**PIU Energy Review Working Paper**

# The Economics of Nuclear Power

## *Introduction*

Nuclear power and the various forms of renewable energy are the two main virtually-zero carbon electricity supply options.[1] Even if UK energy efficiency is improved dramatically, new electricity supply options will be needed on a significant scale as older stations of all types are retired. In a world constrained to achieve major carbon emission reductions, nuclear power and renewables assume particular importance. The contribution that each could make to the UK energy mix is potentially large - but strictly limited if current market conditions alone determine investment choices. Renewables are mostly embryonic technologies with costs higher than gas-based alternatives, especially combined cycle gas-turbines (CCGTs). Nuclear power is a more mature technology, though also not currently competitive as a new investment option.

The purpose of investigating the current and potential future economic status of nuclear and renewables is not that a choice, public or private, must necessarily be made in favour of one and at the expense of the other - though a large nuclear programme could in practical terms ‘crowd out’ other options including renewables. The purpose is rather that investment in both technologies might in principle receive taxpayers’ or consumers’ financial support. Knowledge about the present and future economic status of such potentially supported technologies is therefore important in informing public decisions about whether, to what levels and over what periods, such support might be provided. Investment decisions about nuclear new-build will be made by private markets which could well take a different view on nuclear economics to that presented here.

Renewables have been financially supported by the Fossil Fuel Levy and will soon be supported by the Renewables Obligation[2]. Nuclear power is not currently supported in such ways.

The PIU has taken care to ensure that the same analytical principles have been applied to assessment of the economics of both renewables and nuclear power. There is a substantial amount of recent and publicly available data on the economics of some renewable energy (e.g. wind and photovoltaics). However, in the case of other renewables and nuclear power, there has been no recent commercial experience. In such cases estimates of costs are necessarily highly uncertain and a substantial error band needs to frame the most probable outcomes. Reporting the results of PIU work

[1] Carbon capture and sequestration is a further relevant potential option but due to its uncertainty it is ignored in this working paper

[2] Analysis of the current and prospective economics of renewables is mostly contained within Annex 6 of the PIU (2001) References to renewable economics in this working paper are mostly confined to a brief discussion about system cost issues and learning.

on nuclear power in this paper has the additional handicap that much of the data presented to the PIU were necessarily commercially confidential.

## *Methods of Economic Analysis*

Investment decisions on new nuclear power (and renewable energy) are not determined narrowly by economic evaluation. Both nuclear and some renewables (most notably onshore wind) experience considerable local environmental opposition, and this translates into difficulties in securing planning permission. For nuclear power, nuclear waste policy remains an unresolved issue and this may, or may not, constitute a large obstacle to new nuclear investment. Such wider issues do of course have cost consequences and add greatly to investment uncertainty, but for the most part this paper concentrates on conventional economic issues.

The most comprehensive economic analysis would examine the *system* cost of new nuclear and other potential investment (i.e. including all transmission costs and any necessary system reinforcements) and would try to include monetary evaluation of all *externalities* involved.

For the purposes of this paper, however, system issues are ignored and currently unpriced externalities are set aside. System costs associated with new investment in electricity generation are highly dependent on both location and existing system characteristics. This means that the extent of costs incurred beyond the plant boundary will vary substantially with individual proposals. If any new nuclear plant were to be located on existing nuclear sites and replaced shut-down nuclear capacity (as proposed by British Energy), incremental transmission costs would be zero or negligible. Such considerations will be important for real investment decisions on nuclear power, and could give some advantage to nuclear over alternatives. However, this paper follows the practice of both British Energy[3] and BNFL[4] in considering only ‘single station’ economics, at existing market prices and under existing taxation structures.

The approach taken to the future economics of renewable technologies is to use both ‘learning curves’ and engineering judgements and analysis.[5] Engineering judgements, in which the lower limits to the costs of producing certain types of physical structure are directly estimated, are important where learning curve techniques are difficult to apply, and these were used for several of the renewables. Their drawback is that expert judgements vary and there is often no obvious way of choosing one over another.

Where possible, empirical use of learning curve analysis avoids some of the judgement problems in the engineering approach. The idea of learning, and the expectation of cost reductions as a consequence of learning, is as applicable in principle to nuclear power as to renewables and any other technology. Essentially a learning curve reflects an estimated *technical* relationship between a production

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[3] British Energy (2001)

[4] BNFL (2001)

[5] See especially Annex 6 to PIU (2001).

process and its costs. It can be expressed in a variety of ways but the most widely used method is in terms of doubling time – the percentage reduction in costs for each doubling of production. This is often known as the 'learning rate'. Characteristic learning rates in manufacturing are in the range 10% to 30%. Learning rates will not however generally be constant, and as technology matures, the learning rate will often fall. It is generally agreed that the relevant learning is an international phenomenon and so learning refers to worldwide, not single-country experience.

The principles which underpin the use of both learning curves and engineering judgements are explored in more depth in Annex 1 of the PIU Working Paper on generating technologies: potential and cost reductions to 2020.

**Application of learning curves:**

The use and interpretation of classic learning curves is not entirely straightforward in the case of nuclear power. The reasons for this are several. Classic learning curve analysis generally assumes that products or technologies are available in very large numbers; that technical and market development is continuous; and that there is little influence on costs from wider social and economic processes. The problems in the nuclear case are that:

- Individual components of nuclear power stations are subject to classic learning analysis in a straightforward way, but whole stations have been subject to long, complex and internationally variable regulatory and political processes. These processes have provided substantial 'interference' in the technical process of cost evolution. Learning for most technologies is a global phenomenon, and takes place most rapidly in the context of large and well integrated global markets (IEA 2001). However, particularly in the first decades of development, nuclear power programs were pursued separately in several countries, with limited information sharing because of concerns about strategic national interest. This served to impede technology transfer and hence learning.

- Nuclear power technology development has not been continuous and there have been major changes in technological routes followed, especially in the UK. 60% of current OECD nuclear capacity was ordered before 1973, 20% from 1974 to 1979 and the remaining 20% more recently. In the UK only one nuclear power station has been ordered in the past twenty years (and no orders within the OECD since 1993). [6] The one nuclear order in the UK (Sizewell B) was for a water cooled pressurised water reactor (PWR), a radically different design from all previous UK nuclear technologies, which had been based on gas cooling. Further, the UK design at Sizewell differed in important respects from other PWRs then being built internationally.

- Where learning effects are readily detectable, the learning rate is likely to be lower for large and complex technologies like nuclear reactors than for

[6] IEA (2001), p. 100.

smaller, simpler and more rapidly constructed technologies like most renewables. The learning and cost reduction expected by British Energy in its proposed programme of ten nuclear units derives from design standardisation, the scale effects of series construction (longer production runs, conventional economies of large-scale production) and from learning in the construction process itself.

- Additional learning processes such as feedback from operational experience into innovation and future design are likely to be slower for nuclear power than for renewables for four reasons.

  - Nuclear power is a relatively mature technology with a 50-year history of development, and this means that dramatic ‘technological stretch’ is less likely than for newer technologies
  - the relatively long lead times for nuclear construction and commissioning mean that improvements derived by feeding back information from operating experience on the first units are necessarily slower.
  - the fact that individual nuclear designs need safety licenses, which are not available quickly, means that large improvements in design resulting from operating experience take time to incorporate into the next generation of plant.
  - the scope for economies of large-scale manufacturing production is less in the nuclear case, where components are large and production runs short (even in series build), than for renewables, where there may be thousands of units built.

For these reasons, observed learning rates for nuclear power are likely to be quite low. Empirical support for this comes from a recent paper[7] which suggests a learning rate of 5.8% for the OECD over 1975-93. By contrast learning rates for most energy technologies lie in the range 15 – 20%, and those observed for wind energy and photovoltaics are in the 18 – 20% range (IEA 2000, McDonald et al 2001).

However, these kinds of result do not at all prove that learning must necessarily be limited in the case of nuclear power. Still less do they prove that overall cost reductions in nuclear power must be small. It is possible that increased standardisation of products, globalisation and privatisation of the industry and a retreat from public sector reactor development programmes pursued in the national interest will serve to accelerate learning above the historic rate. It is necessary to apply engineering judgement to estimates of future nuclear costs, and such judgements can in principle involve substantial cost reductions – it is not automatically true that relatively mature technologies like nuclear power are always constrained to reduce costs slowly.

[7] Quoted in McDonald (2001), p.257)

‘Nuclear’ technology itself embraces a very wide range of variants and sub-technologies, though development work has for some time concentrated on improving existing variants of PWR and BWR. To the extent that new technological routes may now be more vigorously pursued within nuclear technology development, future nuclear costs could be much lower than past costs. This is reinforced for the UK, where past nuclear costs have, by international standards, been relatively high. While costs may fall for these reasons even if limited numbers of units are built, standardised designs may lead to further cost reductions as a new investment programme evolves. Such ‘learning’ effects might be gained more quickly in the UK if there were international construction of AP1000s, as some of the cost reductions might be genuinely international. However, as no utility anywhere in the world has yet ordered any kind of AP1000, this route to faster cost reductions cannot be relied on at present.

Overall, it is therefore necessary to rely more on engineering judgement that learning curve analysis to come to views about future nuclear economics. The drawback with engineering judgements is that they can differ, and such differences are likely to be all the greater where there is both no recent construction experience, and the proposed design has not yet been built to commercial scale anywhere in the world. In such circumstances, the range of uncertainty over future costs is bound to be very substantial.

It has been important in the PIU evaluations of generating options to establish common rules by which to make generating technology evaluations. For both renewables and nuclear power, therefore the PIU has

- used 8% and 15% real pre-tax cost of capital (discount rates) to reflect the range of financial practice in industry[8]
- established best estimates of current construction costs and used learning and engineering judgement approaches to assess future costs
- for nuclear power, in particular, looked at the issues of ‘back end’ costs (waste and decommissioning) as well as the related issue of accident risks that are hard to quantify.

## *UK Nuclear history, and nuclear cost expectations by 2001*

The history of nuclear power in the UK is one of ambitious plans that were initially broadly adhered to in the 1950s and 1960s, followed by further ambitious plans in the 1970s and early 1980s that were largely abandoned. In the 1950s and early 1960s a substantial programme of Magnox reactors was built. Their costs were relatively close to expectation and this encouraged the idea that a further programme of Advance Gas-Cooled Reactors (AGRs) would be successful in the mid-1960s. However the first five AGR stations, with construction starts stretching from1965 to

[8] The partial exception to this is in the PIU’s analysis of wind energy, where a diversity of policy environments (and associated financing practices) and a high degree of site specific factors impact upon wind costs (wind energy output is a function of the cube of the wind speed and thus highly sensitive to wind regime differentials). Rather than disaggregate these complex factors the PIU explore the potential for learning in the context of a range of costs between ‘high cost’ and ‘low cost’ wind developments. This range reflects both discount rate and financing variations and technical factors. This will tend to provide a wider spread of costs than the impact of discount rates alone.

1971) were technically difficult, subject to long delays in most cases, and had much higher costs than expected.

This poor AGR experience meant that different designs were examined for later reactors, and as early as 1973 the CEGB proposed a programme of at least 18 PWRs, none of which was ever built. By 1978 the CEGB was allowed to prepare to build a single Westinghouse PWR and in addition two further AGRs were ordered, one in England and one in Scotland. In 1979, the commitment to a single PWR was changed into a programme of 10 PWR reactors, to be constructed at the rate of roughly one a year through the 1980s, with Sizewell B as the first. The Public Inquiry for Sizewell B was lengthy, as was the Inspector's writing up period, and it was only in 1987 that the Inquiry report was published[9] and approval for construction given. A Public Inquiry for a proposed Hinkley Point C PWR supported construction in 1989, but these plans were overtaken by electricity privatisation, and the expectation that the costs of Hinkley Point C would be too high in the new liberalised market.

Sizewell B was completed in 1994, and on Nuclear Electric's own reporting in 1990, was expected to generate at 5.0p/kWh (1990 prices and 8% discount rate)[10]. The construction cost budget was revised upwards on three occasions, and the final cost of construction was at least 35% higher in real terms than that quoted as firm at the time of project approval in 1987.[11] In 2000 money, the construction cost was approximately £3000/kW including first of a kind costs, or around £2250/kW in their absence. Making reasonable assumptions about operating performance, this makes the total generating cost of Sizewell B around 6p/kWh, (again in year 2000 prices) *excluding* first of a kind costs.

By the time of the Government's 1995 White Paper on nuclear power[12], the industry had proposed a new strategy of a twin-unit PWR with construction costs of c.£1640/kW at year 2000 prices (quoted in the White Paper as £1343/kW in 1993 money). This translated into just over 3.5p/kWh in 2000 money (2.9p/kWh in 1993 prices) at an 8% discount rate, or around 4.5p/kWh (3.7p/kWh in 1993 prices) at the discount rate of 11% then thought by Nuclear Electric as appropriate for private investment in nuclear plant in a competitive generation market.

In 2001, British Energy proposed a ten unit programme (five twin units) of the AP1000,[13] an 'evolutionary' design based on the Westinghouse PWR but with more passive safety features and a simplified design using substantially less materials. Generating costs at 8% discount rate are expected to range from around 3p/kWh (first twin unit) to around 2.5p/kWh for later twin units. BNFL's views are similar: it suggests a cost range of 2.2p/kWh to 3p/kWh[14]

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9 Layfield (1987)
10 Goddard (1991).
11 MacKerron 1994, pp.2-5.
12 DTI (1995)
13 British Energy (2001) especially p. 13.
14 BNFL (2001) especially, pp, 17-19.

**Table 1: Nuclear Generating Costs**
**(8% real, pre-tax discount rate; year 2000 money values)**

| | Sizewell B out-turn * | 1995 Review | Expected 1st unit (2001)** | Expected 4th unit (2001)** |
|---|---|---|---|---|
| | | | | |
| **£/KW** | 2250 | 1640 | XX | XX |
| **p/kWh **** | c.6 | 3.5 | 3.0 | 2.2-2.5 |

* excluding first of a kind costs.
** Discount rate (real, post-tax) of c. 12% (British Energy) and 7% (BNFL)
XX Indicates commercially confidential

Industry expectations are therefore for radical reductions – halving or better - in nuclear costs between the late 1980s and the present. The most important factors in support of an engineering judgement in favour of large cost reductions are greater competition to nuclear plant, wider internationalisation of construction practice, and changes in design.

- Nuclear plant faces stronger competition all round the world than was the case 10 years ago and this has put pressure on its owners to reduce costs. The combined cycle gas turbine has emerged as a major new generation technology and there has been significant progress in developing renewables. Competition between different generating technologies has been enhanced by widespread electricity market liberalisation., Nuclear stations in the UK and elsewhere now operate at higher availabilities and with lower operating and maintenance costs than a decade ago. Operating availabilities now average 75% to 80% across the OECD[15], with 85% in some cases. UK AGR operating performance has improved from around 50% to 75% and better.
- In terms of construction practice, procurement is now much more efficient than for Sizewell B, much of which was carried out while the industry was still nationalised. Future contracting would probably be by full international competitive practice. This should lead to the possibility of firmer, and lower, contract prices than was possible in the 1980s.
- In terms of design, the AP1000 is a much simpler machine than the Sizewell B PWR. It is much smaller in 'footprint' and is expected to use much smaller quantities of many of the most expensive input materials: for example a reduction in valves by 50%, in pipe by 80% and in cable by 70%[16] In addition, more of the construction takes place in factories and much less on site, which also tends to reduce costs and accelerate progress on site.

The industry claims that the combination of these factors produces current estimates of nuclear generating costs at least 50% below those experienced at Sizewell B, and significantly below those put forward by the industry in 1994. The question is whether these 'headline' figures put forward by the industry represent a full picture of the range of uncertainty attaching to future UK nuclear construction.

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[15] IEA (2001), p.107
[16] BNFL (2001) p. 18.

## *Cost estimates for nuclear new build: implications of uncertainty*

The PIU received two main submissions on future nuclear costs, from British Energy (BE) and from British Nuclear Fuels Ltd (BNFL). Both submissions take the AP1000 design as the main basis for their cost estimates, though British Energy also gives attention to the NG CANDU design. The AP1000 is an 1120MW reactor of Westinghouse design, which BNFL now owns via its Westinghouse subsidiary. The CANDU design is for a next generation heavy water reactor from Canada, though this will not be commercially available for two or three years. As fewer details are provided on the CANDU, attention here is confined to the AP1000. Much of the BE evidence for costs of the AP1000 is based on BNFL cost information, modified in various ways. As outlined above, the industry estimates for new build are taken to be in the range 2.2p/kWh (BNFL, and if a programme of 10 reactors is constructed) to 3p/kWh (for a single site).

### Appraisal uncertainties

Before looking at the ways in which uncertainty may impact on particular variables within the economic appraisal, it is first necessary to give a fuller account of the industry's own numbers. While the 'headline' figures for generating cost provided by BE and BNFL are similar, the assumptions that underlie them are in important respects different. The most important cases are:

- BNFL figures assume a 7% real, post-tax discount rate, while BE uses 8.2% real, post-tax%;
- BNFL use 30 year lifetimes while BE use 20 years;
- BNFL assume single units per site, while BE assume twin units;
- BNFL use a slightly lower estimate of plant availability.

In the first two cases BNFL assumptions would give lower costs than BE; in the latter cases, the reverse will be true. As far as possible the PIU has established, for each company, what the generating cost figures would be (for first and eighth units) using the standard PIU assumptions of 8% and 15% discount rates and 15 and 20 year lifetimes.

Table 2 shows the results as provided by the industry. Two results stand out:

**Table 2: Industry nuclear generating cost forecasts (p/kWh)**

| | | ***15 years*** | ***20 years*** | ***30 years*** |
|---|---|---|---|---|
| | | | | |

| **Discount rate** | Unit no. and company estimate | | | |
|---|---|---|---|---|
| 8% | 1st – BNFL | 3.90 | | 3.19 |
| 8% | 8th - BNFL | 2.83 | | 2.31 |
| 8% | 8th - BE | 2.22 | | - |
| 12% | 1st - BE | | 3.0 | |
| 12% | 8th - BE | | 2.47 | |
| 15% | 1st - BNFL | 5.74 | | |
| 15% | 8th - BNFL | 3.79 | | |
| 15% | 8th - BE | 3.24 | | |

Source: data supplied to PIU by British Energy and BNFL

- Estimated costs are quite sensitive to both discount rate assumptions (though the effect seems to be less marked in the BE case) and to whether or not there is series build;

- Using a 15 year life, the range of possible costs is very wide – from 2.22p/kWh to 5.74p/kWh, depending on exact assumptions made.

The uncertainties reflected in Table 2 are all concerned with *appraisal* issues – the underlying assumptions about the specific values of parameters (e.g. construction cost) are broadly similar, and what changes are assumptions about the way that markets will conduct the appraisals. In particular, Table 2 shows clearly the impact of changing assumptions on discount rates and lifetimes, where lifetimes are defined in terms of the maximum likely period of borrowing for plant construction. Until markets are engaged in actual decisions on new build, the ‘correct’ values for discount rates and lifetimes are difficult to predict.

**Other sources of uncertainty**

A second source of uncertainty in the figures for nuclear generation costs derives from the individual assumptions about specific parameters, both economic and physical. There are some parameters where either the values are well established, or the results are insensitive to large changes in the values assumed. There are two main types of cost where there will be little impact on total cost

*Operations and Maintenance (O&M) costs plus front-end fuel costs*

These are the costs of acquiring fresh fuel, but not managing spent fuel. These are a small part of the total cost and their likely scale can be more easily established from analysis of current reactors: the industry estimates reflect this.

*Back end costs (waste and decommissioning) and insurance for accidents*

Given the importance of these costs – especially waste – in the political debate, it is surprising at first sight to find that the values assumed here have very little impact on total generating costs.

On wastes, one view, represented by the RCEP, is that new nuclear construction should not be permitted until the waste management problem has been solved to the satisfaction of both the scientific community and the general public.[17] This is essentially a political judgment and is not directly related to the economic argument about the possible uncertainties in overall nuclear generating costs due to uncertainties about decisions on nuclear waste policy. In the PIU Review, no position was taken on the general question of the acceptability of new build in the absence of 'solutions' to the waste problem. It is important to note that BE estimate that the increase in waste volumes from lifetime operation of a new ten-unit programme would only be 10% on the current stock of UK waste.

Back end costs are incurred a relatively long time after the plant is constructed, even if decommissioning is prompt and wastes are treated quickly and comprehensively. In general it is fair to assume that there will be around 50 years (and possibly more) between the start of a nuclear project and the need to start incurring significant back end costs, given an expectation of a planning /construction period of up to a decade, plus an expected operating life of around 40 years. Provided that potentially 'external' costs are fully internalised and funded – most likely by an annual payment into a segregated fund as is currently the case for British Energy decommissioning – then the final cost of back end operations can be discounted by whatever rate of accumulation of funds can be reasonably assumed. At present, BE uses an average 3.5% (real) fund accumulation rate, and the arithmetic of even such low rates such as 3.5% is powerful. A cost 50 years from now at 3.5% has a present value only 18% of its undiscounted value. In other words, £18 invested now at an annual rate of return of 3.5% will accumulate to £100 in 50 years' time.

This means that decisions about new build are relatively insensitive to back end costs even if back end costs are highly uncertain. The potentially most important category is spent fuel management and waste costs. The industry has not updated its estimate of waste management costs produced for the Government's Nuclear Review of 1995 and at that time waste costs appear to have contributed less than 0.1p/kWh to overall generating cost.[18] Currently waste policy is possibly even more uncertain than it was in 1995 (given the abandonment of the NIREX Rock Characterisation Facility in 1997). It is therefore impossible to estimate waste management costs in any useful way at present.

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[17] RCEP, para. 7.19
[18] Information provided by BNFL

However, it would need very large increases in expected waste costs compared to 1995 for waste costs to influence the overall generating cost more than marginally. If waste costs were to rise by a multiple of three compared to 1995 expectations, then waste costs might amount to something under 0.3p/kWh. However, waste may remain an area of concern for potential investors, and some adverse impact on the economics of new build cannot entirely be ruled out. Nevertheless, while waste may be a large issue politically in the new build equation, it is unlikely to be a *determining* factor in the economics.

There is also the risk of damage to third parties as the result of a nuclear accident. At present the Government underwrites residual risk beyond £140 m, though the limit is expected to rise under the Paris and Brussels Conventions to 700 million euros.[19] No such accidents have yet occurred in the UK or the rest of the OECD, and so the value of the underwriting is impossible to establish objectively, as is the potential scale of damage if such a serious accident ever should occur. In addition, nuclear insurance is compulsory up to the limit of liability, and no-fault liability is also applied (in both cases more rigorously for nuclear than for other generation). It is therefore difficult to know how much of a 'shadow price' to attach to nuclear generating costs for this reason. However, it seems that such a shadow price of underwriting insurance, given the lack of serious accidents to date, is likely to be very small.

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The elements of nuclear cost where total generating cost is most sensitive to possible variations in assumed values are construction cost (including impacts of delay risks), and operating availability. The reason, in both cases, is that nuclear power is highly capital-intensive, and so its economics depend both on keeping capital costs low and utilising nuclear assets as intensively as possible.

*Construction costs (and times)*

The main problem in judging the accuracy of construction cost estimates for nuclear power is the lack of recent construction experience and also the lack of published data. This has two elements:

- The lack of any recent nuclear construction experience anywhere in OECD Europe – even France last placed a nuclear order in 1993,[20] and only in Japan and Korea, with different cost structures across all energy technologies, have recent orders been placed.
- The fact that while the components of the AP1000 design are familiar, the overall design configuration is novel, as are some of the (desirable) passive safety features. Only the smaller AP600 has yet cleared the US generic regulatory process, and no full-size AP-type reactor has yet been built anywhere in the world.

These uncertainties contribute to the fact that neither BNFL nor BE can currently be sure that any construction contract for an AP1000 station could be at fixed price. Substantially stronger construction cost guarantees are available today for CCGT

[19] Information provided by British Energy
[20] IEA (2001) p. 100.

construction, and for the more established renewable technologies such as onshore wind.

In these circumstances it is difficult to judge the potential accuracy of the industry's expected figures for construction costs and times . Possible benchmarks in the absence of real data for recent construction costs are the figures from recent IEA reports on expected construction costs for nuclear new build across seven OECD countries, excluding the UK but including countries with historically low construction costs (France) or expecting low costs in future (Canada). These suggest a range of $1518/kW to $2521/kW, implying an average expectation of around $2000/kW[21] The British Energy and BNFL construction cost figures are below the bottom end of this range, suggesting that risks may be asymmetrical – higher costs than current industry figures are more probable than lower costs.

There are development and first-of-a-kind (FOAK) costs that are additional to the cost estimates provided by BE and BNFL. BNFL estimate 'launch costs' at over £100 m.[22] while BE quote the higher figure of £300 m. to cover FOAK and development[23]. Such costs need to be added in to the estimates provided by the companies. They would also be incurred ahead of plant investment and would therefore be subject to negligible discounting. While even the £300 m. cost would have relatively little impact on generating costs if spread over 10 units, the impact on a smaller investment programme would not be negligible.

The impact of higher costs and longer construction periods have been estimated by BE. If the construction cost escalated by 10% this would add 0.18p/kWh to generating cost, and a 20% escalation would add 0.35p/kWh. A one year delay in construction time would add 0.15p/kwh and the combined effect of a 20% overrun and a one year delay would be to add 0.5p/kWh to costs. If, say three units were built, the impact on the generating cost of each would (by interpolating BE data on construction cost escalation) be an increase of around 0.18p/kWh (See Table 3 below).

Both BE and BNFL expect reductions of about one quarter in construction costs between first and fourth twin units. Evidence from experience in Korea suggests that the reduction in cost between a first and fourth double unit of the same standardized design amounted to 23%. This suggests that the expectation of similar cost reductions between first and fourth units for the UK is reasonable.[24] It is thought within the industry (for example by EDF, who have substantial experience in construction of replica nuclear plants) that few significant further economies may be gained after seven or eight identical units.[25] The question that remains is whether or not the *starting point* for this cost reduction in later units can in all circumstances be expected to be as low as currently predicted by the industry .

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[21] IEA (2001) pp. 130-131).
[22] BNFL (2001) p. 28
[23] BE (2001), para. 40, p. 13.
[24] British Energy Supplementary evidence provided to PIU, October 16 2001 and BNFL Supplementary evidence provided to PIU, October 18 2001.
[25] Interview with officials in Engineering and Services Division, EDF, Paris, November 20 2001.

*Operating availability*

BE expects the operating availability of AP1000 reactors to be slightly better than BNFL. As IEA (2001) makes clear, average current OECD lifetime performance is 75-80% availability, with good units averaging 85%.[26] It is true that the best units have been achieving 90% or better in recent years. However, it is not yet clear that such levels can routinely be achieved over whole plant lifetimes, including the early settling-down years (especially on a new design ofplant not yet built), and later years in which performance may deteriorate to some degree. Both BE and BNFL use figures for availability that are substantially higher than the 75-80% range of recently achieved performance.

It seems unlikely that any party to a future nuclear construction contract would be prepared to guarantee the kind of high lifetime availability expected by BE and BNFL for an AP1000, bearing in mind that it is yet to be built anywhere in the world. By contrast, performance guarantees for very high operating availability are available for CCGTs, and recent data indicates that operating availability for wind turbines is also very high[27]. . Because of the probable lack of performance guarantees on an AP1000 and because BE and BNFL expect very high levels of performance, the risks seem likely to be asymmetrical - a lower availability seems more likely than a higher figure. It is therefore worth investigating the impact of a slightly lower availability on generating cost.

If the average availability of an AP1000 were 8% poorer than currently expected by BE (or some 5% poorer than expected by BNFL), then generating cost would rise by some 0.2p/kWh (Table 3).

**Table 3 Impact of adverse changes in construction and performance variables on nuclear generating costs**

(11% cost of capital; 20-year lifetimes)

| Change | Resulting increase in generating cost |
|---|---|
| A. 10% escalation in construction cost | + 0.18p/kWh |
| B. 20% escalation in construction cost | + 0.35p/kWh |
| C. 1-year delay in construction | + 0.15p.kWh |
| D. Impact of B and C combined | + 0.5p/kWh |
| E. FOAK costs spread over 3 units | + 0.18p/kWh |
| F. Operating performance lower by 8% (compared to BE expectation) | + 0.2p/kWh |

Note: Data on impact of adverse changes supplied by British Energy (Rows A-D and F) or interpolated from the same data (Row E).

## *Conclusions on Generating Costs*

[26] p. 106/107

[27] Operational availability for wind turbines is currently 99%, though wind speed variations reduce the capacity factor to around 30 – 35%. DWTMA, 2000

The industry's best estimates for the generating costs of new nuclear construction lie in the range 2.2p/kwh to 3p/kWh. However as Table 2 shows, changes in appraisal assumptions (eg the possibility that only one unit might be built, and applying the 15% discount rates and 15 year financing lifetimes that are also applied to other technologies appraised by PIU) can easily bring costs to levels well above 3p/kWh. Such figures take as given the industry's assumptions about the values of individual variables like construction costs and operating performance.

However, there are also questions about whether the industry's assumptions about critical variables like construction costs and operating performance are 'central' - in other words have the same risk that they will turn out more favourable as less favourable. To achieve figures much below 3p/kWh depends on:

- construction costs some way below the bottom end of the recently quoted range for nuclear power costs in seven other OECD countries;
- the building of a large programme of up to 10 identical large units; and
- operating performance well above the current OECD average;
- waste costs at levels similar to those expected in 1994;
- discount rates below 15%.

The industry figures also omit FOAK costs of up to £300m.

This overall performance would also probably have to be delivered in the absence of robust performance guarantees for cost and operating availability. These industry assumptions may nevertheless prove to be well founded. However there must be a significant risk that:

- fewer than 10 identical units would be built
- there could be some delay and cost escalation, especially on early units
- operating performance might be slightly below the high industry expectations
- while the overall economics are not critically dependent on waste costs, there could be some escalation compared to 1994 expectations.

Table 3 shows the implications of some of these risks. Bearing in mind the variations. due to different appraisal assumptions from Table 3, an overall future range of generating costs of 2.2p/kWh to 5p/kWh is perfectly possible. However this is a very wide range, and it is important to give a more central range as well. Especially given the rather significant risk that all ten units might not be built, it is easy to see how 3p/kWh is a more realistic lower bound to this central range, with 4p/kWh representing a credible upper bound. While still regarding the 2.2p/kWh to 2.5p/kWh figures as possible, **the PIU analysis suggests that a range of 3p/kWh to 4p/kWh is a more realistic range of likely future nuclear costs**, still representing a major reduction (up to halving) in the costs experiences at Sizewell B, the most recent UK nuclear unit to be built

## *Timing and the longer term economics of nuclear power*

BE suggest that an early start on a programme of AP1000s could lead to the start of commissioning of the first station in 2011. This could lead to the addition of 10GW of new build by around 2021. However, this timetable assumes an immediate commitment by Government and BE and this seems unlikely. It also assumes a much shorter planning period than has been typical of large energy and nuclear projects in the past. A more realistic view would suggest that it would be more like 2014 or 2015 before new build could be commissioned and it might therefore be 2025 before the full 10GW could be completed.

The question is then whether a new generation of cheaper and safer reactors, possibly smaller and more modular, would then be available for ordering as a result of international developments, such as the new US DoE ‘Generation IV’ programme. The target for this programme is to develop reactors with better safety and environmental performance than the current generation of designs at a target cost of $1000/kW (£690/kW),[28] some way below the BE expectation of the ‘settled down’ cost of the AP1000. A number of different designs may be developed, including the part-BNFL funded Pebble Bed Modular Reactor (PBMR), a modular design of high temperature reactor at around 110MW. There are a number of major technical and regulatory issues to be resolved on reactors of this and other radical designs before they could be expected to compete commercially, and it seems unlikely that such designs could become available to generate power commercially much before 2015, and more likely 2020. At such time however, it is possible that such new designs might provide a very competitive source of low carbon power.

PIU
February 2002

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