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Assessing the sustainability of nuclear power in the UK

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Summary findings and recommendations for policy and decision makers

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Executive summary

SPRIng is a UK research consortium formed in 2006 and funded by EPSRC and ESRC. Led by the University of Manchester, SPRIng has worked in collaboration with City and Southampton Universities as well as with a number of partners from industry, government and NGOs. It brings together a unique range of expertise from different disciplines – energy technology, chemical engineering, environmental science, resource management, economics, safety, social and political science.

The main objective of SPRIng has been to consider the potential role of nuclear power in contributing towards a future sustainable energy system in the UK. For these purposes, SPRIng has developed a decision-support framework and a toolbox that can be used by decision-makers and other stakeholders to gain an understanding of sustainability issues related to nuclear and other electricity options and to make informed choices for a more sustainable energy system in the UK.

This report summarises some of the key findings of the project. Further information can be found in the SPRIng publications which are listed at the end of the report.

Key messages

- Decisions on the future of nuclear power and other electricity options in the UK must take into account a range of sustainability criteria rather than be based solely on a market-led approach dominated purely by economics.

- In very low energy consumption futures, the nuclear option is not essential. However, it could make a significant contribution to reducing UK greenhouse gas emissions by 2035. In futures with high energy consumption, the role of nuclear power becomes much more important for meeting climate change targets.

- Decarbonising the UK electricity mix to meet climate change targets could worsen other sustainability aspects, including resource availability, ozone layer depletion, toxicity and health impacts from radiation.

- Limiting the temperature rise to 2°C does not seem feasible unless a huge expansion of renewables (constituting 55% of the electricity mix by 2020) and nuclear (35% by 2035) became possible.

- Uranium shortages will constrain within a few decades any significant global expansion of uranium nuclear plants unless major new uranium reserves can be identified and exploited.

- Carbon taxation could play a significant role in promoting low-carbon electricity options, including nuclear. For example, a carbon price of £100 per tonne of carbon dioxide would be sufficient to trigger disinvestment from gas generators and would make nuclear plants of currently available designs highly profitable.

- If no subsidies are given to low-carbon options, nuclear power could become competitive in 2015 compared to natural gas. By contrast, onshore and offshore wind power could become competitive with gas in 2032 and 2040, respectively.

- Even when the radiological consequences of a large accident are taken into account, nuclear power remains one of the safest sources of electricity.

- Nuclear power poses complex ethical questions regarding its intergenerational impacts. Future generations, who were neither responsible for the decisions to build nuclear reactors nor enjoyed the benefits of electricity, will nevertheless have to bear both risks and costs of nuclear decommissioning and waste management.

- There is no ‘best’ electricity option overall but the choice of ‘sustainable’ options depends on stakeholder preferences and their value system.

- Findings suggest that solar, hydro and wind are the most favourable electricity options for the UK public. The least favourable are oil, coal and gas power.

- The majority of the UK public believe that the most important sustainability issues when choosing among different electricity options are water and land contamination followed by greenhouse gas emissions. Electricity cost appears to be least important, suggesting that the public believe that there is a greater difference between electricity options in terms of environmental pollution than their cost.

- Delivering sustainable futures, especially in the realms of climate change, will require large numbers of coherent decisions. This may imply a need to micromanage outcomes. In a predominately market-led approach, policy-making is distributed among a very large number of effectively autonomous agents. It is not clear as to whether such an approach can create the coherence of decision-making needed to deliver on sustainability goals. However, markets tend to be more creative in producing a range of innovative solutions to complex problems than centrally planned systems.

- Investment in low-carbon options, including nuclear, will depend among many other factors on investor confidence. Government should be clear on its energy policy to avoid undermining confidence in investment for fear of future major changes preventing appropriate returns on capital.

- Individual preferences for economic, environmental, social and ethical aspects of electricity (or any other) options will influence decision options – this should be acknowledged and borne in mind in any future decision making.

1. Introduction: The challenge of sustainability

On the face of it, 'sustainability', or 'sustainable development', would seem to be a relatively straightforward concept. It has been expressed simply, for example by the Brundtland Commission[1] in 1987, as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". The World Summit in 2005[2] noted that this would require the reconciliation of three elements: environmental, social and economic, the so-called 'three pillars' of sustainability. This is illustrated in Figure 1 which indicates that the three pillars of sustainability are not mutually exclusive but can be mutually reinforcing.

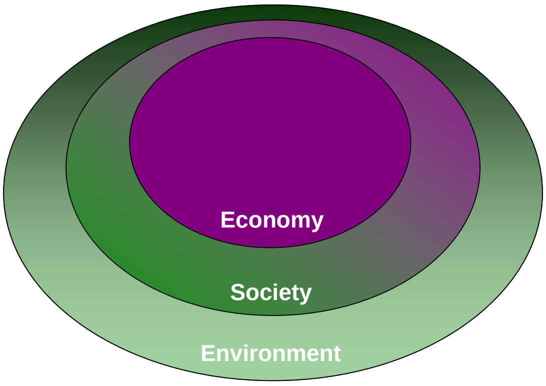

Figure 1 The three pillars of sustainable development

However, as is often the case, there is a danger that the simplicity of the definition breeds a rather simplistic debate. There are tensions of various descriptions both among and within the three pillars. For example, economic sustainability, certainly in systems which display broadly a competitive market philosophy, implies profitability. Since any industrial activity involves use of resources and creation of some pollution along supply chains, it does not seem feasible that businesses can ever reduce their environmental consequences to zero. Perhaps most elusive, and therefore least openly acknowledged, is the concept of social (and political) sustainability, especially in those democracies in which decision-making has become highly decentralised and distributed. It is not clear how a democratically accountable government could take radical action, say to reduce greenhouse gas emissions. The challenges lie in at least two areas: whether policy initiatives could be taken without widespread public support (there being evidence of growing scepticism about climate change in many countries); and whether, even if they did have such legitimacy, they have the levers of power to encourage or ensure a huge number of potentially unwilling decision-makers to take the necessary steps.

To look within one of the pillars, say environment, a thoroughgoing focus on reducing greenhouse gas emissions would have unavoidable or potential environmental consequences elsewhere, be they in terms of radioactive emissions from nuclear facilities, disruption to wildlife and visual intrusion associated with renewables or technical challenges around carbon capture and storage which could result in local environmental problems or enormous accidental releases of carbon dioxide.

It is plain, then, that sustainability cannot mean leaving the planet in precisely the same state as it was before the industrial revolution, or even as it is today – some detriment is inevitable.

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[1] WCED (1987). *Our Common Future*. Oxford University Press, Oxford.

[2] UN (2005). *World Summit Outcome*. para 48. www.who.int/hiv/universalaccess2010/worldsummit.pdf.

It should be noted that historically there have been many examples of policies or approaches which would have been unsustainable in the long term, being naturally superseded by technical innovations. When a particular resource gets short (and/or expensive) it is often the case that an alternative way of delivering the product or service in question is developed. So to argue, for example, that because uranium is ultimately a limited resource then once-through fuel cycle nuclear power is not sustainable may be true in the long term but does not of itself preclude the use of nuclear power today, if only as a stepping stone towards a truly sustainable solution.

However, certain policies might have such severe effects – 'boundary conditions' to sustainability – as to preclude recovery even if alternative techniques should be developed in due course. Even if a workable definition of sustainability can be agreed, then, in practice a policy can only be considered 'sustainable' if it does not breach boundary conditions in all the component elements of sustainability. For example, however attractive a policy might appear from say economic and environmental standpoints, if it is not sustainable socially or politically it cannot be regarded as a sustainable way forward.

It is perhaps easier to recognise a policy which is patently not sustainable rather than to define one which is. Many elements of global energy and industrial policy are clearly not sustainable, leading to a conclusion that the overall approach is also unsustainable. Global energy supply is dominated by oil, coal and gas, which collectively accounted for 80% of global traded energy in 2010. Although the precise size of the resources can be debated and is undoubtedly larger than currently realised, these resources have reserve-to-production ratios of a few decades (some estimates suggest 46 years for oil, 59 years for gas and 118 years for coal[3]). Although in recent years discoveries of oil and gas have more than kept pace with global energy demand growth (which grew by nearly 50% between 1990 and 2010), it is not feasible that this can continue indefinitely. Furthermore and perhaps even more importantly, emissions of carbon dioxide from use of energy grew by 47% between 1990 (the Rio/Kyoto base year) and 2010, putting severe strain on the global climate. At the same time, energy has remained a significant cause of social and political disruption, whether it be the belief that major military conflicts have been motivated in part by concerns over oil and gas, or the political reaction to nuclear events such as Chernobyl or Fukushima, or major proposals for renewable energy such as the Three Gorges hydropower scheme in China or onshore wind.

Thus, it is clear that in evaluating the sustainability of a particular set of policies, decision-makers will have to cope with huge factual uncertainty, *e.g.* over the precise consequences of climate change, the political future of a number of key countries owning energy resources of various descriptions or potential technological breakthroughs. They will also need to reflect the very deep differences in ethical beliefs among people and political parties.

Claims are often made that, for example, nuclear power or renewables can represent simple solutions to the question of energy sustainability – or indeed that they can be written off – because they do or do not fulfil some aspects of sustainability, say resources, economics, carbon emissions or political manageability. Such claims are unlikely to aid decision-makers in negotiating their way through the complex environment in which decisions about energy will need to be taken to move the world away from its currently deeply unsustainable course into one more in harmony with the principles of sustainability. The perfect is often the enemy of the good. Often one particular lobbying or pressure group or another will reject any policy stance which does not deliver on all of its demands. This hands an excuse for inaction to any policy maker looking for such an excuse.

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[3] BP (2011). *Statistical Review of World Energy*. www.bp.com/sectionbodycopy.do?categoryId=7500&contentId=7068481.

In an attempt to help clarify the energy and particularly nuclear sustainability issues associated with the three pillars of sustainability (techno-economic, environmental and socio-political), the SPRIng consortium has brought together experts in a wide range of sustainability aspects with two broad aims:

- to develop ways of taking a holistic view of the sustainability of nuclear and other energy options against a number of future scenarios; and
- to enable policy-makers and other stakeholders to explore, in a transparent and systematic way, the sustainability implications of different energy futures for the UK.

Two possibilities may emerge. First, it may be that there are no feasible policy frameworks which can deliver a sustainable energy future. In this case, policy makers might be advised to follow courses which most closely approximate to sustainability and prepare for a system crash. Alternatively, there may be a number of alternative sustainable futures, based on the ‘best’ trade-offs between different sustainability aspects.

However, it is unrealistic to expect that such an exercise can be based on a ‘black box’ into which data can be inputted and the answer to the question ‘Is this sustainable?’ will emerge. Decision-making based on values and judgments will still be required. Therefore, the SPRIng decision-support framework and related tools have been developed with this in mind – whilst the input data may be the same regardless of who is asking the question, the answers on the ‘best’ course of action can be quite different, depending on value judgements. Thus, the purpose of the SPRIng tools is not to provide a definitive answer to the question of sustainability of nuclear or any other power option but to offer significant support and clarity to such decision-making.

2. Nuclear power, policy and sustainability

The early years of this century saw energy policy return to the political agenda both in the UK and internationally. When SPRIng was formed in 2006, the environment in which nuclear energy was operating looked very different from today’s. Indeed, the change in the profile of nuclear power in many countries, not least the UK, during the first decade of the new century was one of the most startling aspects of the rise of energy up policy agendas.

In 2003 the UK Energy White Paper said[4]:

> *”Nuclear power’s current economics make it an unattractive option for new, carbon-free generating capacity and there are also important issues of nuclear waste to be resolved. This White Paper does not contain specific proposals for building new nuclear power stations.“*

Just three years later the 2006 Energy Review[5], by contrast, concluded:

> ”N*ew nuclear power stations would yield economic benefits in terms of carbon reduction and security of supply (and) the Government considers that new nuclear has a role to play in the future UK electricity generating mix alongside other low-carbon generating options.“*

The Stern Review[6] provided further impetus to addressing the problem of climate change, estimating that the power sector around the world would have to be at least 60%

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[4] DTI (2003). *Our Energy Future: Creating a Low-carbon Economy.* www.decc.gov.uk/en/content/cms/legislation/white_papers/white_paper_03/white_paper_03.aspx.

[5] DTI (2006). *The Energy Challenge*. http://webarchive.nationalarchives.gov.uk/+/http://www.berr.gov.uk/files/file31890.pdf.

decarbonised by 2050 to stabilise emissions of carbon dioxide at a manageable level. In 2008 the Nuclear Energy White Paper was stating[7]:

> *"The Government has concluded that nuclear should have a role to play in the generation of electricity. Nuclear power is a tried and tested technology. It has provided the UK with secure supplies of safe, low-carbon electricity for half a century. More than ever before, nuclear power has a key role to play as part of the UK's energy mix."*

The 2008 Nuclear White Paper in effect removed the barriers to new nuclear build which had existed for almost two decades[8].

Government's broadly pro-nuclear stance largely survived both a change of political control and, it seems, the accident at Fukushima. The coalition government formed between the Conservatives and the Liberal Democrats in the General Election of 2010 produced a detailed Coalition Agreement[9] which dealt with nuclear power as follows:

> *"Liberal Democrats have long opposed any new nuclear construction. Conservatives, by contrast, are committed to allowing the replacement of existing nuclear power stations provided that they are subject to the normal planning process for major projects (under a new National Planning Statement), and also provided that they receive no public subsidy. We will implement a process allowing the Liberal Democrats to maintain their opposition to nuclear power while permitting the Government to bring forward the National Planning Statement for ratification by Parliament so that new nuclear construction becomes possible."*

Although the Secretary of State for Energy and Climate Change, Chris Huhne, comes from the Liberal Democrat Party, his statements as Minister made it clear that he would support nuclear new build as long as the 'no subsidy' condition was met. Further, it became clear 'no subsidy' was to mean that nuclear power would receive no specific subsidy that was not available to other energy sources: providing a floor on the carbon price, for example, would be legitimate even though it would improve nuclear economics[10].

Key recent developments related to nuclear power have included:

- The publication of a 'Justification Decision' for Areva's EPR and Westinghouse's AP1000 reactor designs in October 2010 (after three years of consultation), saying that in each case the benefits of building such reactors would outweigh any disadvantages[11].
- Indication of a positive Generic Design Assessment[12] to Areva's EPR and Toshiba/Westinghouse's AP1000 reactor designs, subject to satisfactory resolution of some outstanding issues, meaning that issues about the safety and effectiveness of these designs will not need to be examined on each occasion a new reactor is proposed.

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[6] Stern et al. (2006). *Stern Review on the Economics of Climate Change*. http://webarchive.nationalarchives.gov.uk/+/http:/www.hm-treasury.gov.uk/sternreview_index.htm

[7] DECC (2008), *Meeting the energy challenge: a White Paper on nuclear power.* www.decc.gov.uk/assets/decc/what%20we%20do/uk%20energy%20supply/energy%20mix/nuclear/whitepaper08/file43006.pdf.

[8] Greenhalgh, C. and A. Azapagic (2009). Review of Drivers and Barriers for Nuclear Power in the UK. *Environmental Science & Policy* 12(7) 1052-1067.

[9] Cabinet Office (2010). *The Coalition – Our Programme for Government.* www.cabinetoffice.gov.uk/sites/default/files/resources/coalition_programme_for_government.pdf.

[10] DECC (2011). *Electricity Market Reform White Paper.* www.decc.gov.uk/en/content/cms/legislation/white_papers/emr_wp_2011/emr_wp_2011.aspx.

[11] HM Government (2010). Statutory Instruments 2010 No. 2844, The Justification Decision (Generation of Electricity by the EPR Nuclear Reactor) Regulations 2010. www.legislation.gov.uk/uksi/2010/2844/made?view=plain.

[12] DECC (2009). *Generic Design Assessment.* www.decc.gov.uk/en/content/cms/meeting_energy/nuclear/new/generic/generic.aspx.

- The publication of a National Policy Statement[13] in July 2011, including a clear statement from government that it "*believes that energy companies should have the option of investing in new nuclear power stations. Any new nuclear power stations consented under the Planning Act 2008 will play a vitally important role in providing reliable electricity supplies and a secure and diverse energy mix as the UK makes the transition to a low carbon economy.*" Eight sites were identified as suitable for nuclear new build and the measure was passed in parliament by 267 votes to 14.
- Regulators and the nuclear industry working with government to develop planning and other regulatory approvals processes so as to avoid unnecessary delay and uncertainty, including setting down clear practicable public consultation processes[14].
- The creation of the Office for Nuclear Regulation (ONR), part of the Health and Safety Executive, bringing together the Nuclear Installations Inspectorate, the Office for Civil Nuclear Security, the UK Safeguards Office and the Department for Transport's Radioactive Materials Transport Division.
- Setting and moving to implement a national policy on the management of radioactive wastes through the Committee on Radioactive Waste Management (CoRWM)[15]. Local authorities in Cumbria expressed an interest in hosting a national waste repository if geological conditions can be met.
- Planning permission granted to EDF Energy to carry out preliminary works at Hinkley Point in Somerset[16]; applications lodged for a Site License and Environment Agency approvals, prior to a full application expected late in 2012.

After the nuclear accident at Fukushima in March 2011, a report on the safety and security of British nuclear power plants was ordered under the leadership of Mike Weightman, the Chief Inspector of Nuclear Installations. The report, published in October 2011[17], concluded that there was no need to stop current operations and that an earthquake on the Japanese scale was extremely unlikely in the UK. With regard to regulation, Weightman found: "*In the course of our examination of the events in Japan, we have not seen any significant defects in the UK's approach to nuclear regulation – i.e. a broadly goal-setting system, underpinned by a flexible and adaptable licensing regime*". The report concluded that the Safety Assessment Principles were still appropriate and that there was no need to change siting strategies or the policy towards multi-reactor plants, though a human factors analysis was likely to be fruitful. Similar reports in other countries broadly came to similar conclusions, though in some cases (Germany, Switzerland, Italy, Japan itself) there were major changes in government policy towards nuclear new build and/or existing plants.

Yet despite these developments, it is far from clear how sustainable the nuclear option is overall, compared to other electricity options. Issues such as wider environmental impacts, health and safety, investment risks, security (in both the fuel and proliferation senses), political support, public trust and public perceptions must also be considered to understand the full sustainability implications of nuclear generation. Any decisions about the future of nuclear power will need to consider these and other relevant issues, taking an integrated, balanced and impartial approach to evaluating the relative techno-economic, environmental, and socio-political sustainability of nuclear power. To assist with this process, SPRIng has developed a decision-support framework and a toolbox outlined in Figure 2. The following sections discuss how the framework can be applied and what key messages emerge from the consideration of different aspects of sustainability of nuclear and other energy options.

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[13] DECC (2011). *National Policy Statements for Energy Infrastructure*. www.decc.gov.uk/en/content/cms/meeting_energy/consents_planning/nps_en_infra/nps_en_infra.aspx.

[14] Hendry, C. (2010). Speech to the Nuclear Industry Forum, DECC. www.decc.gov.uk/en/content/cms/news/NIF10/NIF10.aspx.

[15] DECC (2011). *Managing Radioactive Waste Safely*. http://mrws.decc.gov.uk.

[16] West Somerset District Council (2011). *Proposed New Nuclear Power Station, Hinkley Point C*. www.westsomersetonlinegov.uk/HinkleyPoint.

[17] Weightman, M. (2011). *Japanese Earthquake and Tsunami: Implications for the UK Nuclear Industry.* Final Report. HM Chief Inspector of Nuclear Installations, Office for Nuclear Regulation. September 2011. www.hse.gov.uk/nuclear/fukushima/final-report.pdf.

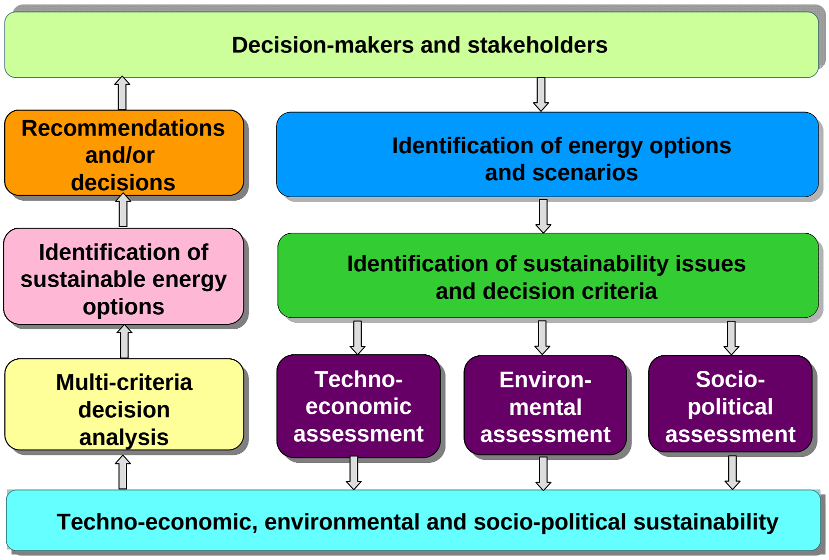

Figure 2 SPRIng decision-support framework.

The framework enables decision-makers and other stakeholders to consider different aspects of sustainability in an integrated, impartial and balanced way and to identify sustainable energy options for the UK. Although the focus of SPRIng was on nuclear energy, the sustainability assessment is in the context of all energy options available to the UK.

3. Techno-economic considerations

Key messages

- It is essential to consider the full implications of fuel availability for all energy options, including uranium used in most of today’s nuclear reactors.
- Uranium shortages will constrain within a few decades any significant expansion of uranium nuclear plants unless major new uranium reserves can be identified and exploited.
- In the absence of major new uranium discoveries, other fuel cycles such as plutonium-based fast reactors, and/or thorium-fuelled cycles, would be needed. However, all would require a considerable quantity of uranium and/or its by-product plutonium, to get them started.
- The expansion of fast reactor capacity will be constrained by the number of the initial uranium reactors from which plutonium would be extracted and the speed at which fast reactors could be built. Even in the more optimistic scenarios, fast reactors could not supply the world’s present consumption of electricity until the beginning of the 2100s.
- Photovoltaics are currently benefitting from far higher financial incentives through Feed-in Tariffs (FiTs) than any other electricity option. The subsidies exceed its levelised costs making PV profitable without selling any electricity back to the grid.
- Although nuclear power does not benefit from FiTs and Renewables Obligation Certificates (ROCs), it effectively receives an incentive by not being subject to the carbon tax.
- Carbon taxation could play a significant role in promoting low-carbon electricity options, including nuclear. For example, a carbon price of £100 per tonne would be sufficient to trigger disinvestment from gas generators and would make nuclear plants of currently available designs highly profitable.

- The effects of any carbon taxation on investment in low-carbon options, and on electricity prices, will depend on their time path, that is whether the tax is introduced immediately or progressively over the next two decades.
- If no subsidies are given to low-carbon options, nuclear power could become competitive in 2015 compared to natural gas. By contrast, onshore and offshore wind power could become competitive with gas in 2032 and 2040, respectively.

Key findings and discussion

Uranium reserves

Britain cannot have a nuclear power policy independent of the rest of the world. Currently the UK accounts for less than 2.5% of world nuclear power production and has no independent reactor manufacturing capacity. With regard to nuclear fuel, the UK has no indigenous uranium, the fuel used in most of today's reactors, so it is totally dependent on imports from other countries.

Estimates of global uranium reserves range widely, from a few decades to over 100 years, assuming current consumption of about 43,000 tonnes per year[18]. SPRIng has developed a range of models[19,20] to address the issue of uranium supply and the economics of its mining. The models indicate that the world has too little easily-mined uranium to deliver low-carbon electricity by 2040 or 2050 and to sustain the electricity demand growth we saw in the past twenty years (1.9% per year)[21] for more than a decade or two after that – unless considerable new uranium reserves are discovered and/or new economic and environmentally attractive ways of utilising low-grade resources are developed.

After the easily-mined uranium has been exhausted, perhaps the most obvious next step would be 'fast reactors' which extend the lifetime of uranium fuel by a factor of 50 (similarly for thorium) – enough energy for hundreds of years. However, they require an initial loading of plutonium, which must be extracted from spent uranium fuel. Although the UK has more plutonium than most countries, that could still only meet 20% of today's UK electricity needs. Therefore, the UK would remain almost totally dependent on external supplies of uranium to fuel today's reactors and to provide the extra plutonium needed to start up fast reactors.

Once started, a fast reactor can produce more plutonium than it consumes (this is often referred to as 'breeding') and it needs no fresh plutonium or any other fuel for hundreds of years. Hence an existing fleet of fast reactors can generate surplus fuel to start up additional fast reactors. However, this 'growth rate' may be at best 5% (and probably realistically around 3%) of the initial amount of plutonium per year so a small starting fleet of fast reactors needs a long 'growing' time before it can contribute significantly to electricity supply. This suggests that decarbonising electricity supply via nuclear power would require a large fast reactor programme as soon as possible to break the dependence of the plutonium supplies on the existing uranium reactors. However, fast reactors will not be available commercially for an estimated 30 years so that, until then, building up the plutonium stocks will remain dependent on burning uranium in conventional reactors.

An example of a possible transition pathway from the conventional light water reactors (LWR) to fast reactors (FR) is illustrated in Figure 3. This scenario observes practical

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[18] Azapagic, A. and S. Perdan (2011). Sustainability of Nuclear Power. Chapter 9. In: *Sustainable Development in Practice: Case Studies for Engineers and Scientists*, 2nd ed. (Azapagic, A. and S. Perdan, eds.). John Wiley & Sons, Chichester.

[19] Evatt, G., P. Johnson, S. Howell, P.W. Duck and J. Moriarty (2010). The Expected Lifetime of an Extraction Project. *Proceedings of the Royal Society A*, 467 (2125) 244-263.

[20] Evatt, G., P. Johnson, S. Howell and P.W. Duck (2010). The Measurement and Inclusion of a Stochastic Ore-grade Uncertainty in Mine Valuations Using PDES. *IAENG International Journal of Applied Mathematics*, 40(4).

[21] BP (2011). *Energy outlook 2030*. London. www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2011/STAGING/local_assets/pdf/2030_energy_outlook_booklet.pdf

constraints but it makes no attempt at economic optimisation. It assumes a world nuclear programme which grows by 2035 from today's 376 GW to 2600 GW of LWR, slightly over the current global electricity demand of around 2300 GW. As illustrated in Figure 3, the cumulative plutonium output could start the growth of FR capacity sometime around 2045. However, FR would not be able to provide today's global electricity demand until 2100. Fast reactor growth would eventually catch up the growing electricity demand but not until well into the 22nd century.

The expected 30 year delay in bringing a major fast reactor programme on line would place an enormous extra strain on proven uranium resources. For example, in the scenario described here, it would be necessary to provide several times the world's presently known economically extractable uranium supply. However, this is not necessarily out of the question. For example, global oil and gas reserves each trebled over the course of the thirty year period from 1980-2010 (see Figure 4). Arguably, there is a greater potential of increasing the known uranium reserves due to the relatively low level of exploration in recent decades and the increasing possibility of extraction from alternative sources such as phosphates and, at higher prices, sea water.

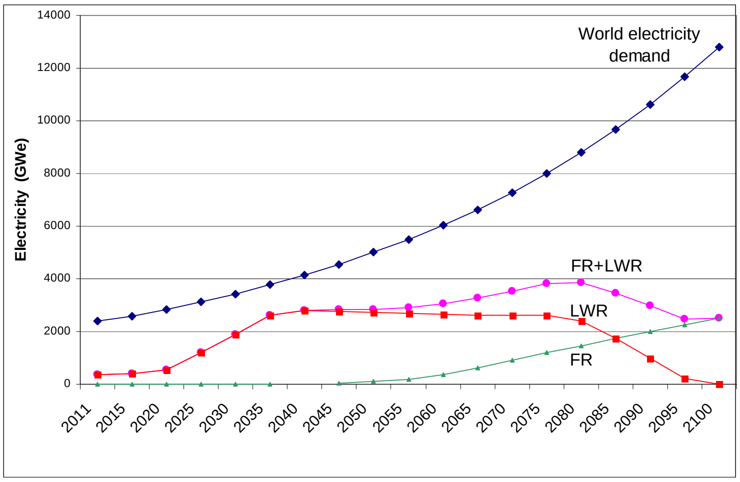

Figure 3 An example of transition from present light water reactors (LWR) to fast reactors (FR). FR are not able to meet the present world electricity demand until 2100.

Assumptions: FR growth rate: 3.5% per year, 15 years doubling time. Electricity demand increase over the period: 1.9% per year. The introduction of fast reactors: 30 years after the uranium leaves LWR. Assumes availability of reprocessing plants to separate the plutonium. Current world stocks of spent uranium and separated plutonium are excluded as having minor impact.

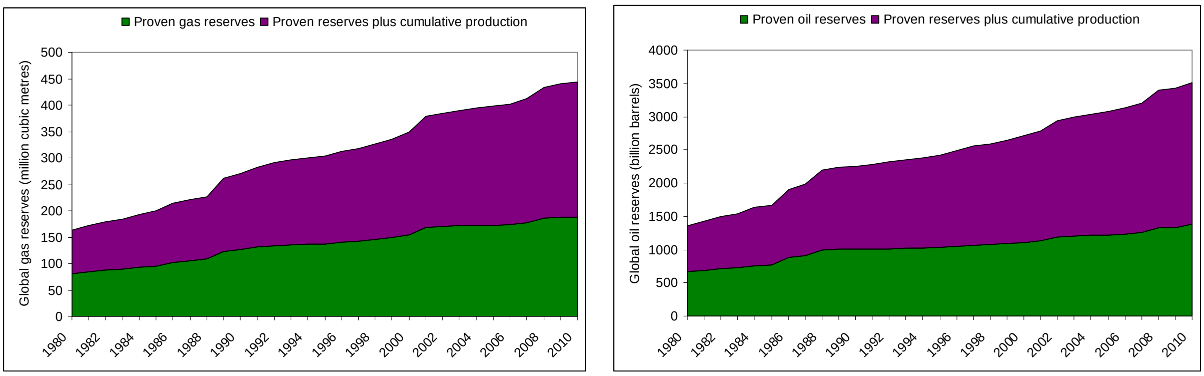

Figure 4 Growth in global gas and oil reserves from 1980-2010[3]

Electricity costs

Costs of electricity depend on capital, operational, fuel and decommissioning costs. Taking all these into account, electricity from gas is currently the cheapest option, with an estimated cost of 6.6 pence/kWh (Figure 5). The most expensive option is electricity from photovoltaics (PV), costing five times more than electricity from gas (30.2 pence/kWh). These costs depend on many factors, including capital costs to build power plants, costs of fuel as well as the discounting rates (*i.e.* rates of return on investment) assumed in the calculations. For example, 80% of the cost of nuclear power is due to the capital cost while the cost of fuel – uranium – contributes only 5% to the total. The converse is true for gas, where 75% of the cost is due to the fuel and less than 20% due to the cost of the power plant.

The fact that nuclear as well as wind and PV are highly capital-intensive makes them more susceptible to discount rate choice, with higher discount rates making them more expensive. For example, increasing the discounting rate for nuclear power from 5% to 10% increases the total levelised costs by around 60%[22].

There is much argument over discounting and its role in sustainability, the main premise of which is that high discount rates grossly diminish liabilities that occur far into the future (like nuclear plant decommissioning) and that this is effectively a theft from future generations. Some people argue that a low or zero discounting rate should be used in such cases. However, given that power stations in the UK are privately owned and operated (although some public contribution often exists), they will be commissioned or otherwise on a market basis. Therefore, making decisions based on a very low or zero discount rate is economically unrealistic as it neglects both the opportunity cost of investment and the financial risk to the investor[23].

A high capital component in the total costs of an electricity option can be a particular problem in an uncertain market as it exposes owners to greater losses if plant lifetime is cut short for any reason. A recent example are German nuclear power plants which, following the Fukushima events, are going to be closed down well before they reach the end of their economic lives.

On the other hand, electricity options that have high fuel cost component are susceptible to fuel price volatility, particularly over periods as long as the lifetime of a power plant. As such, they are the major component of future cost uncertainty. This is a significant problem for fossil fuel power stations, particularly as fuel reserves decrease and demand grows fast due to developing countries such as China and India. Gas plant owners are particularly exposed to highly uncertain operating costs in future as gas constitutes 75% of the total levelised costs. Coal plants are also vulnerable to fuel price increases as coal costs contribute around 30% to the levelised costs of electricity.

Financial incentives

Two types of financial incentives can be distinguished:

- regulatory tools used by government to drive the market in a particular direction and
- hidden subsidies that are not used as market tools.

Examples of regulatory tools include the Feed-in Tariffs (FiTs), Renewables Obligation Certificates (ROCs) and carbon tax paid by fossil-fuel electricity generators. They are all aimed at promoting investment in low-carbon technologies. Figure 5 compares the total effect of these regulatory mechanisms for nuclear, wind and PV electricity[25]. As shown, PV is currently benefitting from far higher incentives than any other technology as the government attempts to make it financially viable via regulation. It is interesting to note that the total

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[22] IEA and NEA (2010). *Projected Costs of Generating Electricity 2010 Edition*. OECD Publications, Paris.

[23] Stamford, L. and A. Azapagic (2011). Sustainability Indicators for the Assessment of Nuclear Power. *Energy* 36 6037-6057.

incentives for PV (at 40.6 p/kWh) exceed its levelised costs (30.2 p/kWh), making it under current conditions profitable without selling any electricity back to the grid (but this may change from 2012 under current proposals[24]). Although nuclear does not benefit from FiTs and ROCs, it still profits from not being subject to the carbon tax, effectively receiving an incentive of 0.51 p/kWh.

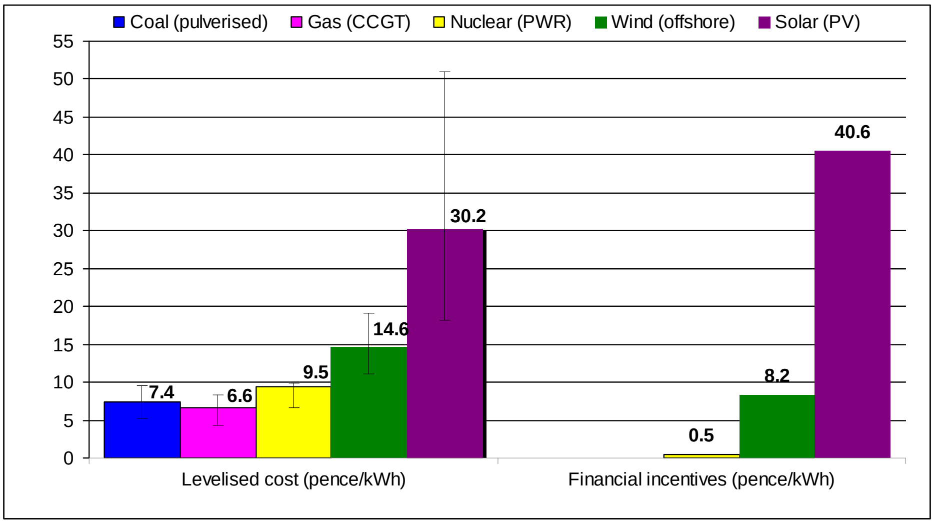

Figure 5 Levelised costs and financial incentives for different electricity options[25]. Electricity from photovoltaics (PV) currently has the highest levelised costs (30.2 pence/kWh) and from gas the lowest (6.5 pence/kWh). Electricity from PV also has the highest incentives (40.6 p/kWh) and nuclear the lowest (0.51 p/kWh); wind receives 8.2 p/kWh.

The levelised costs comprise capital, operational, fuel and decommissioning costs. The figure shows the average costs and the costs variation (the latter is shown in the figure as error bars). The financial incentives comprise Feed-in Tariffs (FiTs), Renewable Obligation Certificates (ROCs) and carbon tax avoided. The latter is estimated assuming the current carbon price of £13/t CO_2 and that nuclear and wind replace combined cycle gas turbine (CCGT) plants which emit 400 g CO_2/kWh. This amounts to 0.51 p/kWh which is the only ‘incentive’ nuclear receives. PV benefits from the average FiTs payment of 40.6 p/kWh for generating electricity and wind receives 7.7 p/kWh as ROCs.

Hidden subsidies, on the other hand, include costs that are borne by the economy indirectly and which serve to increase the economic attractiveness of particular technologies. They can include:

- operator insurance caps;
- the administrative cost of technology-specific market tools (ROCs, FiTs and carbon tax);
- increased maintenance costs incurred by thermal power plant owners as they are forced to run their plants more variably to compensate for intermittent renewables on the grid;
- the costs of increased system reserve due to intermittent renewables and single large capacity plants on the grid;
- any subsidies in the production of gas and coal in the UK; and
- subsidies to fossil fuel production in fossil fuel exporting countries.

Taking insurance caps as an example, nuclear installations in the UK are currently only required to insure for a maximum liability in case of an accident of £140 million (although this

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[24] The Government is proposing to reduce the FiT payments by 50% for PV installations smaller than 250 kW. www.decc.gov.uk/en/content/cms/meeting_energy/renewable_ener/feedin_tariff/feedin_tariff.aspx.

[25] Stamford, L. and A. Azapagic (2012). Comparative Sustainability Assessment of Electricity Options for the UK. Forthcoming.

is currently being amended to the equivalent of ~£1.05 billion)[26]. By comparison, the estimated losses to Belarus as a result of the Chernobyl accident are in the region of £145 billion over 30 years[27]. Therefore, the difference arguably represents a subsidy that plant owners receive by not being required to insure their true liability (although it is also true that such large sums cannot be insured by the market).

However, most of the hidden incentives have not been analysed thoroughly for the UK, so that it is not possible to put an estimate on the total hidden costs for different electricity options. Therefore, much further research is needed in this area.

Carbon tax and investment

Carbon tax could play a significant role in promoting investment in low-carbon options. Carbon reduction is a ‘shared good’ but at present carbon emissions (and the harm they might cause) are only weakly charged to the emitter. However, for this to work, carbon price must be high enough to trigger disinvestment in fossil power and investment in alternatives such as nuclear and renewables.

It is clear that the EU Emissions Trading Scheme (ETS) has had a very limited effect on the financial viability of low-carbon technologies owing to a low carbon price[28] – in 2010/11, trading at an average of £13 per tonne of CO_2. To strengthen the scheme, the Government has proposed to introduce a Carbon Price Floor (CPF) from 2013, starting at £16/t CO_2 and rising to £30/t by 2020 and £70/t by 2030 (2009 real prices)[10]. This change will have a modest effect on the incentives received by PV and wind installations, as they already receive far greater incentives from the FiTs and ROCs. Nuclear power, on the other hand, does not receive ROCs or FiTs benefits and has levelised costs significantly lower than wind or PV, meaning that this increase in carbon price will significantly strengthen its economic case.

Going even further, SPRIng models suggest that a price of around £100/t CO_2 would make nuclear plants of currently available designs highly profitable, encouraging investment. Assuming a reasonably economically efficient nuclear industry, consumer prices for nuclear power should be largely unaffected by this increase in carbon price as no nuclear generator will need to pay it. However, the costs of electricity generated by fast reactors (FR) may prove higher than those from today’s nuclear reactors because FR are more complex and rely on fuel reprocessing and refabrication. But, as the fuel itself accounts for a small proportion of nuclear electricity costs, this should not raise prices of electricity greatly.

The effects of carbon price also vary with their time path. If the price were to rise to £100/t CO_2 now and no replacement nuclear capacity were available, gas generators could, and presumably would pass the tax on to consumers, raising electricity prices by about 40%. This could have significant deflationary effects on the wider economy – if the carbon costs were passed on suddenly and fully to electricity consumers they would lose spending power, weakening the demand. In that case, government might need to recycle enough of the carbon tax in public expenditure (*e.g.* by subsidising energy efficiency equipment or techniques) or by reducing other taxes, to keep living standards up and encourage economic activity.

By contrast, raising the carbon price progressively to £100 per tonne over two or three decades (the lifetime of one gas generator) would be likely to trigger progressive

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[26] DECC (2011). Implementation of Changes to the Paris and Brussels Conventions on Nuclear Third Party Liability: A Public Consultation. www.decc.gov.uk/en/content/cms/consultations/paris_brussels/paris_brussels.aspx.

[27] The Chernobyl Forum (2006). Chernobyl’s Legacy: Health, Environmental and Socio-Economic Impacts. International Atomic Energy Agency, Austria.

[28] Perdan, S. and A. Azapagic (2011). Carbon Trading: Current Schemes and Future Developments. *Energy Policy*. 39(10) 6040-6054.

replacement of gas generators as they reach the end of their economic lives. In that case, investors would lose less investment and electricity consumers would not face a huge increase in electricity price, which should increasingly be set by the level of competition between nuclear plants.

The SPRIng models also indicate that, if gas prices continued to increase and no subsidies were given to low-carbon options, nuclear power could become competitive relative to gas in 2015. On a comparable basis, onshore and offshore wind power could become competitive with gas in 2032 and 2040, respectively[29].

4. Environmental considerations

Key messages

- It is very difficult to construct any futures in which growth in energy consumption continues and climate change targets (in terms of limiting temperature rises to 2°C) can be met.
- Even in very low energy demand scenarios, it is likely that electricity consumption will grow due to the anticipated increase in electricity use for heating, cooling and transportation.
- In very low energy consumption futures, the nuclear option is not essential. However, it could make a significant contribution to reducing UK greenhouse gas emissions by 2035.
- The higher the overall energy use, the more important a nuclear contribution to reducing greenhouse gas emissions would become.
- Meeting the 2°C target does not seem feasible unless a huge expansion of renewables (constituting 55% of the electricity mix by 2020) and nuclear (35% by 2035) became possible.
- Changing the energy mix to mitigate climate change must not be at the expense of other environmental consequences. The SPRIng results show that on a life cycle basis most environmental impacts are increased while trying to reduce carbon emissions. These include human and eco-toxicity, ozone layer depletion and health impacts from radiation.

Key findings and discussion

Carbon emissions

SPRIng developed four energy scenarios up to 2070 addressing total UK energy demand, including electricity and considering different climate change targets. As with all scenario analyses, the intention is to illustrate various possible energy futures and pathways rather than attempting to make any forecasts or predictions.

The first scenario (AB) assumes that there is relatively little effort to tackle climate change while the second (C1) assumes that the UK broadly follows its current path towards 80% reduction in carbon emissions by 2050 compared to 1990 levels and does this with an overall reduction in energy demand. The third scenario (C2) assumes identical emission reductions as in C1 but with a high increase in energy demand. Finally, the fourth scenario (D) assumes more rapid emission reductions to limit the global temperature rise to 2°C or less.

Total electricity demand assumed in the SPRIng scenarios and the related targets for reduction of (direct rather than life cycle) carbon dioxide emissions are given in Figure 6. As shown, there is little difference in actual electricity demand in scenarios AB, C1 and D, all showing slight increases over time. In scenario C2, however, there is a three-fold increase in

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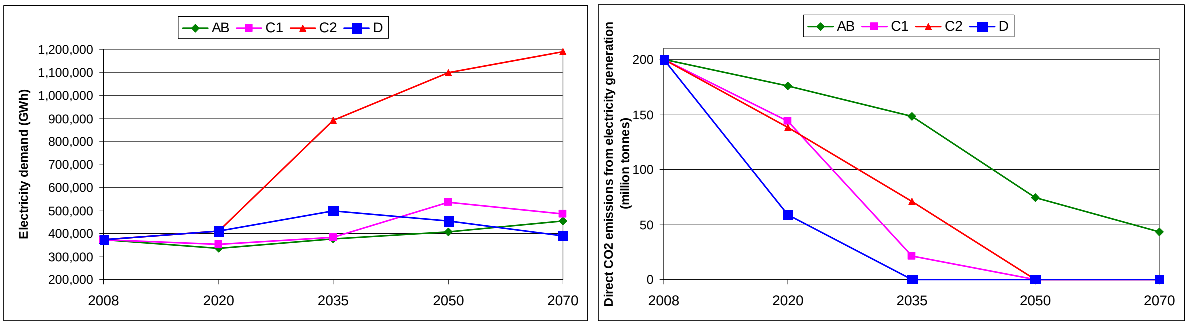
[29] Thomas, P. and N. Chrysanthou (2012). Using Real Options to Compare the Economics of Nuclear and Wind Power with Electricity from Natural Gas. *Nuclear Energy. Special Issue of J of Power and Energy.* In press.

demand as all energy is assumed to be provided by electricity by 2070, including heating and transport. Scenario D is the most challenging with respect to climate change targets: limiting the temperature rise to 2°C requires CO_2 emissions from electricity to drop very rapidly from today's 200 Mt to just under 60 Mt by 2020 and to near zero (0.2 Mt) by 2035.



(a) Electricity demand **(b) Carbon dioxide reduction targets**

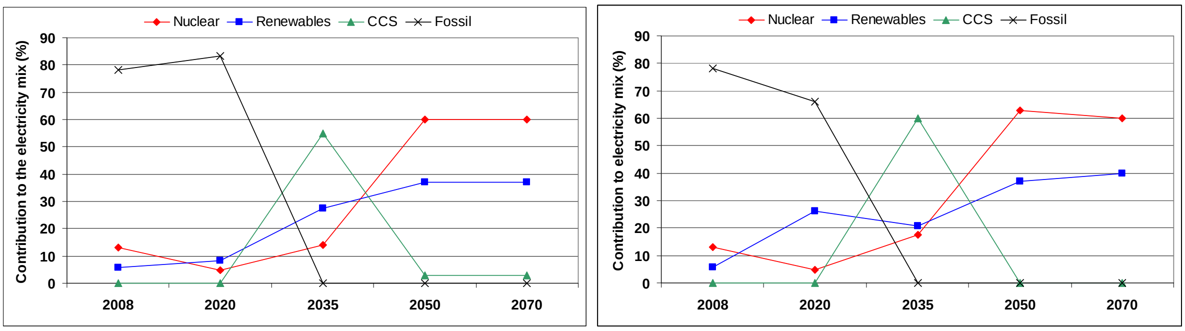
Figure 6 SPRIng electricity scenarios for the UK up to 2070

Whichever scenario is examined, it is clear that there is a need to decarbonise electricity generation to meet the climate change targets. Clearly, the increasing demand for electricity and the need for low- and zero-carbon generation have significant implications for the generation technologies that are used and the potential role for nuclear power.

With respect to the role of nuclear power in meeting the UK carbon reduction targets, based on the assumptions our scenario analysis shows that:

- Nuclear is not essential under the assumptions of Scenario AB, the least carbon constraining scenario – however, climate change targets are not met in this case.
- Reducing carbon emissions by 80% by 2050 while increasing electricity demand only slightly over time (Scenario C1) can only be achieved with high penetration of low-carbon technologies, including nuclear, renewables and carbon capture and storage (CCS). For example, by 2035 the electricity mix would need to be 55% CCS, 14% nuclear and 28% renewables. By 2050, CCS would need to go down to 3%, nuclear up to 60% and renewables to 37% (see Figure 7). From today's perspective, this looks infeasible.
- Meeting the 80% carbon target by 2050 but with a very high energy demand (Scenario C2) is even less feasible and can only be achieved by violating too many constraints. For example, it would be necessary for the electricity mix to be 60% CCS and 18% nuclear by 2035. By 2050, all CCS would need to be discontinued, requiring a massive rise in nuclear to 63%, with renewables contributing 40% of the total electricity demand in 2050 (Figure 7).
- Meeting the 2°C target (Scenario D) is not feasible unless a huge expansion of renewables (constituting over 55% of the electricity mix by 2020) and nuclear (over 35% by 2035) became possible. Due to the stringent carbon emission targets, only a very small amount of gas CCS (<1.5%) can be used.

Therefore, as SPRIng findings show, meeting the carbon targets with the currently available technologies will be challenging, if not impossible. Therefore, either a drastic reduction in energy demand or breakthrough technologies (*e.g.* fast reactors or fusion) or both may be needed.



(a) Scenario C1 **(b) Scenario C2**

Figure 7 Example results for the UK electricity mix that would be required to meet the climate change targets.

The results indicate that meeting the climate change targets would only be feasible at an extremely high penetration of renewables, nuclear and carbon capture and storage (CCS), currently thought infeasible. In both scenarios, fossil-based electricity technologies would require rapid decommissioning with the contribution from renewables, nuclear and CCS growing very fast. CCS would need to be deployed rapidly from 2020-2035 and then discontinued equally rapidly by 2050.

Carbon emissions vs other environmental impacts

Meeting the carbon reduction targets should not be achieved at the expense of other environmental impacts. Therefore, before any carbon-driven changes are made to the UK energy mix, it is important that the life cycle environmental implications of any such changes are fully understood.

The SPRIng work shows that in most scenarios considered, human and eco-toxicity are increased while trying to reduce carbon emissions. In some cases, other environmental impacts, such as ozone layer depletion, eutrophication and impacts from radiation also go up. Figure 8 provides an example which indicates that meeting the carbon targets by 2050 in Scenario C1 would increase human toxicity and ozone layer depletion by a factor of 2 and the radiation impacts by a factor of 5, mainly due to the high contribution of nuclear power to the electricity mix.

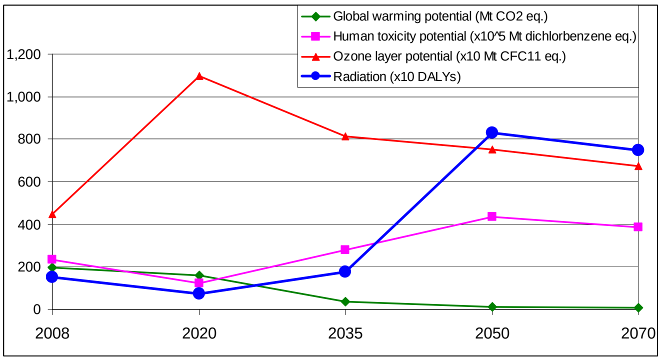


Figure 8 An example of the trade-offs between carbon emissions and other environmental impacts. The figure shows that all impacts increase while trying to reduce the carbon emissions (shown here as global warming potential).

The figure shows the results for Scenario C1 (80% reduction of CO_2 by 2050). All impacts are on a life cycle basis, including CO_2 equivalent emissions (represented as global warming potential). Electricity mix assumed in 2050: 60% nuclear, 37% renewables (23.6% wind, 11% biomass, 1.3% hydro and 1.1% marine) and 3% gas CCS. DALYs: Disability Adjusted Life Years (sum of total years of potential life lost due to premature mortality and the years of productive life lost due to disability). The values for some impacts have been scaled to fit on the same graph. To obtain the original value for an impact, multiply its value shown on the vertical axis by the scaling factor for that impact shown in brackets in the legend.

5. Socio-political and ethical considerations

Key messages

- Even when the radiological consequences of a large accident are taken into account, nuclear power remains one of the safest sources of electricity.
- The public perceives radiation as a significant potential health risk. As a result, government may feel particular pressure to respond by putting various measures in place to demonstrate that it is taking seriously any possible major accident. This may require expenditure of large sums of money which could bring little overall benefit. Indeed, if such a response leads to an increase in psychological harm (fear, stress etc.), its overall effect may be to exacerbate health problems, not diminish them.
- In many countries and states including the UK, governments cannot take decisions such as ‘new nuclear plants should be built’, being only in a position to seek to influence the decisions of other agents.
- The decisions necessary to reduce energy use significantly and to move to a low-carbon future are many and complex. The current mixture of market mechanisms and frequent state intervention has not thus far delivered anything approaching the reductions in greenhouse gas emissions necessary to limit temperature rises to 2°C. Indeed it may not be capable of doing so in principle.
- Investment in low-carbon options will depend, among many other factors, on investor confidence – government should be clear on its energy policy to avoid undermining confidence in investment for fear of future major changes preventing appropriate returns on capital.
- Nuclear power poses complex ethical questions regarding its intergenerational impacts and potential to harm or benefit future generations which must be taken into account when assessing its sustainability.
- The nuclear option also raises the intriguing issue of international moral and legal responsibilities in the context of climate change, namely whether the UK and other industrialised countries have moral rights to deny certain countries to develop new nuclear capacity if they themselves regard it necessary, even critical, for reducing their emissions of greenhouse gases. However, any application of this type of ethical reasoning in practice needs to take into account the risk of nuclear proliferation and related socio-political concerns.

Key findings and discussion

Safety risks

As events such as Fukushima, Chernobyl and BP Macondo demonstrate, technological solutions to big energy problems can be accompanied by high human and environmental hazards, even if their probability of occurrence is low.

Decisions on expenditure on schemes to protect humans and the environment inevitably involve a large measure of subjective opinion, often resulting in some striking inconsistencies as to the cost of saving a life between, say, road travel and nuclear power. The new ‘J-value’ framework[30] applied within SPRIng to assess safety risks of different electricity options allows a more objective assessment of how much money ought to be spent and offers decision makers a more level playing field when assessing risks across different technologies.

For example, the J-value method has been applied to calculate the amount of money that might reasonably be spent to eliminate entirely the residual risk from different electricity

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[30] Thomas, P., R. Jones and J. Kearns (2010). J-value Safety Assessment: The Two Trade-offs. *Measurement + Control* 43(5) 142 – 145.

options, taking the construction and fuel chain into account[31]. As the results in Figure 9 suggest, nuclear power would require the lowest investment. The spend for gas and wind is about an order of magnitude higher and for coal two or three orders of magnitude higher.

Figure 10 illustrates how the J-value method can be used to convert the reduction in life expectancy into the amount of money that should be spent to prevent an accident.

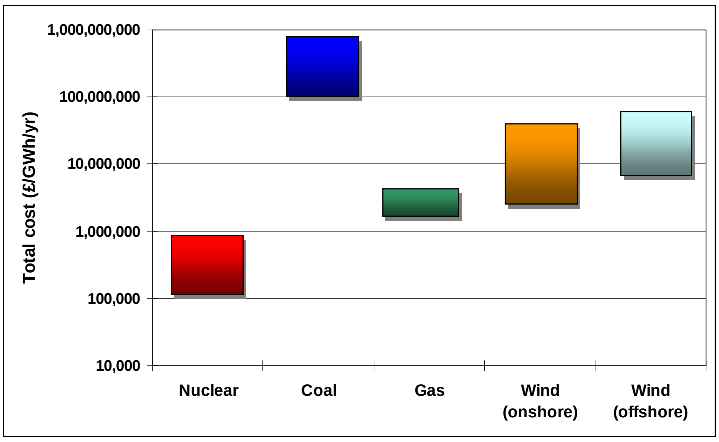

Figure 9 Cost of eliminating entirely the safety risks from different electricity options.

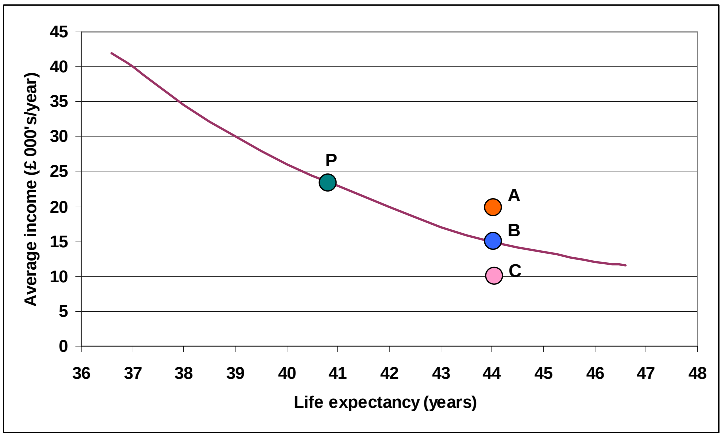

Figure 10 An example of how J-value method can be used to convert the reduction in life expectancy into the amount of money that should be spent to prevent an accident.

Illustration based on the UK data for 2007. Point P represents the average length of time a UK citizen can expect to live from now on (just under 41 years) and the GDP per head (just under £23,000). Suppose health and safety schemes A, B and C can each extend average life by about 3 years, to just over 44 years. The average person is left with £20,000 to spend after paying for their share of scheme A, £15,000 if scheme B is installed and £10,000 if scheme C is implemented. Scheme A leads to a point above the curve and will boost the living standard, Scheme B is on the line and will therefore leave it unchanged, while Scheme C, if implemented, will lead to a deterioration in the living standard. Scheme A is obviously the best, but if A were not available, B is the most expensive scheme that should reasonably be implemented. Option C should not be implemented even if A and B were not available as it is too expensive at no additional benefit.

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[31] Kearns, J., P. Thomas, R. Taylor and W. Boyle (2012). Comparative Risk Analysis of Electricity Generating Systems Using the J-Value Framework. *Nuclear Energy. Special Issue of J of Power and Energy.* In press.

Governance and investors

The extent to which the government could create an environment that would encourage multi-national companies to invest in the construction of new nuclear power stations may be limited. Unforeseen events, the composition of the nuclear and electricity industries and the political structure of Britain itself tend to increase the effectiveness of some policy actions or decrease the impact of others.

SPRIng research[32] suggests that would-be nuclear investors are influenced by their perception of the extent to which the government of the day is prepared to champion nuclear power and whether there is cross-party political support for a new programme of nuclear build. The strategy of the previous and current governments of actively and publicly championing nuclear power has made a positive impression on potential nuclear investors.

Would-be nuclear investors are also influenced by whether or not they believe they could easily secure planning permission for nuclear build. The previous Labour government sought to streamline the process by which nuclear power stations are licensed by encouraging Britain's nuclear regulators to assess the plans for nuclear power stations in advance. This eliminates expensive delays during the construction process and has gone some way to persuading potential nuclear investors to view Britain as a viable investment opportunity. However, the complexity of nuclear regulation and Britain's tradition of democratic government afford plentiful opportunities for those opposed to nuclear power to challenge government decisions through judicial review. In addition, Scotland has an independent legal system and the governing Scottish National Party (SNP) is opposed to new nuclear build. In supporting new nuclear build, the British Government in Westminster has also provided an opportunity for the SNP to bolster its nationalist credentials, especially in light of the fact that opposition to nuclear waste disposal in Scotland was significant in the formation of the SNP.

It is important that government is clear about its energy policy[33]. Sometimes government acts as though energy is a commodity, to be delivered through a market following market logic, government's role being to set the parameters of the market in order to internalise economic externalities and prevent gaming but then to stand back. Sometimes it acts as though energy is a social service which must deliver on certain social goals, government's role being to intervene in the market on a regular basis to ensure these goals are delivered. The danger of pursuing a hybrid of these two approaches is that government divests itself of the levers to direct energy policy, while at the same time undermining confidence in investment for fear of future major rule changes preventing appropriate returns on capital being delivered. As a result, the worst of both worlds may emerge.

Ethical aspects

An integral part of the concept of sustainable development is the need to safeguard the interests of future generations. The concept of sustainable development consistently stresses the obligations of one generation to all future generations, both in terms of access to environmental resources, systems and services and in terms of not passing on the direct or indirect costs of development on those who have no share in the benefits of that development. This has often been referred to as 'intergenerational equity'.

Nuclear technology poses complex ethical dilemmas in this regard[18]. On one hand, nuclear energy could play a significant role in reducing emissions of CO_2 and thus preventing climate change – for the benefits of future generations as well as of our own. As the most devastating effects of climate change are predicted for the future, one could argue that we

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[32] Baker, K. and G. Stoker (2012). Assessing the Prospects for a Revival of Nuclear Power in Britain. *Nuclear Energy. Special Issue of J of Power and Energy*. In press.

[33] Grimston, M. (2012). Have We Been Here Before? Will Nuclear History Repeat Itself? *Nuclear Energy. Special issue of J of Power and Energy*. In press.

have a moral duty to future generations to use all technologies at our disposal to mitigate these effects. Since nuclear energy is a low-carbon technology, we are arguably duty-bound to pursue some kind of nuclear option.

On the other hand, as high-level nuclear waste remains dangerously radioactive for hundreds of thousands of years, nuclear reactors will need to be secured for decades whilst decommissioning takes place. Future generations, who were neither responsible for the decisions to build nuclear reactors in the first place, nor enjoyed the benefits of electricity from those reactors during their lifetime, will nevertheless have to bear both risks and costs of nuclear waste management and decommissioning. Considering the current uncertainties over the total costs and risks of long-term waste management, it is difficult to reconcile these issues with the sustainable development principles.

The fact that nuclear technology poses ethical dilemmas should not be surprising. Almost all decisions about complex technologies, however scientific and 'fact-based' they may appear at one level, have an ethical dimension – in terms of prospective 'winners' and 'losers' and wider impacts on people and society. Nuclear power, however, appears to be particularly charged with such considerations as its waste legacy has clear inter-generational impacts. Its potential to harm or benefit future generations must therefore be taken into account when assessing whether nuclear power presents a sustainable energy option.

There is also another important ethical question raised by nuclear power that has implications for its sustainability. It concerns the issue of international moral and legal responsibilities and obligations in the context of climate change. Industrialised countries such as the UK intend to develop new nuclear capacity, arguing that nuclear power is necessary, even critical, in reducing emissions of greenhouse gases. However, they simultaneously claim that some other countries should not be permitted to follow the same course of action. As the UK Sustainable Development Commission[34] points out, countries such as the UK need to be fully aware of the implications of developing new nuclear capacity, particularly in the context of international treaties such as the UN Framework Convention on Climate Change (UNFCCC). Under the UNFCCC terms, developed countries are morally and legally obliged to help other countries develop appropriate carbon abatement technologies. In fact, the UNFCCC explicitly encourages "*the development, application and diffusion, including transfer of technologies, practices and processes that control, reduce or prevent anthropogenic emission of greenhouse gases*"[35]. If nuclear power is part of the UK's chosen solution to climate change, then it should be considered a suitable solution for all countries. It could be argued that, from an ethical point of view, a decision to develop nuclear power in the UK essentially removes the UK's ability, both morally and legally, to deny the technology to others. However, any application of this ethical reasoning in practice needs to take into account the risk of nuclear proliferation and related social and political concerns.

6. Integrated sustainability considerations

Key messages

- Individual preferences for economic, environmental and/or social aspects of electricity (or any other) options will influence decisions – this should be acknowledged and borne in mind in any future decision making.
- Many of the sustainability aspects are subject to huge factual uncertainties (*e.g.* the economic effects of climate change). Many others depend on the particular ethical value

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[34] SDC (2006). *The Role of Nuclear Power in a Low Carbon Economy - Position Paper*. Sustainable Development Commission. London, March 2006.

[35] UNFCCC (1992). *The United Nations Framework Convention on Climate Change.* Article 4.1c. United Nations, New York. www.unfccc.int.

system of the individual or society involved (for example, it is not an objective fact that economic growth is a good or bad thing).

- There is no 'best' electricity option overall but the choice of 'sustainable' options depends on stakeholder preferences and their value system.
- The SPRIng surveys suggests that solar, hydro and wind are the most favourable electricity options for the UK public with 90% having a favourable opinion about these electricity sources. Biomass power is favoured by 69% of the population and nuclear electricity by 42%. The least favourable are oil (6%), coal (11%) and gas power (18%).
- When asked how important they believed different sustainability issues are when comparing electricity options, most respondents chose as the most important water and land contamination followed by greenhouse gas emissions. Electricity cost appears to be least important, suggesting that the public believe that there is a greater difference between the electricity options in terms of environmental pollution than their cost.
- The SPRIng decision-support framework and toolbox allow consideration of different economic, environmental and social aspects taking into account both objective and subjective parameters. The intention of the toolbox is to aid decision-makers, not replace them.

Key findings and discussion

Nuclear vs other options

Policy decisions carry environmental, economic and social impacts beyond the monetary cost of their implementation. However, it can be difficult to determine what types of impact should be considered and what the outcomes will be. The SPRIng project engaged with numerous organisations, from utilities to government to NGOs as well as the public, to identify what sustainability aspects mattered to whom and how much. This engagement led to the development of the SPRIng sustainability indicators addressing impacts of nuclear and other electricity options as diverse as climate change, energy security, human rights and intergenerational equity[23]. The indicators cover the whole life cycle of electricity, from mining of fuels and minerals to decommissioning.

Example findings are illustrated in Figures 11 and 12. As shown in Figure 11, our pursuit of low-carbon power may inadvertently exacerbate other problems: a carbon-motivated shift from coal to gas and/or photovoltaics would be detrimental to the ozone layer when the whole life cycle is considered. In contrast, both nuclear and wind power perform extremely well against both indicators.

A different picture emerges if employment and levelised costs of electricity are compared, as shown in Figure 12. A trend exists in which more expensive technologies, such as solar and wind, tend to employ more people throughout their life cycles, posing the question: is it better to maximise employment regardless of economic cost, or to assume that cheaper electricity will benefit the economy as a whole, indirectly increasing employment?

The main disadvantages of offshore wind are its relatively high costs, as shown in Figure 12, and its economic and technical inability to follow load. Nuclear power is also less suitable for load-following than coal or gas, despite new reactors being superior to current ones in this respect. As a result, a future electricity mix with large contributions from both nuclear and wind power may become difficult to manage. The other disadvantages of nuclear power include long construction periods (on average 6-7 years), the potential proliferation risk of fuel cycles in which plutonium is recycled (including for fast reactors), and of course the burden of care placed on future generations by the production of waste requiring long-term storage (approximately 5500-6500 m^3 per reactor lifetime). This final point would, however, also apply to carbon capture and storage technologies.

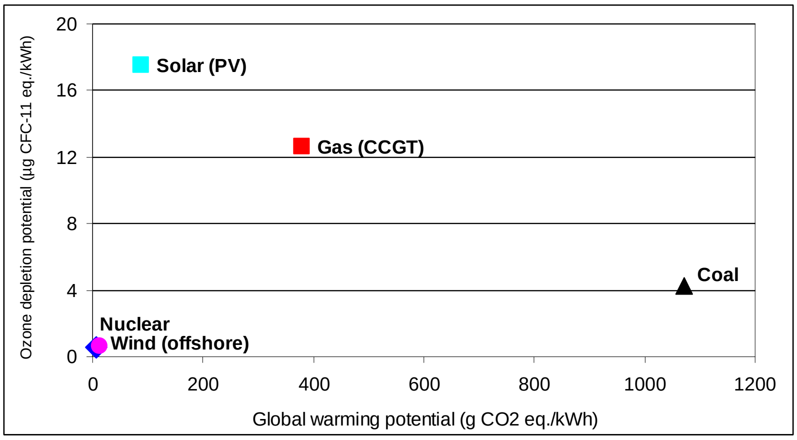


Figure 11 Trade-offs between global warming and ozone layer depletion. Switching from coal to gas and low-carbon options such as solar photovoltaics could cause other sustainability problems, in this case ozone layer depletion.

Both environmental impacts are on a life cycle basis, from ‘cradle to grave’.

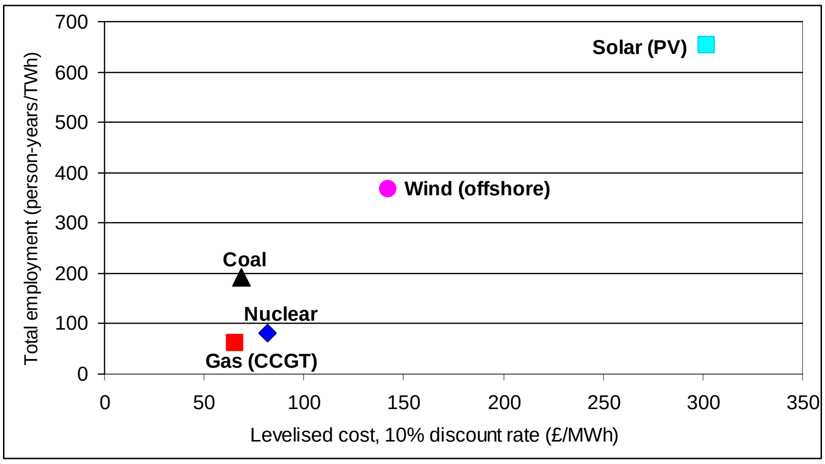


Figure 12 Comparison of life cycle employment and levelised electricity cost: nuclear and gas are cheaper than the other technologies shown but also employ fewer people on a life cycle basis (including mining, processing, operation and decommissioning).

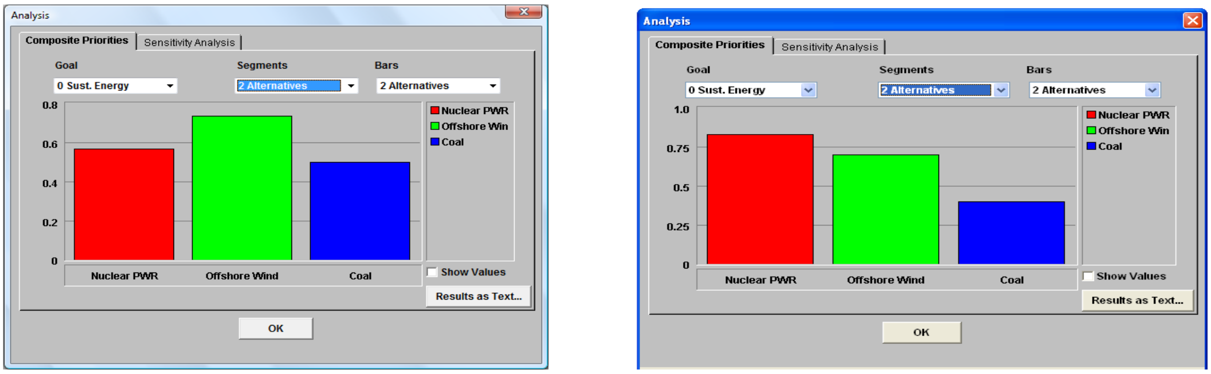
The costs exclude financial incentives and subsidies.

Stakeholder preferences

Ultimately, the sustainability assessments of nuclear and other energy technologies serve more to highlight the trade-offs that need to be made between different sustainability aspects than to provide clear-cut answers as no one technology is the ‘best’ by all measures.

The preferred options are perhaps best identified by eliciting stakeholder preferences for the different sustainability aspects captured by the indicators. SPRIng has used multi-criteria decision analysis (MCDA) to find out how important different sustainability indicators are to different stakeholders. An example result is indicated in Figure 13, comparing the overall sustainability of nuclear (pressurised water reactor, PWR), offshore wind and coal electricity, using the SPRIng sustainability indicators[23]. If all the sustainability indicators are considered to be of equal importance, power from offshore wind is the most sustainable option, followed by nuclear and then coal (a higher score corresponds to a more sustainable option). If however, stakeholder preferences change and some criteria (sustainability indicators) become more important, then the ranking of options changes. In the example shown in Figure 13 (b), nuclear becomes the best option, followed by offshore wind and then coal.

This example shows that there is no single ‘best’ solution and that choice of ‘sustainable’ options will always depend on stakeholder preferences and their value system. To help different stakeholders and decision makers explore their preferences and find out which electricity options may be most sustainable based on their priorities, SPRIng has developed a suite of MCDA tools. These can be used by individuals or in group discussions and can be a useful tool in consensus building, helping to reconcile stakeholder differences.



(a) All sustainability indicators considered equally important by stakeholders

(b) Sustainability indicators weighted according to stakeholder preferences

Figure 13 Using multi-criteria decision analysis to help decision makers and stakeholders identify sustainable electricity options, based on their priorities for different sustainability issues.

Public perceptions

Policy debates on the future UK electricity mix often and almost exclusively focus on climate change and energy security. Consequently, many surveys of the public opinion of different electricity options have centred on these aspects. To broaden the debate and obtain a more informed picture, SPRIng has for the first time carried out a comprehensive survey of public opinions on a range of sustainability indicators and electricity options.

When asked how important they believed different sustainability issues were when comparing electricity options, on average the respondents[36] said that ‘water contamination from toxic substances’ was the most important issue to consider, followed by ‘land contamination from toxic substances’, then ‘greenhouse gas emissions’. This is illustrated in Figure 14. Interestingly, the least important issue to the respondents appears to be ‘costs of electricity’. Although one could speculate on the reasons for such responses, these results suggest that the public believes that there is a greater difference between the electricity options in terms of environmental pollution than their cost – they hear a lot about the former, largely in the media, but they only see the latter as a single electricity bill rather than a breakdown between the costs of different technologies.

With respect to different electricity options, solar, hydro and wind power were found to be the most popular with around 90% of the sampled UK public having a favourable opinion about these electricity sources (Figure 15). Biomass power is favoured by 69% of the population and nuclear electricity by 42%. The least favourable are oil (6%), coal (11%) and gas power (18%).

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[36] Based on 625 responses.

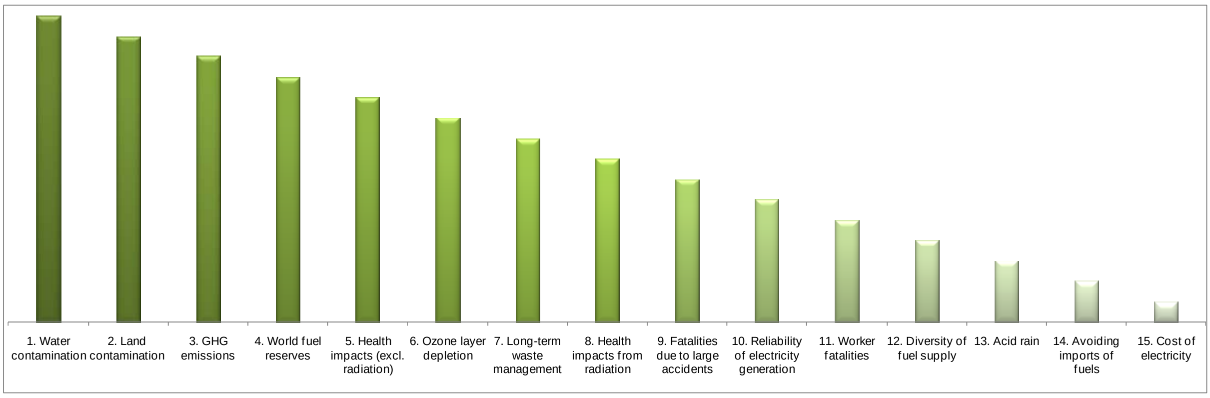

Figure 14 The importance of different sustainability aspects to the UK public: water contamination is most important and cost of electricity least important in distinguishing between different electricity options.

Ranking order: 1 = most important; 15 = least important

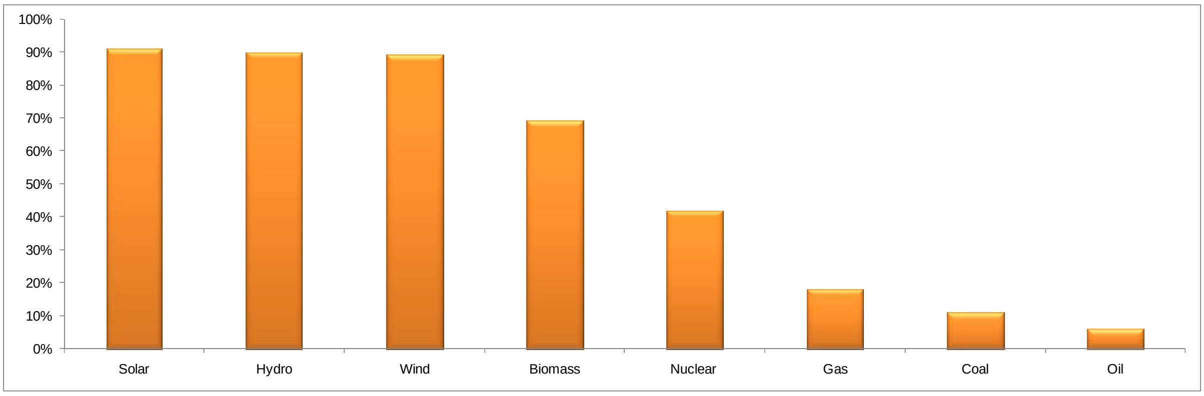

Figure 15 Solar, hydro and wind power are the most favourable options for the UK public. Nuclear power is favourable for 42% of the public and fossil fuel options are least favoured.

The results are based on 625 responses. The values on the vertical axis show the percentage of the respondents that favoured each electricity option.

7. Concluding remarks

At its heart, the issue of energy sustainability can perhaps be expressed, albeit simplistically, in a single question which brings together the techno-economic, environmental and socio-political aspects: Are decision-makers and their publics sufficiently scared about climate change to put economic efficiency at risk? If so, there may be strong arguments put forward for returning decision-making to a single centralised body. (And the international angle is of course crucial – no single country or even single continent can deal with this challenge on its own.) However, past experience suggests that centralised approaches of this nature, while they might offer a coherence of decision-making, tend not to be as innovative as markets in developing a range of approaches.

The tension, then, is to encourage a range of feasible approaches while not slipping into an indefensibly optimistic belief in ‘miracle cures’. Various candidates already mooted include smart grids, hydrogen economy, large scale nuclear programmes with alternative fuel cycles, renewables, public education, state subsidies etc. Any or all of these may materialise and might expand the scope of fragmented approaches to the issue but it is highly questionable whether even collectively they can offer enough certainty that goals can be met. As the SPRIng research shows, this is especially true of the climate change targets.

In summary, a market approach might deliver on the goals if it should prove politically possible to set tight enough carbon targets with high enough penalties for non-compliance. Whether such leadership is possible is highly questionable. Even more doubtful is whether various stakeholders, including the UK public, would accept it.

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