UK Nuclear Horizons

An independent assessment by the UK National Nuclear Laboratory

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Position Paper

National Nuclear Laboratory

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Conditions for a "Nuclear Renaissance" are falling into place in many countries. New nuclear build, financed by private investment, is now recognised by UK Government to have a clear role as part of the future energy mix, with the benefits of building and operating new reactors in the UK clearly outweighing the detriments. Nuclear energy is now viewed as affordable, dependable and safe, while also being capable of providing a low-carbon energy and increasing diversity thereby reducing the UK's dependence on any one technology or country for our energy or fuel supplies. In order to implement a workable strategy, there are several areas which need to be considered and addressed.

This paper sets out the National Nuclear Laboratory's assessment of these areas and proposes options for moving forward. The analysis and views contained in this paper are those of the UK National Nuclear Laboratory and not necessarily the view or policy of UK Government.

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Introduction

This paper provides an independent review by the UK National Nuclear Laboratory (NNL) of the areas which must be considered and addressed if a successful expansion of nuclear energy is to be achieved in the UK. These include fuel supply and sustainability, economics, waste management and disposal, future fuel cycle options such as plutonium management, non-proliferation and infrastructure requirements, amongst others. This paper reviews a range of nuclear scenarios against 15 key topics which are judged by NNL to be pertinent to evaluating nuclear energy and are consistent with metrics being developed by the NNL in collaboration with Oak Ridge National Laboratory in the United States.

Based on facts and information available, an assessment is made of each of the 15 areas in turn. The paper then goes on to provide a summary of NNL's assessment and position statements based on the findings. It is concluded and recommended that the credible scenarios plus the items and position statements identified in this paper should be developed and used to produce a subsequent UK nuclear energy roadmap. The intention is that this paper and the NNL's position statements should provide an input to assist decision and policy makers in the UK e.g. Government, utilities, investors and regulators.

This paper is intended to complement the recent Royal Academy of Engineering (RAE) paper on energy systems[1] and the Energy Research Partnership's (ERP) paper on nuclear fission[2] by considering the specific nuclear topics that the respective future scenarios and/or role of nuclear energy raise. Although this study has deliberately focused on nuclear energy, NNL have remained cognisant of other energy studies and scenario assessments.

NNL has many years experience of the nuclear energy industry and associated fuel cycle science and technology, including fuels, reactors and reprocessing. We are therefore in an ideal position to be able to independently assess and advise decision makers on both the current and future roles of nuclear energy and the associated fuel cycles. The statements in this note are backed up by extensive experience of nuclear R&D and the nuclear industry worldwide, including nuclear energy assessments and programmes in which NNL has been involved.

Conditions for a "Nuclear Renaissance" are falling into place in many countries and with the Generic Design Assessment (GDA) and purchases of prospective sites now well underway, this statement is equally true for the UK. Reasons for the UK renaissance are numerous and include: the concerns of energy security and volatility of natural gas prices, the positive contribution of nuclear energy to clean electricity production and avoidance of CO_2 emissions and the safe and economic operation of the existing and future nuclear plants; much of this is reflected in the DECC White Paper on Nuclear Power[3]. In light of this, private companies are positioning to invest in new nuclear build and the suitability of Toshiba-Westinghouse AP-1000 and AREVA European Pressurised Water (EPR) designs are currently being reviewed by the Nuclear Directorate of the Health and Safety Executive under the GDA process.

The prospect for renewal of nuclear power in the UK raises many high level strategic questions for government, regulators and investors that must be addressed including ensuring that any decision taken now must consider the longer term implications e.g. waste management, fuel cycle options, investment in facilities and infrastructure.

The UK National Nuclear Laboratory (NNL) has carried out an assessment of future deployment scenarios in order to consider and begin to address the questions that are likely to arise. This "UK Nuclear Horizons" paper presents NNL's position on future nuclear deployment and highlights those areas that will need addressing in order to inform any future decisions.

The assessment looks at a number of scenarios that encompass all future outcomes that might reasonably be anticipated and that will be useful for future reference. Only limited analysis has been performed to date and it is expected that follow-up studies will be conducted to provide a more detailed assessment as and when required. This position paper summarises NNL's findings from the initial study.

New build scenarios

Five reference scenarios have been examined in this initial study and are expected to form the basis of any future, more detailed assessments. Four of the scenarios have been designed so that they align with the four cases considered in the recent report[4] by Malcolm Wicks MP (former Special Representative of the Prime Minister on International Energy in 2009) as this study represents the most recent and far reaching assessment of UK energy scenarios published by the UK Government. The fifth scenario represents the limit at which the reactors could be built up to 2050 and is intended to reflect the Level 4 nuclear trajectory postulated in the recent 2050 Pathways Analysis Report published by DECC[5]. The objective of this paper is not to make predictions as to likely future outcomes, but rather to encompass all conceivable scenarios and Scenario 5 is specifically intended to delineate the boundaries of what might be technically possible, even though it may not be realistic. The five scenarios are:

- Scenario 1: **No new nuclear build** and phase-out of existing nuclear plants according to latest forecast shutdown dates.
- Scenario 2: **Replacement capacity** case in which existing nuclear capacity is maintained. Electrical output rises slightly because of the anticipated higher availability achievable with new build plants compared with historic UK gas reactors. This equates to the construction of 9.2 GWe of Pressurised Water Reactor (PWR) capacity (equates to 8.6 GWe output, assuming 93% availability) e.g. comprising four twin AP-1000 plants or equivalently six EPR plants.
- Scenario 3: **High capacity** case with 23.0 GWe of PWR capacity (equates to 21.3 GWe output), equivalent to 10 twin AP-1000 plants or 14 EPRs.
- Scenario 4: **Very high capacity** case with 41.4 GWe of PWR capacity (equates to 38.4 GWe output), equivalent to 18 twin AP-1000 plants or 26 EPRs, corresponding with

1 Generating the Future: UK energy systems fit for 2050, The Royal Academy of Engineering, March 2010

2 Nuclear Fission, Energy Research Partnership Technology Report, September 2010

3 Meeting the Energy Challenge: A White Paper on Nuclear Power, January 2008

4 Energy Security: A national challenge in a changing world, August 2009

5 2050 Pathways Analysis, Department of Energy and Climate Change. www.decc.gov.uk, July 2010, Section G Nuclear, pages 167to 173

a major expansion of nuclear into the transport sector as well as electricity production.

- Scenario 5: **Bounding maximum nuclear growth** case with 138 GWe capacity (equates to 128 GWe output), equivalent to 60 twin AP-1000 plants or 86 EPRs, meeting the bulk of total UK energy requirements.

Table 1 (below) provides a summary of the five Scenarios.

Scenario 1 aligns with the Base Case in the Wicks Report, in which nuclear does not contribute to future energy output. Scenario 2 equates to the 80% emissions reduction case in the Wicks Report, in which nuclear contributes 5% to primary energy demand. Scenario 3 corresponds to the 90% emissions reduction scenario in the Wicks Report, with nuclear satisfying 15% of primary energy demand. Scenario 4 represents a very high nuclear case, which satisfies 34% of total primary energy demand. Total UK electricity output at the reference date of 2050 is estimated to be 600 TWh, assuming 1% per year escalation from current output. The nuclear component of electricity production is 12.5%, 31.0% and 55.6% of total electrical output on this basis for Scenarios 2, 3 and 4 respectively. Scenario 5 is not necessarily considered realistic, but is intended to define a bounding case that will encompass any future scenario that might be postulated. It is envisaged that Scenario 5 might apply in the event that UK primary energy demand does not decrease as much as required in the Wicks Report scenarios and in which very high nuclear capacity is needed to meet the additional energy demand.

Scenario	Description	Number of new build reactors		New build annual output		Reactor start-up dates	
		Twin AP1000	EPR	(TWhe)	(GWye)	First in fleet	Last in fleet
1	No new build	0	0	0	0	-	-
2	Replacement capacity	4	6	75	8.6	2020	2026
3	High capacity	10	14	187	21.3	2020	2038
4	Very high capacity	18	26	336	38.4	2020	2054
5	Bounding nuclear growth	60	86	1124	128.3	2020	2049

Table 1: Five scenarios considered

In Scenarios 4 and 5, it is envisaged that some of the nuclear plants would make significant contributions to the transport sector, either by producing electricity used in charging electric vehicles, or in producing hydrogen or synthetic hydrocarbon fuels.

Impact assessment

NNL have carried out an impact assessment of the five scenarios under fifteen different high-level headings chosen for their strategic importance to nuclear energy:

1. Output

Table A.1 indicates the electrical energy outputs of the five scenarios and how they relate to total primary energy demand. Scenario 2 has a low strategic impact in terms of energy security, with new nuclear plants contributing only 5% to primary energy demand. Although the installed capacity is comparable to the current nuclear fleet (~9 GWe), annual electrical output will be higher because of the higher availability expected from the new build plants compared with the existing fleet, which are mostly gas cooled reactors (90% availability compared with ~70% for the gas reactor fleet). In Scenario 3, nuclear contributes 15% of primary energy demand, which is much more important strategically, placing a premium on reliability and availability. In Scenario 4, the UK would be very heavily dependent on nuclear (34% of primary energy) and its strategic importance would be extremely high.

The escalation in strategic importance in Scenarios 2, 3, and 4 results partly because of the increasing nuclear capacity and partly because of decreasing primary energy demand of the Wicks report scenarios. This is a very important point to emphasise, that in the high emissions reduction cases, the strategic role of nuclear is increased because there is a high nuclear component combined with low primary energy demand. As such, there has to be greater importance placed on the successful operation of the plants, including their availability.

In Scenario 4, the UK's dependence on nuclear is probably as high as is practicable to be, if it is considered desirable to have a balanced portfolio of energy sources, without excessive reliance on any single source. Scenario 5 goes beyond this point and relies on nuclear to meet most of the UK's primary energy demand. In Scenario 2 it would be desirable but not essential to have more than one reactor design in the fleet to avoid vulnerability to common mode failures affecting the entire fleet and having just one design might nevertheless pose acceptable risk.

2. Carbon avoidance

Lifecycle direct emissions from nuclear plants (including their associated fuel cycles and uranium mining/extraction) are small (see Table A.2) even for a very high nuclear component as in Scenario 5 (<25 MtCO2/year). Although there is uncertainty in the figures, the absolute emissions are so low that any plausible uncertainty allowances will have no significant impact.

The avoided emissions from the new build nuclear fleets are very significant compared with fossil plants, with central estimates of ~40, 100, 200 and 650 million tonnes per year for Scenarios 2, 3, 4 and 5 respectively. By way of comparison, total UK CO_2 emissions from fossil fuel burning in 2006 are estimated to have been approximately 600 million tonnes per year. It is therefore clear that nuclear has a notable role to play in CO_2 avoidance and in the UK aiming to meet its reduction targets.

3. Uranium demand

While uranium availability poses a strategic risk, this will most likely materialise as an escalation of uranium prices that will have only a limited impact on total generating costs; uranium ore makes up only a small percentage (approximately 5%) of the overall nuclear generating cost. The uranium ore demands in Scenarios 3, 4 and especially 5 are large enough to be significant in the world market (see table below) and it is likely that there would be strategic benefits in investing in alternative fissile material sources such as plutonium recycle, reprocessed uranium (Rep U) recycle or the thorium fuel cycle in the event of these scenarios. In the more modest Scenarios there is unlikely to be a concern over the availability of uranium ore, but given an equivalent increase in demand worldwide, an escalation of uranium prices would be inevitable.

Scenario	Ore requirement (tu/year)	Percentage relative to projected world uranium production in 2010
1	-	-
2	1,700	2%
3	4,300	5%
4	7,700	9%
5	25,000	28%
The World Nuclear Association (WNA Market Report 2009) projects total world uranium demand in 2010 to be ~90,000 tu/year in the reference case.		

Table 2

4. Security of supply

Security of supply for nuclear power depends on the availability of new fuel and the associated uranium ore and enrichment services. Other factors, such as operating reliability, spent fuel and waste management are also involved, but fuel availability is generally one of the main vulnerabilities, as it typically depends on overseas suppliers, although this could change (see table below). Nuclear plants are regarded as being much less vulnerable than fossil plants to fuel availability, because relative to total generating cost, uranium ore procurement represents a much smaller proportion. Moreover, uranium ore is available from politically stable countries such as Australia and Canada and finished fuel is available from European countries (including the UK) and USA, all of which helps assure security of supply.

AP-1000 and EPR plants are already under construction and should pose little risk in terms of technology readiness for the fuel or the reactors. The potential need for the deployment of Generation IV reactors designs in Scenarios 3, 4 and 5 (when the importance of recycle and a closed fuel cycle becomes more clear) would require R&D to mitigate technology readiness risks.

Scenario	Fuel requirement (tU/year)
1	-
2	170
3	426
4	766
5	2,553

Table 3

5. Sustainability

This could be regarded as encompassing a wide range of different fuel cycle issues. Security of supply and uranium demand can be regarded as sustainability issues. Other relevant issues include environmental impact, spent fuel storage, spent fuel disposal/reprocessing, waste management and the efficient use of fuel resources, particularly the fissile material.

Scenarios 3, 4 and 5 are the only ones which are likely to raise any sustainability concerns, principally in terms of materials availability and their impact on capacities for reactor construction, spent fuel storage or disposal. The rate of build could become a limiting factor for Scenario 3 and particularly Scenarios 4 and 5, with significant demand placed on resources, including the construction teams and scientific and engineering expertise in the UK. Furthermore, the efficient use of the fuel resource (uranium) and fissile material becomes ever more important for Scenarios 3, 4 and 5 and as such, the consideration for the need to recycle and re-use the reprocessed uranium and plutonium becomes ever more important (see sections on "Recycle" and "Plutonium and reprocessed uranium").

6. Spent fuel and Vitrified High Level Waste (VHLW) arisings

Spent fuel from new build plants is of a type that is already used in the UK and is well understood and characterised and widely used internationally. With no reprocessing (as is the current UK Government position for new build), Scenarios 2, 3, 4 and 5 will increase the Committee on Radioactive Waste Management (CORWM) Materials and Wastes Inventory Baseline spent fuel mass by factors of approximately 3, 6, 10 and 30 respectively (see Table A.3)[6]. Packaged spent fuel volumes would increase by factors of approximately 4, 8, 13 and 40. While these factors may appear high, this is largely because only a small proportion of the spent fuel from the existing UK fleet has been designated for storage and disposal (the majority is to be reprocessed) and the spent fuel baseline is therefore very low.

An alternative to spent fuel disposal would be to recycle the fuel by reprocessing (for which a single reprocessing plant of 800 t/year capacity would suffice for Scenarios 2, 3 and 4). Although reprocessing reduces overall waste volumes compared with direct disposal of the fuel, if the spent fuel was reprocessed, reprocessing wastes would nevertheless increase the CORWM Baseline Vitrified High Level Waste (VHLW) volumes by factors of approximately 2, 4, 6 and 20 for the four new build scenarios (Table A.3). These represent substantial increases in high level waste storage and repository capacities.

It has previously been stated that for a new build programme of 10 AP-1000 plants, similar to Scenario 2, the impact on UK legacy wastes is to increment the higher activity (high level and intermediate level) wastes by less than 10% i.e. the material destined for the Geological Disposal Facility (GDF). For Scenario 2 this statement remains valid as the results outlined above only refer to VHLW and not the ILW. For Scenarios 3, 4 and 5 the increment is greater than 10%, though for much larger useful energy outputs. It is important to view these seemingly large increases in spent fuel and VHLW volumes in context. Compared with the UK's historic nuclear fleet, lifetime electricity outputs will be much higher for all the new build scenarios. This comment applies even to Scenario 2, even though the installed

6 "CoRWM's Radioactive Waste and Materials Inventory", CoRWM Document 1279, July 2005

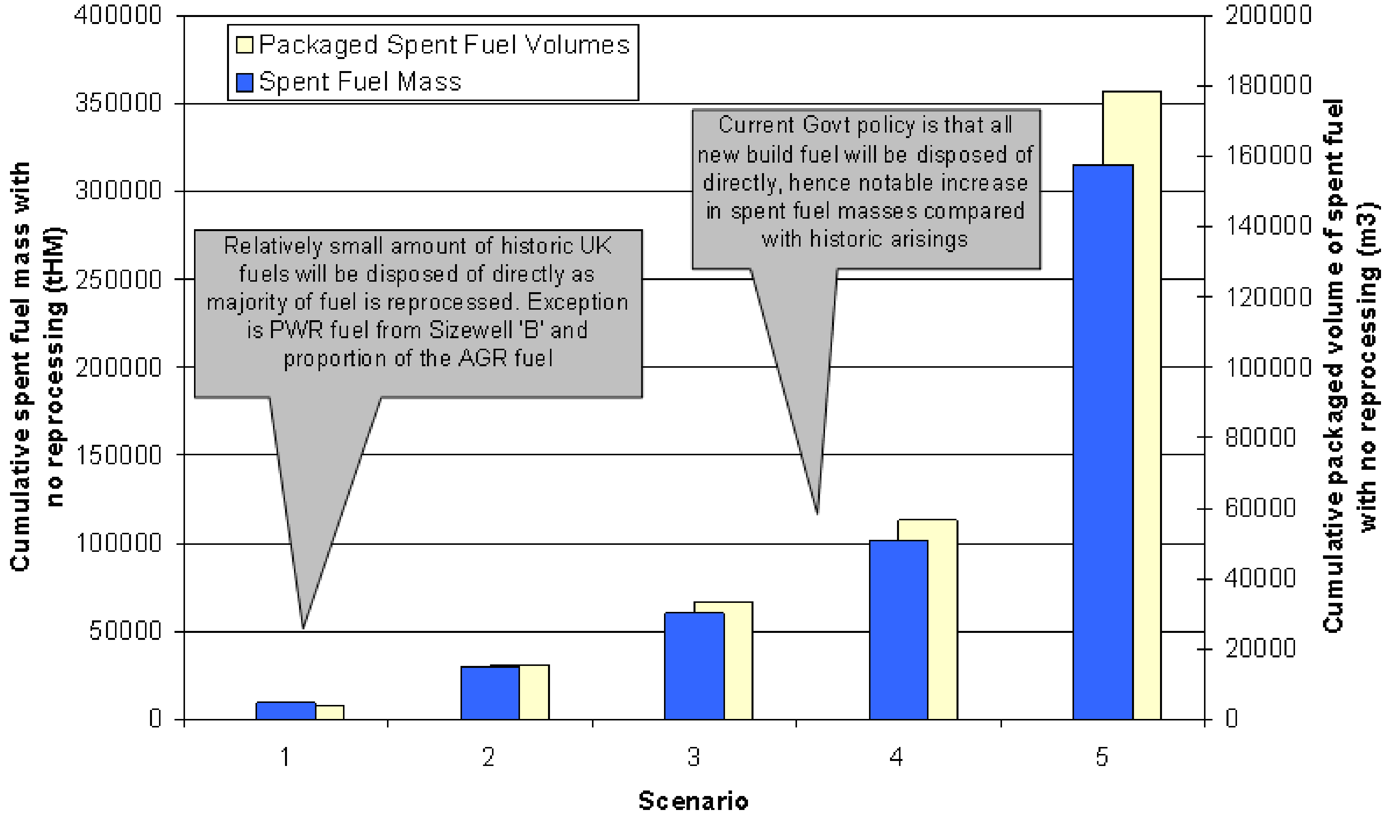


Figure 1: Spent fuel mass and packaged volumes arising from historic and new build scenarios - assuming no reprocessing of new build fuels.

capacity is comparable with the current fleet, because both the new build load factors are expected to be higher and the new build plants are expected to have a 60 year operational lifetime; the new build fleet will generate more than 140% more electricity. Therefore, although the detriments in terms of spent fuel and/or VHLW volumes are much higher, so are the benefits in terms of useful energy output over the lifetime of the new build plants.

7. Operational wastes

For all of the four new build scenarios, reactor operational wastes will only amount to a marginal increase in Intermediate Level Waste (ILW) waste volumes relative to the CORWM Baseline; approximately 10% for Scenario 4 and 30% for Scenario 5 (see Table A.4).

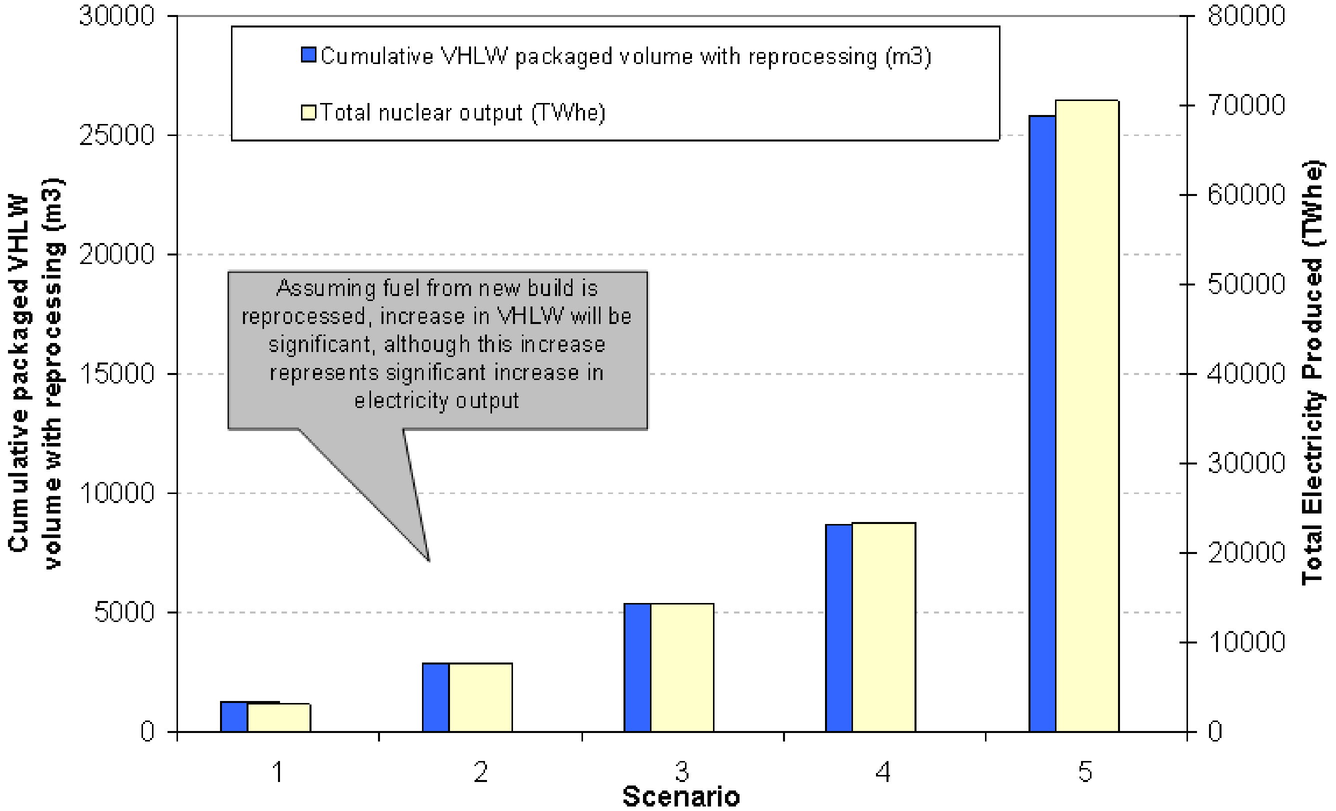


Figure 2: Vitrified High Level Waste arising from historic and new build scenarios - assuming reprocessing of new build fuels.

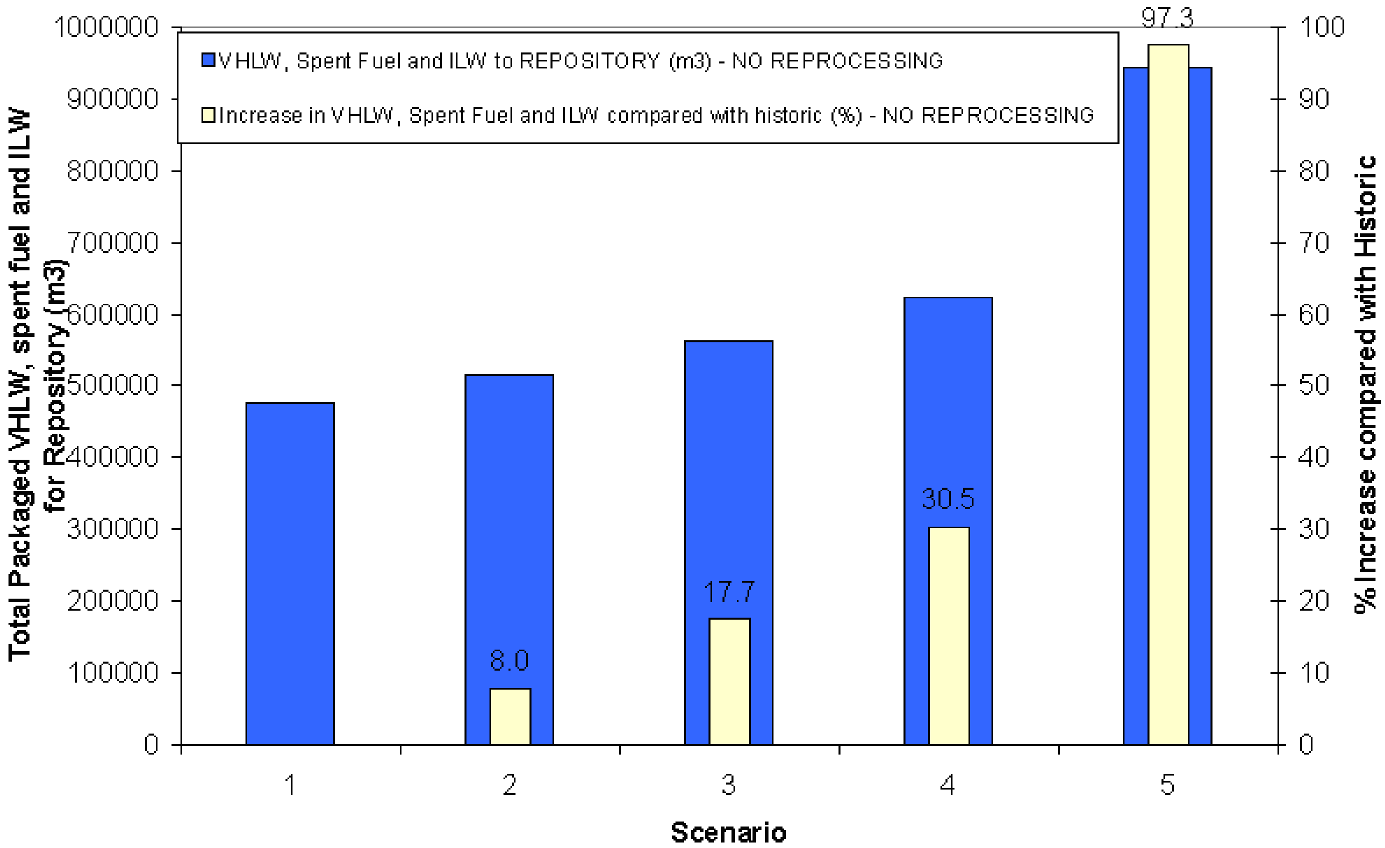


Figure 3: Total packaged volumes of spent fuel, vitrified high and intermediate level waste and percentage increase compared with historic arisings - assuming no reprocessing of new build fuels.

8. Recycle

The current situation where reprocessing/recycle is acknowledged by bodies such as OECD/NEA to be more expensive, could be reversed if uranium ore prices were to rise significantly. At present, there is little prospect of this situation arising, but over the 60 year lifetime of the new build plants, it is conceivable that this could occur. Utilities would be interested in reprocessing/recycle in such circumstances, if it was clear that uranium ore prices were going to be high indefinitely. This would represent a market mechanism whereby a utility could limit its exposure to high uranium prices by sourcing some of its fissile material from recycle sources. This eventuality is most likely to occur for Scenarios 3, 4 and 5 where the nuclear component of UK electricity supply is largest.

Other benefits of reprocessing are a reduced demand for repository capacity or possibly the deferral of repository capacity until later dates. The capacity taken up in repository may be reduced if plutonium and possibly minor actinides and/or heat producing fission products are recycled or stored separately. A utility would not see such higher level justification arguments as relevant factors in its operational decision making and within the deregulated market government would need to impose some pricing mechanism to encourage utilities to adopt the favoured strategy.

In the long term, recycle may be required in order to provide the fissile material needed for Generation IV reactors to start up. Reprocessing plant capacities of ~200 tHM/year would be needed for Scenario 2, 600 tHM/y Scenario 3, 1000 tHM/year for Scenario 4, comparable to the Thermal Oxide Reprocessing Plant (THORP). However, Scenario 5 would demand a much more challenging reprocessing capacity of 3000 tHM/year. This is a situation that might be a realistic scenario in the UK in the second half of the century only.

Impact on repository

Even in Scenario 1, with no new build, a GDF will be required in the UK. With no reprocessing, the area taken up in the GDF by spent fuel from the new build plants in the four new build scenarios represent increases by factors of 1.5, 2, 3 and 8 over legacy VHLW and spent fuel, which reflects an assumed GDF design and canister spacing etc[7] (see Table A.5). While these may seem to be large increases, it should be noted that the new build scenarios in return provide very large returns in terms of cumulative electrical energy output, as noted previously. The increase in area taken up in the GDF by ILW is modest; in increments of 8, 20, 36 and 120% for the four scenarios respectively (see Table A.6).

In addition, the heat loads will be dependent on the level of cooling the disposed fuel or HLW has experienced and therefore the assumed cooling time prior to loading into the GDF is also key to any future assessment of the sizing of the facility.

It should also be noted that the cost of the additional volume requirements for new build are expected to be marginal incremental costs above the baseline costs.

10. Plutonium and reprocessed uranium

The cumulative arisings of plutonium from the four new build scenarios represent increases of factors of approximately 2, 4, 6 and 19 over the baseline plutonium inventory of ~100 tonnes, albeit contained in spent fuel based on current UK policy of direct fuel storage i.e. no reprocessing. This could represent a

7 Geological Disposal Generic Design Assessment: Summary of Disposability Assessment for Wastes and Spent Fuel arising from Operation of the Westinghouse AP1000, October 2009

very significant strategic reserve if all or part of the fuel from the new build plants was reprocessed.

If the new build plutonium inventories from Scenarios 2, 3, 4 and 5 were recycled as Mixed Oxide (MOX) fuel in the new build reactors, the useful electrical outputs from the plutonium would be 55, 140, 250 and 828 GWye respectively (see Table A.7). Recycling the reprocessed uranium (Rep U) would generate similar benefits in terms of fuel supply as a strategic asset.

Preliminary technical studies have shown that the AP-1000 and EPR plants are both capable of utilising legacy plutonium and Rep U stocks and there is no reason why the plutonium and Rep U arisings from the new build plants should not also be usable in the same way.

11. Future role of nuclear

In Scenarios 2 and 3 the new build plants are intended exclusively for electrical production and only in Scenarios 4 and 5 are any of them designated for other purposes, such as meeting transport energy requirements or energy storage. Scenario 2 corresponds to a very modest nuclear output which equates to 5% of primary energy output. At this level, the nuclear plants could continue to operate in baseload, where they are most economic and there would be little or no requirement for flexible operation in which the reactors load follow.

In Scenario 3 the nuclear plants provide 15% of primary energy output, which will probably be sufficient to demand at least some of the plants to operate in load follow mode (i.e. plant output following grid demand), which is less favourable than baseload, because the output is lower and the fixed cost components penalised. With a modest load follow requirement, the nuclear plants would not be penalised very much and would continue to be economic. From a technical perspective, the new build reactors are capable of load following and depending on the size and role of any future nuclear fleet, this capability may or may not be a requirement of the nuclear utilities in the future.

Scenarios 4 and 5 are envisaged to apply to a radically different UK energy demand in which some of the nuclear plants are used to meet transport energy requirements, by providing the electricity source for vehicle charging or for use in hydrogen or synthetic fuel production. Additionally, some plants could be used for industrial heat applications, displacing petrochemical sources. Light Water Reactors (LWRs) are not best suited for heat applications, because the operating temperature of 300°C is too low to give optimum efficiency. Alternative reactor systems, such as the High Temperature Reactor (HTR) may be better suited for heat production, if this was the driver for a significant expansion in nuclear power.

12. Alternative fuel cycles

Choices over future fuel cycle options will depend on many factors including the size of the UK nuclear fleet, economics, sustainability, waste management etc and the technologies that are commercially available at the time. For the next 60 years PWR technology is likely to remain the preferred option for the UK and even if innovative reactor designs are deployed, PWRs are likely to remain dominant. Therefore, the base assumption is that the fuel cycle must be compatible with PWR fuel assemblies.

The base assumption for all the scenarios considered here is that the new build plants would use low enriched UO_2 fuel (up to 5 w/o U-235). Alternatively, Rep U and MOX could meet a fraction of the fuel demand, initially using existing Rep U and plutonium stocks. At a later stage, if it was decided to reprocess the spent fuel from the new build plants, the Rep U and plutonium inventories could potentially meet a substantial proportion of fuel demand (20%), significantly reducing exposure to uranium price rises. Both Rep U and MOX are mature technologies that could be deployed at an early stage with little risk (within ~5 years for Rep U and 10-15 years for MOX).

Thorium fuel may potentially be available for use in PWRs in timescales of these scenarios. NNL has recently completed a position paper on the thorium fuel cycle[8], which notes that there are fuel designs being developed in which ThO_2 is used to produce fissile U-233 instead of plutonium, while retaining low enriched UO_2 as the fissile seed. One of the claimed advantages of the thorium fuel cycle is that it will reduce dependence on uranium. However, the NNL position paper notes that the actual reductions in uranium demand are very modest for the fuel designs that are compatible with existing LWR designs. Alternative thorium fuel cycles have been proposed, but they may not be compatible with existing cores and may require radical fuel cycle developments, such as thorium fuel reprocessing and U-233 recycle, both of which present high levels of technical risk. The most promising thorium option for the UK, is ThO_2-PuO_2 MOX fuel. Thorium is potentially a very good matrix for plutonium disposition and could be used in place of conventional MOX fuel as a means of dispositioning the UK's existing stock of separated plutonium.

In the very high capacity scenarios (3, 4 and 5), there is the possibility of fast reactors being required, depending on internal and external pressures for sustainability.

13. Proliferation resistance

All of the new build scenarios considered here will extend for a very long period of time, during which there is likely to be increased pressure for the UK to cease holding stocks of separated plutonium and therefore either disposing of its existing plutonium or re-using in reactors. The UK has the largest stock of separated civil plutonium in the world today and currently has not developed a firm plan to utilise or dispose of it.

A decision to recycle the new build fuel might be linked to first re-using the existing plutonium stock and also to minimising stocks of separated plutonium. This would demand close integration of reprocessing and MOX recycle facilities and in particular managing the plutonium throughput, such that the separated plutonium inventory is kept as low as possible. There may also be pressure to adopt different reprocessing schemes to reduce the proliferation potential, such as using a uranium-plutonium co-product. Opting for the thorium fuel cycle is unlikely to provide even a modest benefit in terms of proliferation resistance, however.

14. Siting

Scenario 2 has 9.2 GWe capacity provided by four twin AP-1000 or equivalently six EPRs. In either case the eight sites identified in the Government review would be able to host the required number of reactors with margin to allow for any sites that might be rejected at a later date.

Scenario 3 is only marginally viable with the existing eight sites assuming that the site boundaries are not extended further. It is advisable that each of the existing sites should be assessed for the potential to extend the site boundaries to host two or more twin plants.

8 "The Thorium Fuel Cycle: An Independent Assessment by the UK National Nuclear Laboratory", August 2010

15. Economics

An important consideration for new build plants is economic competitiveness and sensitivities to variations in the economic parameters need to be understood by the investors. A recent UK Government study[9] estimates the total generation cost for new nuclear plants in the UK to be 38 £/MWh. The sensitivities underlying this generating cost are vital to the justification of the economic case of new build.

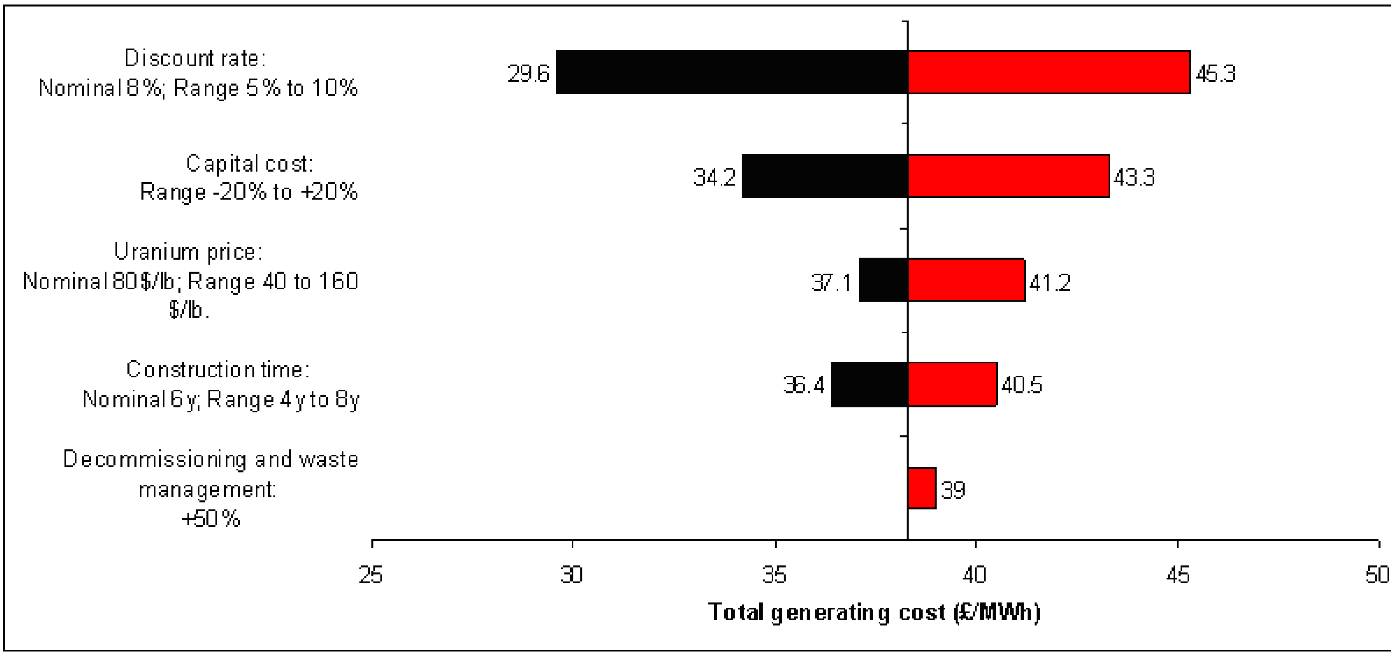
NNL has produced its own economic analyses based on the original UK Government figures and from which a sensitivity analysis has been completed. The figure below illustrates the main sensitivities.

As can be seen, the total generating cost of the new build plants is sensitive primarily to the discount rate used to finance the capital costs and to the construction cost. Other sensitivities, such as to the uranium ore price, construction time and decommissioning/waste management cost are relatively minor. The discount rate ranges from 5% to 10%, which is considered by OECD-NEA to be a realistic range[10]. The range of variation of the other parameters are judged to be reasonable upper and lower bounds. In NNL's economic analyses, waste management and decommissioning costs are treated as provisioned items, but even so, the overall generating cost shows little sensitivity.

The economics of nuclear power in a deregulated market are not straightforward and the assumptions are open to confirmation and debate and this is the reason why this topic continues to be key. Ultimately, it is the economics that will govern whether new build goes ahead and whether it will be successful; the fact that private consortia are positioning themselves to invest is the strongest indication that new nuclear plants are believed to be and will be competitive and the same level of confidence must be seen from the investors and financiers.

9 The Future of Nuclear Power: The Role of Nuclear Power in a Low Carbon UK Economy, Consultation document, May 2007

10 How competitive is nuclear energy? NEA News, No28.1, 2010



Conclusions

Based on five scenarios for future nuclear build in the UK, the UK National Nuclear Laboratory (NNL) has evaluated their impact analysed in fifteen areas. It is envisaged that these five scenarios will act as the basis of future detailed analysis that will be used to inform policy makers and assist in developing a future UK nuclear energy roadmap. Recognising that new build scenarios in the UK would be strongly influenced by world-wide developments, it is envisaged that for each scenario a corresponding world scenario should also be adopted. As far as possible, these should be consistent with scenarios developed by internationally recognised bodies such as the OECD International Energy Agency (IEA) and the OECD Nuclear Energy Agency (NEA). Developing the world scenarios in parallel with the UK scenarios would allow the UK scenarios to be understood in the appropriate context.

NNL believes that this paper should be used as the basis of a UK nuclear energy roadmap in which the socio-economic, strategic and technical areas above must be thoroughly addressed. The recommendations from the resulting roadmap should then be used to assist the decision and policy makers in the UK along with the investors and financiers.

NNL position statements

Economics

- Total generating costs for nuclear energy are most sensitive to the assumed discount rate. Uncertainties in the regulatory and approvals process (hence introducing delays) along with source of investor funding (hence the range in discount rates assumed) are the major source of investment risk, leading to high discount rates and measures to streamline them are key to investment in new build.
- In the event of an increase in energy production from nuclear, consideration should be given to the strategic and economic benefit to invest in a new fuel fabrication plant in the UK.
- At modest generation levels of nuclear, there is unlikely to be a concern over the availability of uranium ore, but given an equivalent increase in demand worldwide, the escalation of uranium prices would be inevitable. In the event of nuclear dominating the electricity supply in the UK, the uranium ore demands are judged to be large enough to be significant in the world market and the potential impact on uranium ore supply, price and generating cost from nuclear needs to be evaluated.
- Although those reactors being considered for deployment in the UK can load follow from a technical perspective (as already demonstrated today in France), an economic, strategic and financial mechanism would need to be in place if the utilities were to consider this option.

Waste Management

- Any new build will result in an increase in the spent fuel and/or VHLW volumes. Although higher, there are notable economic and strategic benefits in terms of useful energy output over the lifetime of the new build plants given their higher availability factors and lifetimes. A more complete evaluation of the spent fuels and associated inventories for new build is recommended.
- An assessment akin to "Justification" would be the most appropriate way to evaluate the benefits and detriments of waste management options.
- Regardless of the size of any new build fleet, a geological disposal facility (GDF) is still required for the current fleet and needs to be progressed.
- The increases in high level waste storage and repository capacities for new build, although it may be technically feasible, will result in the need for additional capacity (albeit at potentially marginal increases in cost) and in some scenarios, these volumes could result in the need for more than one repository.

Spent Nuclear Fuel

- Spent fuel from new build plants is of a type that is already used in the UK today and is well understood, well characterised, widely used internationally and suitable for long term dry storage.
- Assessment of the long term storage of spent PWR fuel, either on-site or in a centralised store, must also be part of the consideration of future fuel cycle options.

Policy and Strategy

- Scenario 1 is the default position in the case of no new build in the UK. Scenarios 2, 3 and 4 are all realistic and feasible, though Scenario 4 would present challenges for investment, build-rate and resource availability and spent fuel/waste management. However, Scenario 5 would present very large strategic challenges in all these areas and its feasibility has to be regarded as questionable unless there is Government intervention based on policy at that time. Scenario 5 is specifically intended to be a bounding case that represents the limit at which the reactors could be built up to 2050.

- Nuclear has a notable role to play in CO_2 avoidance and in the UK aiming to meet its reduction targets by 2050.
- In the event of a notable increase in electricity production in the UK from nuclear (greater than 25 GWe), an extension to the existing site boundaries or larger number of sites than those already identified may be required. It is therefore recommended that some of the existing sites should be assessed for their suitability to host the equivalent of two or more twin plants, for example, by extending the boundary fences.
- In the event that nuclear dominates the electricity generation, the strategic importance of nuclear is so high that it would likely pose unacceptable risk to rely on just a single reactor design; reliability and thus availability of the nuclear fleet becomes of much greater importance. Consideration should therefore be given not just to an energy mix, but also a technology mix in this event.
- The rate of build could become a limiting factor in the event of a dramatic nuclear expansion in the UK, with significant demand placed on resources, including the construction teams and scientific and engineering expertise in the UK.
- If nuclear is to dominate electricity supply in the UK, alternative roles including electricity source for electric vehicles or for use in hydrogen fuel production should be recognised and considered as nuclear would be a virtually zero CO_2 energy source.

Fuel Cycle

- PWR technology is likely to dominate and be the preferred reactor option over the next 60+ years in the UK and internationally. As such, any future fuel cycle options, including waste management, sustainability etc must be compatible with this fuel and reactor type. Regardless of the scenario, the more efficient use of uranium ore and the possible exploitation of secondary fuel sources, such as Reprocessed Uranium (Rep U) and tails re-enrichment, needs to be considered by the nuclear industry. Furthermore, the more efficient use of uranium ore and the fissile material needs to be considered, including associated development of new fuels and associated manufacturing processes e.g. looking to achieve higher burnups, thus extracting more energy out of each tonne of uranium ore mined.
- In PWRs, the recycle and re-use of reprocessed uranium and plutonium could meet a substantial proportion of fuel demand for the UK and assist in the sustainability of nuclear, particular if nuclear produces a larger proportion of electricity than previously i.e., act as a strategic resource. Government intervention and policy on reprocessed uranium and plutonium recycle needs to be clear and consistent as it will have an impact for many decades ahead and to date there is insufficient knowledge to choose the optimum option.
- UK Government policy on Rep U and plutonium recycle needs to be clear and consistent as it will have an impact for many decades ahead and to date there is insufficient knowledge to choose the optimum option.
- For the future, if nuclear is a significant part of the energy mix, it is judged that PWRs alone could not meet all of the UK's strategic requirements (including transport, heating etc) and as such new Generation IV reactor systems and an associated closed fuel cycle, including reprocessing, would be needed at an earlier stage to match the potential changing role of nuclear and to improve sustainability. As such, there is the need for investment in Generation IV research in the UK to mitigate technology risks and to ensure that the UK nuclear organisations (industry, national laboratories and academia) play a full commercial role in the deployment of these technologies in the UK and internationally, ensuring that the technologies being considered are safe, secure, economic and with increased proliferation resistance.
- The full value of separated plutonium would not be realised without a fast reactor programme, which is another important strategic driver to consider a future fully closed fuel cycle and UK investment in Generation IV research.
- In the longer term, Generation IV reactor operating a breeding cycle could be deployed which could in principle vastly reduce dependency on uranium ore.
- The current situation where reprocessing is acknowledged by bodies such as OECD/NEA to be more expensive than direct storage, could be reversed if uranium ore prices were to rise significantly. At present, there is little prospect of this situation arising, but over the 60 year lifetime of the new build plants, it is conceivable that this could occur. Other benefits of reprocessing and recycle including reduction in the demand on the repository and effective use of the fissile material for the reasons of sustainability must also be considered in evaluating future nuclear fuel cycles for the UK. An integrated strategic assessment of future fuel cycle options is therefore required for the UK taking into account fissile material management, spent fuel and waste arisings, non-proliferation, impact on geological disposal facility and economics. Any consideration of recycle would require Government intervention and policy in order for this to be considered by the utilities.

APPENDIX A

SUPPLEMENTARY DATA

Where available, all data for the Scenario 1 (no new build) has been based on the CORWM report .[6] *For each of the new build scenarios, the data has been derived from the NNL's own internal assessments as part of the Signature Research Programme.*

Table A.1: Nuclear output as a fraction of total primary energy demand in 2050

Scenario	Wicks Report scenario	Total UK primary energy in 2050 (PJ)	Equilibrium nuclear output (PJ)	Nuclear output as a fraction of total electrical output (%)*	Nuclear output as fraction of total primary energy demand (%)	Total nuclear output from 2010 (GWye)
1	Base	7700	0	0	0	73.0
2	80% emissions reduction	5300	270	12.5	5	586.4
3	90% emissions reduction	4400	670	31.0	15	1356.4
4	95% emissions reduction	3500	1200	55.6	34	2383.2
5	-	-	4050	-	-	7773.4

* Assuming 1% escalation of electrical output per year to 2050

Table A.2: Carbon dioxide emissions at equilibrium (Mt carbon per year)

Scenario	Output (TWhe)	Emissions $MtCO_2$ per year	Avoided emissions $MtCO_2$ per year
2	75	0.5 – 1.7	27.0 - 60.6
3	187	1.3 - 4.1	67.1 – 151.4
4	337	2.4 – 7.4	120.7 – 272.4
5	1124	7.9 – 24.7	402.4 – 908.2

Table A.3: Cumulative spent fuel and waste arisings in the five scenarios (tHMi)

Scenario	Cumulative spent fuel mass with *no* reprocessing for new build (tHM)	Cumulative packaged volume of spent fuel with *no* reprocessing for new build (m^3)	Cumulative VHLW packaged volume with reprocessing for new build (m^3)	Cumulative ILW packaged volume with reprocessing for new build (m^3)
1	4700	8150	1290	468420
2	14700	30950	2890	478420
3	30200	66350	5390	493920
4	50700	113150	8690	514420
5	157700	357150	25790	621420

Table A.4: Operational waste arisings from new build plants

Scenario	Cumulative ILW (m^3)	Cumulative LLW (m^3)
2	7200	62400
3	18000	156000
4	32400	281000
5	108000	936000

Table A.5: Impact on spent fuel capacity in Geological Disposal Facility (GDF) scaled from NDA assessments – assumes no reprocessing of new build fuels

Scenario	Number of disposal canisters	Area (km^2)	Area for new build relative to legacy HLW and spent fuel (%)
1	-	-	-
2	5210	0.88	48
3	12800	2.20	120
4	23040	3.96	220
5	76800	13.20	730

Table A.6: Impact on ILW capacity in Geological Disposal Facility (GDF) scaled from NDA assessments

Scenario	Vault length (m)	Vault length for new build relative to legacy ILW (%)
2	520	8
3	1300	20
4	2340	36
5	7800	120

Table A.7: Additional plutonium and reprocessed uranium (Rep U) inventories from new build plants (tonnes)

Scenario	tonnes Pu	tonnes Rep U
2	123	9500
3	306	24000
4	552	42500
5	1838	142000

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