. Similarly, the emissions factor will decrease when either conversion efficiency or load factor increase.

The lifetime of most 1000 MW nuclear plants is estimated at between 30 and 40 years, but studies have shown emissions per megawatt hour are only marginally affected by the lifetime of the plant[26]. Even for aggregate CO_2, all non-fuel emissions must be averaged over the plant lifetime, lowering the contribution of non-fuel related sources compared to those that are fuel related.

4.3.4 Location

Location influences CO_2 output in one of two ways. Firstly, the indirect emissions from material supply and component manufacturing are determined to a great extent by the emissions of the respective energy mix. Countries with significant nuclear power capacity have markedly lower CO_2 emissions per unit of electricity produced, compared to countries with high fossil fuel shares. Currently, the UK is highly dependent on fossil-fired electricity generation, making indirect emissions the primary source of nuclear CO_2 output. If nuclear plants replaced fossil-fired plants as the primary electricity generators, the emissions factor for nuclear power would fall.

The geographical siting of the power plant is also a factor to consider when explaining the disparity between CO_2 output figures. Plants situated further away from their fuel source, enrichment plant or waste disposal facilities will be responsible for more emissions from transport than those that are closer.

4.3.5 Reprocessing

The UK is one of the few countries to undertake the reprocessing of spent fuel, originally for its fleet of Magnox reactors, although now mostly for the AGR plants and international contracts. Although no energy consumption figures are available for closed-cycle reprocessing in the UK, it would be expected to produce less CO_2 than a 'one-through' fuel cycle, because of the reduced need to enrich natural uranium[27], although the subsequent increase in energy inputs for the construction and operation of the reprocessing plant must be considered.

However, reprocessing is an optional waste management strategy for the newer AGR plants, the Sizewell B PWR, and the commercially available PWR designs. Due to cost considerations and safety concerns, several reports have stated that reprocessing is an unlikely choice for a future nuclear programme[28]. However, concerns over the UK's plutonium stockpile, and the ability of newer plant designs to consume 100% MOX fuel, could influence the final decision[29].

4.4 Comparing CO_2 emissions from electricity production

The release of carbon dioxide (CO_2) from nuclear power is estimated by most industry sources to be between 2-20 tonnes per gigawatt-hour (tCO_2/GWh) of electricity produced, about the same as wind power if construction and component manufacture are included.

The average amount of CO_2 emitted by nuclear power in Western Europe is estimated at $16tCO_2$/MWh for a Pressurised Light Water Reactor (PWR)[30] and although this varies according to reactor type, plant characteristics, and location, several sources

[viii] A low load factor would serve to increase embodied emissions by lowering the total output of the plant over time, whilst also lowering the efficiency of the plant through disruption to base-load operations.

have made estimates around this figure[ix]. By contrast, coal emits around 891tCO_2 / MWh while gas is around 356tCO_2 / MWh[31].

An international comparison that analyses the greenhouse gas emissions of different generating technologies was completed by the IAEA in 2000[32]. This concludes that greenhouse gas emissions from nuclear power are in a similar range to onshore wind power and small-scale hydropower.

4.5 Variations in analysis

The wide range of CO_2 estimates also indicates the different assumptions and approaches adopted in each analysis. Most researchers have adopted a life-cycle approach – a 'cradle to grave' analysis of the entire nuclear fuel cycle, including direct and indirect energy inputs. From this they can ascertain the emission factor of CO_2 for each stage of the cycle. This approach requires a detailed definition of both the fuel cycle and the system within which it operates. Decisions over the boundaries of analysis unavoidably involve value judgments, although generally the indirect energy for material inputs and the direct energy for the fuel cycle process are the key factors considered.

The collection and presentation of data also varies between analyses. Some greenhouse gas emissions are expressed in CO_2 equivalent, which includes noxious gases like methane and sulphur dioxide, although the output of these latter pollutants from nuclear power is negligible, and therefore estimates continue to predominately reflect CO_2. Similarly, some analyses include both thermal and electrical energy inputs. It is therefore important to acknowledge these differences before any consistent comparisons can be made. Very few estimates can be a complete and comprehensive assessment, but instead indicate the potential contribution of specific electricity supply options to a future sustainable energy system.

A full explanation of the assumptions behind each of the studies cited can be found in Annex A.

4.6 What future developments in the UK can reduce CO_2 emissions?

Future nuclear power technologies offer a range of options available to reduce CO_2 emissions. Plant life extensions and new plants that address design, fabrication, construction and performance in a streamlined manner will contribute significantly.

Energy consumption from the fuel cycle has already fallen dramatically in recent years with improvements in efficiency. By further improving the energy ratio, the CO_2 directly and indirectly emitted will be reduced. For example, it has been suggested that LWR plants adopting the centrifugal method of enrichment, with the capacity for higher fuel burn-up, will emit less than half the lifecycle CO_2 emissions of conventional plant[33]. Both the ACR and EPR technologies feature efficiency improvements and fewer component requirements, suggesting that future nuclear build will have a lower CO_2 impact, from an already low baseline.

Meanwhile, the indirect emissions related to nuclear power will be reduced from any gradual shift to low or zero carbon sources of energy in other areas. For example, by increasing the use of biofuels in transportation, or renewable / nuclear electricity generation, the emissions stemming from nuclear-related activities will fall. Of course, these developments will have no effect on emissions from cement manufacture, so the only reduction possible here is through more resource efficient designs and construction techniques.

[ix] The Nuclear Energy Agency (NEA), Foratom & the International Atomic Energy Authority (IAEA) all agree that nuclear power emits low amounts of CO_2 – between 2-6 g of carbon equivalent per kWh.

4.7 Is nuclear power carbon free?

An analysis of a wide body of literature on this subject shows that nuclear power can certainly be categorised as a low carbon technology. Carbon dioxide emissions from power production itself are zero, but CO_2 is emitted during the fuel cycle, and the plants themselves have embodied energy. As most of this energy will come from fossil fuels, nuclear power does result in indirect CO_2 emissions. However, this will apply to a greater or lesser extent to all technologies with embodied energy, including renewable technologies such as wind power and solar photovoltaics.

Nuclear power is therefore not carbon free. But with CO_2 emissions at a level comparable to a major low carbon alternative, wind power, the impact of indirect emissions is not included in the following analysis of nuclear's potential contribution to reducing the UK's CO_2 emissions. This is in recognition of the fact that in a low carbon economy, the indirect emissions from nuclear power, along with other low carbon technologies, would be substantially reduced.

5 POTENTIAL CONTRIBUTION OF NUCLEAR POWER

5.1 Future UK scenarios

This section will look at a number of scenarios for the possible contribution of nuclear power to future UK energy requirements, within the context of the shift to a low carbon economy. The baseline scenario will be analysed to determine the impact of the planned decline of nuclear capacity on UK electricity supply and CO_2 emissions. A further two scenarios will then be explored, as follows:

Baseline – no new nuclear capacity is built in the UK, leading to a gradual decline in nuclear output.

Scenario 1: Replacement – nuclear capacity is maintained around current levels through a replacement new-build programme of around 10GW.

Scenario 2: Expansion – a large-scale nuclear programme is commissioned to double the installed capacity of nuclear power in the UK with the addition of 20GW of new capacity, making nuclear the dominant electricity generation source.

The aim of developing these scenarios is to estimate the level of plant construction that would be required to achieve the desired capacity, and the impact of this on CO_2 emissions. Figure 4 shows how UK nuclear plant capacity would differ under the three scenarios. The full set of assumptions behind each scenario, and detailed analysis, can be found in Annex B.

5.2 Baseline

5.2.1 Nuclear capacity and supply

The baseline assumes that plant closures proceed as currently scheduled, and that no new nuclear capacity is built – see Annex B for details of individual plant closures. This may be pessimistic, as it is increasingly likely that plant extensions for some existing plants will be sought.

However, as it currently stands, total capacity will fall from current levels of 12GW, to 3.7GW in 2020, and zero in 2036 with the final closure of Sizewell B in 2035. Figure 6 shows how UK installed nuclear capacity is scheduled to decline up to 2036.

The impact of this loss in capacity on nuclear's share of electricity generation can be seen in Figure 7, which shows the scheduled contribution of nuclear power under three different assumptions for the growth / decline of electricity supply[x]. These assumptions are explained in Annex B.

5.2.2 Impact on CO_2 emissions

As the retirement of current nuclear capacity is scheduled and expected, it should not be considered as having an impact on CO_2 emissions. If emissions targets are to be met, the UK will have to achieve emissions reductions in other areas to compensate for the loss of nuclear capacity, but this is built into the current emissions projections used by the Government to formulate policies to 2020[34].

Current projections, as outlined in the consultation paper to the Climate Change Programme Review, are that after allowing for existing measures, CO_2 emissions will fall from 165.1 MtC in 1990 (the base year), to 142.0 MtC in 2010 (-14%), before rising slightly to 143.9 MtC by 2020 (-12.8%)[35]. Therefore on current projections the UK will not meet targets for a 20% cut in CO_2 by 2010, let alone any more stringent targets up to 2020.

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[x] This is to make allowance for successful electricity conservation at one extreme, or a 1% annual rise in electricity consumption (the average rate of increase over recent years) at the other.

Figure 6: UK nuclear plant capacity under the Scenarios 1-2 compared to Baseline, 2004-2037

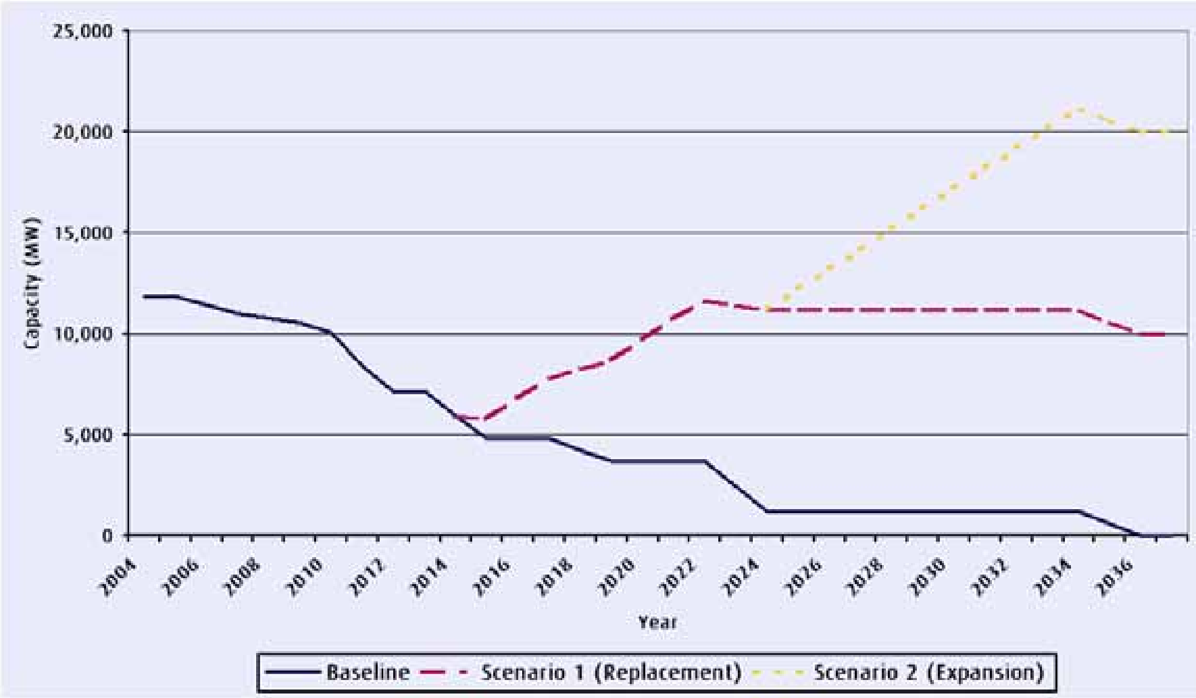
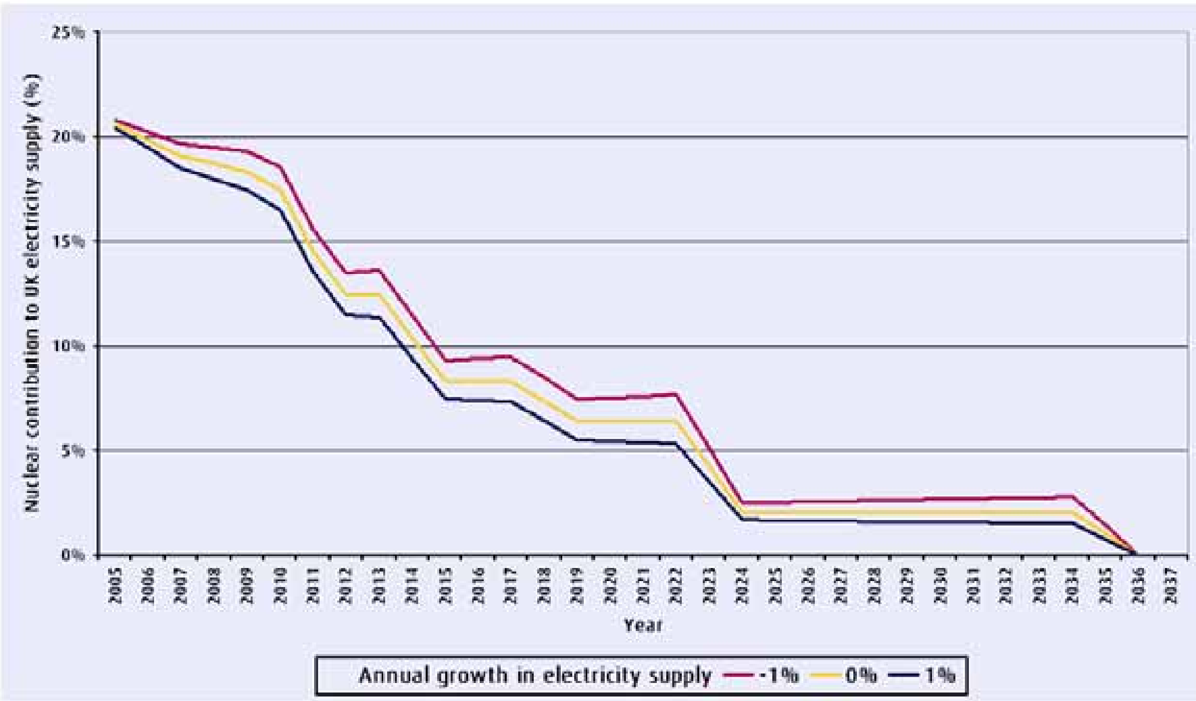


Figure 7: Nuclear contribution to UK electricity supply under Baseline, 2005-2037



5.3 Scenario 1: replacement

5.3.1 Nuclear capacity and supply

Under this scenario a new set of nuclear reactors is commissioned to replace the 10GW of capacity that will be decommissioned over the coming 20 years. It is generally accepted to be very unlikely that a new nuclear plant could be operational before 2015, and that any new build programme would not be able to deliver all 10GW at once. The assumptions laid out in Annex B therefore assume a maximum build rate of 1GW per year starting in 2015, which would deliver the full 10GW by 2024.

Due to the delay in commissioning the new capacity, the contribution of nuclear dips at around 9-11% of total UK electricity supply by 2015, before gradually recovering. By 2024, nuclear could make up between 18-26% of electricity supply under this scenario, depending on the extent of demand growth.

For total energy consumption, this contribution will be lower. If it is assumed that the 12% growth in energy consumption over in the period 1986-2005 is repeated, then the total amount of energy consumed in 2024 would be around 282 mtoe (from 235 mtoe now). The 74,460GWh generated by nuclear amounts to 16.8mtoe, which might represent around 6% of total energy consumption in 2024[xi].

5.3.2 Impact on CO_2 emissions

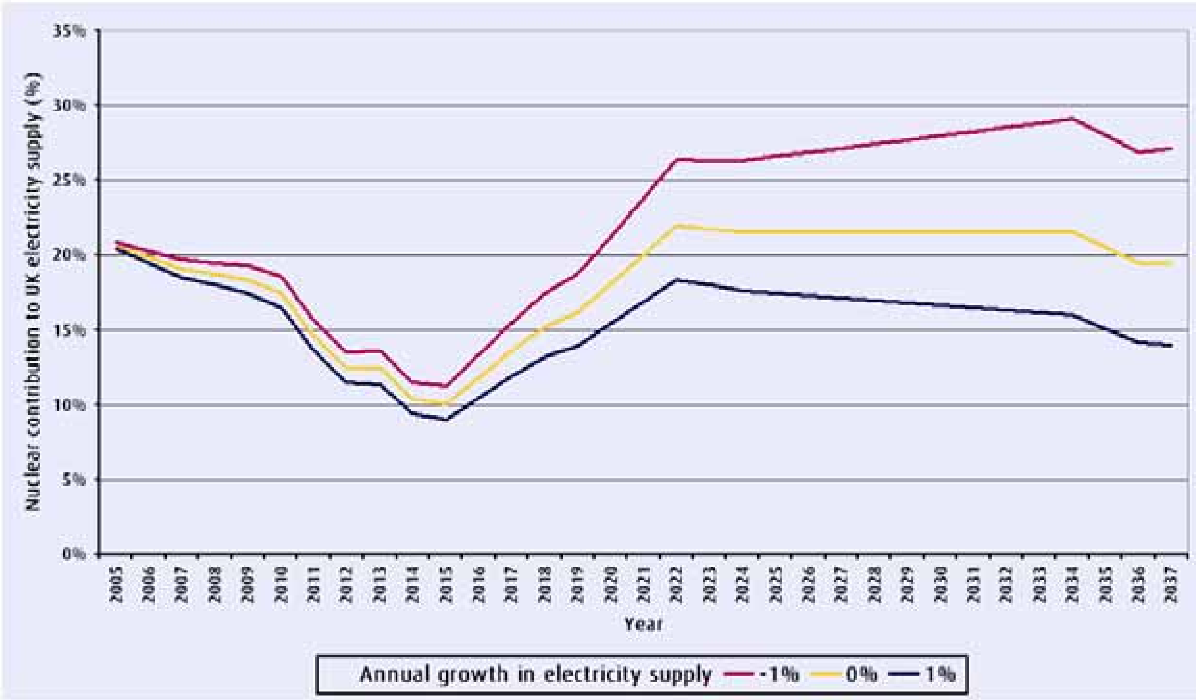
The CO_2 savings have been calculated for the additional nuclear plant, over and above that which is part of the baseline scenario. This has then been combined with emissions data for gas CCGT plant to give the avoided emissions in each year after the new capacity comes online.

The emissions savings reach their maximum in 2024, when all the new capacity is operating. It is assumed that any new nuclear capacity would displace new CCGT gas plant, as this is likely to be the least-cost alternative. Therefore, the annual emissions savings from this scenario, where 10GW of new capacity is built, would be 6.7MtC by 2024

The actual emissions displacement would be less than this if coal-fired generation using carbon capture and storage is a viable alternative to gas by this time, or if renewable sources (such as wind power) became the least cost option. This is because both of these sources do not emit CO_2. Projections from the PIU Energy Review in 2002 suggest that wind power could be the least-cost option by 2020[36], although this analysis does not allow for the potential portfolio benefits that may result from a diverse set of technologies[37].

[xi] This assumes a plant efficiency factor of 38%.

Figure 8: Nuclear contribution to UK electricity supply under Scenario 1, 2005-2037



5.4 Scenario 2: expansion

5.4.1 Nuclear capacity and supply

In this scenario new capacity is built along the same lines as in Scenario 1, except that the programme continues longer until 20GW is built. Assuming that neither the start date nor the rate of construction can be improved, this programme would be completed in 2034, one year before Sizewell B is due to shut down.

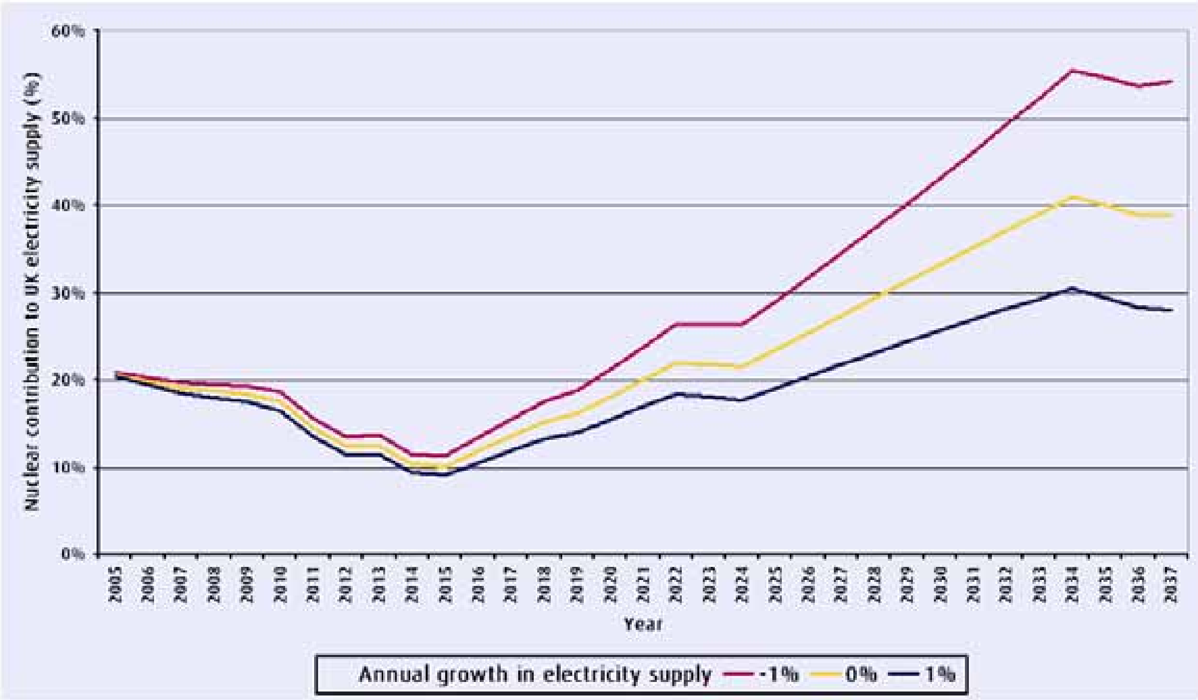
As would be expected, the impact of this expansion scenario is to effectively double the figures from Scenario 1. Therefore, by 2034 nuclear's contribution could be between 30% and 55% of UK electricity supply, again depending on assumptions taken for demand growth.

5.4.2 Impact on CO_2 emissions

Similarly, the impact on CO_2 emissions is an effective doubling of the savings obtained in Scenario 1, albeit over a longer time period. Therefore, possible emissions savings from 2034 would be 13.4MtC, again assuming new nuclear would displace gas CCGT.

However, by 2034 the likelihood of advances in zero carbon technologies is greatly increased, and it is possible that several low carbon technologies will be available at less cost than gas CCGT. This would lower the displacement effect of new nuclear capacity on CO2 emissions for plant coming on-line around this time.

Figure 9: Nuclear contribution to UK electricity supply under Scenario 2, 2005-2037



6 IMPLICATIONS FOR REDUCING EMISSIONS

6.1 Policy context

In the 2003 EWP the Government stated its long-term objective was to cut carbon emissions by 60% from 1990 levels by 2050. From a level of 165.1MtC in 1990, emissions would have to fall to an annual rate of 66MtC by 2050; recent figures show that emissions currently stand at around 158.5MtC[35]. More recently, some scientists have suggested that 80% cuts may be required, which would translate into annual emissions of 33MtC by 2050.

A timescale more relevant to policy decisions on nuclear power might be the period between 2020 to 2030. By 2020, it would be reasonable to assume that leading on from a 20% cut in carbon emissions by 2010, an emissions reduction target of 30 or 40% would be required. For 2030, this figure could be 40 or 50%.

The potential reduction in carbon emissions from nuclear power under each scenario is shown in Table 6.

6.2 Contribution to 2020 carbon reduction targets

Scenarios 1 and 2 both deliver the same level of emissions reduction by 2020, due to the maximum build rate for new plants. Assuming displacement of gas CCGT, a nuclear programme starting in 2015 might deliver around 4.0MtC of emissions savings by 2020.

It is unlikely that any programme of nuclear new build, no matter how ambitious over the long term, would substantially improve on these estimates, unless the maximum build rate and / or the date of first commissioning were shortened. Both scenarios could therefore deliver a cut in emissions of around 2.4% by 2020 from 1990 levels.

6.3 Contribution to 2030 carbon reduction targets

Both scenarios deliver much higher emissions savings by 2030, with the construction programme in Scenario 2 still uncompleted at this time. For Scenario 1, displaced emissions are around 6.7MtC, whereas Scenario 2 could deliver savings of around 10.7MtC.

For Scenario 1, this translates into a cut of around 4.1%; Scenario 2 could deliver cuts of around 6.5% by 2030.

6.4 Importance of other measures

It seems clear that a new nuclear programme alone would not be enough to meet possible future targets for reducing carbon emissions. By 2020 nuclear could deliver cuts of 2.4%, meaning other measures (such as energy efficiency or renewable energy) would be needed to obtain cuts of 30-40%.

The effectiveness of other measures also helps to ensure the maximum impact of any new electricity generating capacity, including nuclear. For example, by reducing electricity demand by 1% a year, the contribution that new nuclear capacity could make to UK electricity supply in the future is dramatically increased.

This theoretically allows low carbon resources that would otherwise have been commissioned to meet an ever increasing electricity demand to be deployed in other sectors; for example, biomass production could contribute more to reducing transport emissions rather than being consumed in power stations.

6.5 The longer term

Over the longer term, Scenario 1 would achieve a 4.1% cut in carbon emissions by

2050, whilst Scenario 2 would achieve a cut of 8.1%. Whilst these cuts are certainly substantial, they are not a panacea solution to the challenges of a low carbon future. A much more substantial nuclear programme would be required to make deeper cuts, but this is probably outside the bounds of reality and could present significant commissioning challenges.

Table 6: Possible contribution of nuclear power to cutting carbon emissions

Year	Possible emissions cut required	Possible emissions level required	Scenario 1		Scenario 2	
			Carbon saving from nuclear	Carbon reduction from nuclear (1990 baseline)	Carbon saving from nuclear	Carbon reduction from nuclear (1990 baseline)
	%	MtC	MtC	%	MtC	%
2020	30	115.57	4.02	2.4%	4.02	2.4%
2020	40	99.06	4.02	2.4%	4.02	2.4%
2030	40	99.06	6.70	4.1%	10.72	6.5%
2030	50	82.55	6.70	4.1%	10.72	6.5%
2050	60	66.04	6.70	4.1%	13.40	8.1%
2050	80	33.02	6.70	4.1%	13.40	8.1%

7 ANNEX A: NUCLEAR CO_2 EMISSIONS EVIDENCE BASE

7.1 Summary of source data

Table 7: Summary of source data and assumptions for nuclear CO_2 emissions.

	Reference	CO_2	Min	Max	Type	Geog	Enrichment	Capacity	Lifetime	Output MW
		kg per MWh								
1	IAEA	2 - 6	2	6	~					
2	Spadaro et al.	2.5 - 5.7	3	6	LWR					
3	Vattenfall 1996	2.82	3	3	BWR	*Sweden*	Centrifuge (60%)		40	1158
4	Koch 2001 (Externe)	2 - 59	2	59	~	~	~	~	~	~
5	World Energy Council	3 - 40	3	40					30	
6	Dermaut 1998 (WEC)	4	4						40	
7	WNA	6	6		BWR	*Sweden*	Centrifuge	80	40	1000
8	Uchiyama	8.56	9		Adv BWR	*Japan*	Centrifuge		30	1000
9	CRIEPI 1995	9	9			*Japan*	Centrifuge			
10	Van de Vate 1997 (IAEA)	9 - 30	9	30	PWR	*W. Europe*			40	
11	Rogner & Khan (IAEA)	9 - 30	9	30						
12	WNA	10 - 26	10	26	BWR	*Finland*	Both	80		
13	Tokimatsu	13	13		LWR	*Japan*	Centrifuge 33%	80	60	1100
14	Gagnon et al	15	15		~	*N. America*	~	~	~	~
15	White, Kulcinski & Radcliffe	15	15		PWR		Diffusion	75		1000
16	White & Kulcinski	15.2	15		LWR		Centrifuge	75	40	1000
17	Meier 2002	15	15		LWR		Centrifuge	75	40	1000
18	Paul Scherrer Institute	16	16			*W. Europe*				
19	Voss 2000	19.7	20		PWR	Germany			40	1375
20	WNA	20	20			*France*	Diffusion			
21	Voss 2002	20	20							

22	Uchiyama 1996	20.02	20		BWR	*Japan*	Diffusion		30	1000
23	WNA	22	22		BWR	*Japan*				
24	Rashad & Hammad	25.7 (9-30)	26		PWR		Diffusion	75	30	1110
25	CRIEPI 1995	28	28			*USA*	Diffusion			
26	Oko Institute 1997	34 - 60	34	60		*Germany*				
27	Uchiyama 1995	34	34		Adv LWR	*Japan*	Centrifuge	88	30	~
28	Uchiyama 1995	37	37		Adv LWR	*Japan*	Centrifuge	75	30	~
29	WNA	40	40		BWR	*US*	Diffusion			
30	Uchiyama 1995	77	77		LWR	*Japan*		75	30	~
31	WISE	140-230	140	230			Diffusion			

7.2 Detailed references & assumptions

1. IAEA (no date). *Nuclear Power & Sustainable Development.*
Available from: http://www.iaea.org/Publications/Booklets/Development/

- Complete chain from resource extraction to waste disposal including construction

2. Spadaro et al (2000). *Assessing the Difference: Greenhouse Gases of electricity generation chains.*
Available from: http://www.iaea.org/OurWork/ST/NE/Pess/assets/Euromoney 2003.pdf

- Complete chain from resource extraction to waste disposal including construction

3. Vattenfall (1996). *Vattenfall's Electricity Life Cycle Analysis.*
Available from www.vattenfall.com

- Resource use and emissions from mining to deep level depositories
- Construction, operation and decommissioning
- Installations dealing with radio-active waste.
- The fuel cycle includes the mining of uranium ore, its conversion, enrichment, and fuel production, as well as transport.
- Assumes fossil fuelled electricity production

4. Koch(2001). *Externalities and Energy Policy: the Life Cycle Analysis Approach.* Available from:
http://www.iea.org/textbase/work/2001/externalities/extern.PDF

- Using LCA ExternE methodology he direct emissions from power plant construction, operation and decommissioning

5. World Energy Council (2004). Comparison of Energy Systems using Life Cycle Assessment. Available from:
http://www.worldenergy.org/wec-geis/publications/default/launches/lca/lca.asp

- All stages of energy production and use
- Raw materials supply
- Production
- Transport
- Energy generation
- Recycling and disposal

6. WEC Dermaut (1998). *A better understanding of GHG emissions from different energy vectors and applications.*
Available from: http://www.worldenergy.org/wec-geis/publications/default/tech_papers/17th_congress/4_1_18.asp

- Greenhouse gas emissions from source or well up to the final user (not included) of the primary or secondary energy vector.

7. WNA (2005). *Energy Analysis of Power Systems Sweden* (Vattenfall)
Available from: http://world-nuclear.org/info/inf11.htm

- The Vattenfall Life Cycle Analysis study tracks energy inputs further back than others, and so is only comparable with data based on similar methodology

8. Uchiyama (1995). *Life Cycle Analysis of Advanced Nuclear Technologies.* CRIEPI, Japan.

- Influence of energy technology on the environment in processes from cradle to grave

9. CRIEPI (1995). *Characteristics of CO_2 emissions by generating type.*

- Life-cycle Co2 emissions including methane (negligible) emissions for each material, or for processing, assembly, from Japanese input-output table

10. Van de Vate (1997). *Comparison of energy sources in terms of their full energy chain emissions factors of greenhouse gases.* IAEA.

- Total Life Cycle emissions

- The entire up- stream and down-stream energy chains for electricity generation

11. Rogner & Khan (IAEA) (1997). Comparing energy options. IAEA. Available from: http://www.iaea.org/Publications/Magazines/Bulletin/Bull401/article1.html

12. See 7.

13. Tokimatsu, K., Hondo, H., Ogawa, Y., Okano, K., Yamaji, K. and Katsurai, M (2000). *Energy analysis and carbon dioxide emission of Tokamak fusion power reactors.* Fusion Engineering and Design 48, pp. 483–498. The life cycle CO_2 emission intensity includes:

- the uranium fuel production chain
- facility construction
- operation
- decommissioning
- spent fuel processing/disposal.

14. Gagnon et al (2001). *Life-cycle assessment of electricity generation options: The status of research in year 2001.* Energy Policy 30(14), pp. 1267-1278.

- Each greenhouse gas is converted to an equivalent of CO_2 and added to the inventory.
- Results vary according to whether studies considered best available commercial technology or average technology.
- All significant ''upstream'' and ''downstream'' impacts the assessment should include extraction, processing and transportation of fuels, building of power plants, production of electricity and waste disposal (biophysical impacts only)

15. White, Kulcinski & Radcliffe(1998). *Birth to death analysis of the energy payback ratio and CO2 gas emission rates from coal, fission, wind, and DT-fusion electrical power plants.*

- Construction
- Operation
- Fuel procurement
- Decomissioning
- The analyses include both thermal and electrical energy.
- The pollutants emitted during the generation of electricity depend on whether the power plant is fueled by coal, uranium, deuterium and tritium, DT, or wind.
- Energy storage not included

16. White & Kulcinski (1998). Birth to death analysis of the energy payback ratio and CO_2 gas emission rates from coal, fission, wind, and DT-fusion electrical power plants. Fusion Technology Institute. Available from: http://fti.neep.wisc.edu/pdf/fdm1063.pdf

17. Meier, P.J. (2002) *Life cycle assessment of electricity generation systems and applications for climate change policy analysis*. Available from: http://fti.neep.wisc.edu/pdf/fdm1181.pdf

- Assuming external reliance on fossil fuels
- MWh_e

18. Paul Scherner Institute (1995). *Gabe Project: Comprehensive Assessment of Energy Systems*.

- The direct emissions from the entire lifetime of power plants as well as all relevant processes upstream and downstream within each energy chain the indirect emissions associated with material and energy inputs

19. Voss, A. (2000). *Sustainable Energy Provision: A comparative assessment of the various electricity supply options.* Proceedings of the SFEN Conference "What Energy for Tomorrow?", Strasbourg, 27-29 November 2000, 19-27.

- Conversion
- Enrichment
- Fuel fabrication

- Electricity generation
- Immediate storage
- Reprocessing
- Final disposal

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8 ANNEX B: NUCLEAR SCENARIO ASSUMPTIONS

1. Growth in electricity supply & demand

As the future growth or decline in electricity consumption is uncertain, three sets of assumptions have been used when calculating nuclear's share of electricity supply. These can be defined as follows:

- 1% annual growth: continued growth of electricity demand at 1% per year, a rate which is consistent with recent trends. This would assume a continuing switch to electricity consumption from other fuels combined with an increasing prevalence and use of electronic equipment, and a lack of effectiveness of electricity conservation measures.
- 0% annual growth: stabilisation at 2004 levels (382.45 TWh) for the foreseeable future. This is slightly below current DTI projections to 2020, and could result from some effectiveness of electricity conservation measures.
- 1% annual reduction: declining electricity use, which would be a significant reverse of recent trends. This could result from sustained and effective electricity conservation measures.

2. Plant commissioning & decommissioning dates

The baseline, and both scenarios, are based on plant closure dates[xii] from Table 8 (see Annex B), and a maximum new build rate where applicable of 1GW every year (effectively, one new plant per year). This rate is ambitious, but does coincide with previous plans for 10 PWRs outlined by the Government in 1979.

[xii] Plant life extensions could substantially alter this data. There are currently proposals for plant life extensions at Hunderston B and Wylfa power stations. Dungerness B was recently given a 10-year life extension to 2018.

Where plants are scheduled to cease operations, half the total capacity lost is subtracted from that year, with the following half taken from the following year; this takes account of the assumption that on average plants will close in the middle of their scheduled year. New capacity is added to the beginning of each year, starting in 2015, which is assumed to be the earliest a new nuclear plant could be built. Again, it is worth stressing that this is widely seen as ambitious.

3. Load factors

For the Baseline, the load factor is assumed to be a continuation of the average load factor of UK plants between 1997 and 2004; this seems reasonable considering the continuing problems experienced by the AGR fleet, and their increasing age.

For scenarios 1 and 2, this load factor is used for the existing capacity, up to the respective plant decommissioning dates. New capacity is assumed to have an improved load factor of 85%, leading to a gradual improvement in the average load factor from 75.9% in 2017 to 85% in 2036 (by which point all the new capacity has been commissioned and all the old capacity is non operational).

4. Emissions displacement

The extent of CO_2 mitigation achieved by building new nuclear plants will depend to a large extent on the type of generation that is displaced. For the foreseeable future, displaced base-load plant is most likely to be gas-fired CCGT; this is certainly the assumption made by the DTI in the way they attribute CO_2 savings to renewables.

The exact displacement will depend on a number of factors, including the extent of coal-fired capacity (taking into account emissions trading, and the extent of the

Large Combustion Plants Directive), and the relative cost of different electricity generating technologies, including renewables and coal with carbon capture and storage. In the longer term, technologies such as wind and tidal power, or carbon capture and storage, may be cheaper than gas. This would reduce the emissions displacement from nuclear power.

In the data presented, emissions displacement assumes gas CCGT displacement using new plant – this would have an emissions level of 90tC/GWh.

5. Achievability

It should be noted that in several areas optimistic assumptions have been made as to the ability of a new nuclear programme to delivery and its level of performance. Most of these are in line with the claims of the industry, however failure on any one of these areas would reduce the potential emissions savings from nuclear power.

Table 8: UK nuclear power stations in order of scheduled close date (sources: BNFL[38], British Energy[39], DTI[40], NDA[41]).

No	Power Station	Capacity (MWe)	Commissioned Date	Close Date	Plant Type	Owner/ operator	Status
1	Berkeley	276	1962	1989	Magnox	NDA/BNG[xiii]	Decommissioning
2	Hunterston A	500	1964	1989	Magnox	NDA/BNG	Decommissioning
3	Trawsfynydd	470	1965	1991	Magnox	NDA/BNG	Decommissioning
4	Hinkley Point A	470	1965	2000	Magnox	NDA/BNG	Decommissioning
5	Bradwell	300	1962	2002	Magnox	NDA/BNG	Defuelling
6	Calder Hall	194	1956	2003	Magnox	NDA/BNG	Defuelling
7	Chapelcross	196	1959	2004	Magnox	NDA/BNG	Defuelling
8	Sizewell A	420	1966	2006	Magnox	NDA/BNG	Operational
9	Dungeness A	450	1965	2006	Magnox	NDA/BNG	Operational
10	Oldbury	434	1967	2008	Magnox	NDA/BNG	Operational
11	Wylfa	980	1971	2010	Magnox	NDA/BNG	Operational
12	Hinkley Point B	1220	1976	2011	AGR	British Energy	Operational
13	Hunterston B	1190	1976	2011	AGR	British Energy	Operational
14	Hartlepool	1210	1983	2014	AGR	British Energy	Operational
15	Heysham 1	1150	1983	2014	AGR	British Energy	Operational
16	Dungeness B	1110	1983	2018[xiv]	AGR	British Energy	Operational
17	Heysham 2	1250	1988	2023	AGR	British Energy	Operational
18	Torness	1250	1988	2023	AGR	British Energy	Operational
19	Sizewell B	1188	1995	2035	PWR	British Energy	Operational

[xiii] BNG stands for British Nuclear Group.
[xiv] This plant was recently awarded a life extension from 2008 to 2018.

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