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THE ECONOMICS OF NUCLEAR POWER

STEVE THOMAS[1]

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1 PSIRU, University of Greenwich

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University of Natural Resources and Life Sciences Vienna, Department of Water, Atmosphere and Environment, Institute of Safety and Risk Sciences, Borkowskigasse 4, 1190 Wien, Austria

URL: http://www.risk.boku.ac.at

EXECUTIVE SUMMARY

Despite more than 50 years of commercial experience of nuclear power plants, there are wide variations in forecasts of the cost of electricity produced by nuclear power plants. There are a number of factors behind this lack of agreement ranging from bias amongst the forecasters to lack of information on important cost elements. Nuclear power also raises serious inter-generational equity issues because of the very long product life of perhaps more than 150 years from start of construction to completion of decommissioning and normal project appraisal techniques do not appear to give adequate weight to very large costs incurred many decades in the future.

Determining the cost of a kWh of nuclear electricity requires the estimation of a large number of costs that are incurred from the start of the pre-construction phase, for example design work, to the completion of decommissioning phase, for example, the disposal of the radioactive waste arising from decommissioning. In terms of their impact on the cost of a kWh of nuclear electricity, the construction cost and the cost of capital are by far the most important. As the existing fleet of nuclear power plants ages, there is increasing interest in the possibility of life-extending them. This is often seen as providing very cheap power because the initial construction costs will have been paid by then, but if significant upgrades are required to make the plant acceptable to safety regulators, the option may not be financially attractive.

A simple model to calculate the Levelized Cost of Electricity from a nuclear power plant shows that depending on the assumptions chosen the cost of power from a nuclear power plant could vary between €80-210/MWh and if serious problems occurred in the construction phase, as, for example at the Olkiluoto plant in Finland, the cost could be €230/MWh or more.

Table of Contents

TABLES

FIGURES

METHODOLOGY

The methodology used in this paper is literature review and forensic examination of all of the cost elements of the life cycle of a nuclear power plant from design to completion of decommissioning and final disposal of the waste.

1 ISSUES WITH FORECASTING NUCLEAR COSTS

1.1 INTRODUCTION

The cost of power from nuclear power plants is an important element in the debate on nuclear power. For some people, nuclear power would not be acceptable at any cost while for others, nuclear power is the only solution to our long-term energy needs so must be made to work regardless of cost. However, for many people in the middle, the cost of power is important. If nuclear really is cheap then this may be enough to overcome concerns about ethical, strategic and environmental issues, if it is not cheap, there would be little justification to pursue a technology that raises so many difficult issues. However, despite more than 50 years of commercial experience with nuclear power, there is still wide disagreement about what the cost of power from nuclear power stations really is.

A related issue of growing importance is the cost of power from existing nuclear power plants. As the stock of nuclear power plants ages and with many units approaching the end of their design/licensed life, the choice arises of whether to retire the plants or to keep them in service for a significantly longer period. The common perception is that because the construction cost of such plants has been paid, extending their life would provide cheap power. The key question is how far plants that are being life-extended should be required to meet current standards.

In this report, we examine the information needed to provide a comprehensive picture of the economics of nuclear power. In detail, in the next section, we identify the main variables and the issues that must be dealt with in forecasting them. In the third section, we look at the techniques for project appraisal and how they deal with issues of intergenerational equity and the tension between corporate and public interests. In the fourth section, we examine the individual variables in more detail. In the fifth section, we examine the determinants of the cost of power from life-extended plants. In the final section, we look at the impact of factoring the relatively low carbon emissions nuclear power results in to the economics.

1.2 PROJECT APPRAISAL, INTERGENERATIONAL EQUITY AND RECONCILING CORPORATE AND PUBLIC INTERESTS

While the cost of decommissioning retired nuclear plants and waste disposal is expected to be huge - in the order of billions of Euro per reactor - this cost has little impact on a corporate decision whether to invest. Under conventional accounting (and as discussed in more detail below), a liability that falls due in 100 years can, by the process of 'discounting', effectively be met by investing a much smaller sum of money and relying on interest earned for this sum to grow to the required level. For example, if the decommissioning cost is expected to be €1bn and decommissioning is expected to take place in 100 years, an investment of only €140m will grow to meet the required sum in 100 years if it achieves a real annual interest rate of only 2 per cent. However, if, for whatever reason, the fund is insufficient, for example, it is lost, does not grow sufficiently or the cost estimate is too low, a future generation will be required to carry out a hazardous task (they will have to do this no matter how good the funding arrangements are) and pay for some or all of it from their own resources. Equally, as has been tragically illustrated by the disasters at Chernobyl and

Fukushima, the scale of damages that can result from a major accident are so huge that it is hard to imagine arrangements that will not require public funds to deal with the consequences.

A country launching a nuclear power program is making a serious financial and safety commitment for many generations forward. Nuclear power programs should therefore only be allowed to proceed with explicit and informed public consent based on knowledge of the scale of the financial and physical commitment they were making for future generations.

1.3 PROJECT APPRAISAL AND DISCOUNTING

When determining the economic value of a project, it is necessary to compare costs incurred over the life of the project. In conventional economic terms, a benefit received today is assumed to be worth more than a benefit of the same real monetary value received in one year's time. This is because the proceeds of a benefit received today could be invested to earn a real rate of interest for that year. So, for example, if investment yields a real interest rate of 2 per cent, a benefit of €100 earned today is worth the same as a benefit of €102 earned in one year's time. Equally, a liability of €102 that has to be met in one year's time is worth the same as a liability of €100 that must be met today. In project appraisal, all costs and benefits are 'discounted' to give their value as if they were incurred or received today. In the jargon, they are 'discounted' to give the 'net present value' or NPV of the project. If the NPV of a project is positive, on economic grounds, it is justified, if it is negative, the project is not economically justifiable because the money invested in the project would earn more interest from, effectively, putting it in a savings account. The higher the assumed interest rate, the more significant this process of discounting becomes on the profitability of a project.

Discount rate

TABLE 1 SIMPLE ILLUSTRATION OF DISCOUNTING

Year	**0%**	**2%**	**10%**
0	-50	-50	-50
5	+250	+226	+155
10	-150	-123	-57
20	-100	-67	-22
Net present value	**-50**	**-14**	**+26**

Source: Author's calculations

To illustrate this process, let us assume a very simple project that incurs construction costs of €50 in year 0, produces benefits of €250 in year 5 and incurs costs of €150 in year 10 and €100 in year 20 (see Table 1). With no discounting, in other words, the value placed on costs and benefits does not decrease over time, the project loses money. If the discount rate is low, this effectively reduces the value of future costs and benefits but not by very much. For example, over 10 years, the use of a 2 per cent rate of interest – discount rate – only reduces the value of a benefit or liability by 18 per cent and in this example, the fact that most liabilities occur after the benefits means that the project is still unprofitable but not by so much. However, if the discount rate is much higher, say 10 per cent, the value of any cost incurred in the future is dramatically reduced. For example, the value of a cost or benefit incurred 20 years in the future is reduced by nearly 80 per cent and, in this simple example, this changes the project from being unprofitable to profitable.

The project life of a nuclear power plant is extraordinarily long. For example, the time from start of construction to completion of decommissioning for some UK plants is expected to exceed 150 years. Over this timescale, the uncritical application of discounting can produce some strange results. We can illustrate this if we multiply the timescales in the example above by a factor of 10, so the benefit of €250 occurs in year 50, the cost of €100 occurs in year 100 and the second cost of €100 occurs in year 200 (see Table 2). With a discount rate of 2 per cent, the benefits in year 50 have a high enough value to make the project apparently profitable because the later liabilities have little value. However, with a high discount rate, none of the future costs and benefits has any significant value and the project becomes apparently unprofitable.

Discount rate

TABLE 2 SIMPLE ILLUSTRATION OF DISCOUNTING ON NUCLEAR POWER PLANT TIME-SCALES

Year	**0%**	**2%**	**10%**
0	-50	-50	-50
50	+250	+93	+2
100	-150	-20	0
200	-100	-4	0
Net present value	**-50**	**+19**	**-48**

Source: Author's calculations

A nuclear power project has very high upfront costs from the cost of construction, a stream of income, over, say, its 40-60 operating life from the sale of power and very high costs for decommissioning and waste disposal which are incurred, perhaps 100 years or more after start of construction. With almost any positive discount rate, the NPV of the decommissioning and waste disposal cost will be very low and will have little or no impact even if the discount rate is low. For example, if the discount rate is 2 per cent, the value of liabilities incurred after construction start if they are not incurred till year 100 will be reduced by a factor of 7.

With a low discount rate, the value of the benefit stream over the operating life of the plant from the sale of power will not be reduced by much especially for the early years of operation and will therefore offset the high construction costs. With a high discount rate, the stream of operating benefits will be heavily discounted and the NPV will be dominated by high construction costs. So, a low discount rate favors nuclear projects and the process of discounting means that the heavy liabilities arising from decommissioning and waste disposal have little impact on conventional project appraisal.

The process of discounting makes some intuitive sense for periods of, say, a decade and where the implications of not discharging the liability do not have serious societal consequences. In the past, the availability of a positive rate of interest could generally be assumed, although in the current period of financial crisis, even this assumption looks questionable. For example, government bonds are usually available at a relatively secure rate of interest over this period, so the underlying model of comparing a project with the alternative of investing the money securely is credible. However, extended over the period of a nuclear project, the assumption that a fixed rate of interest will be available effectively indefinitely is not credible. Over such a period, the assumption that there will not be economically catastrophic events such as wars is not reliable. In addition, clean-up is not an optional process, it must be done to safeguard the health of future generations. These issues are taken up in greater detail when we come to discuss how decommissioning and waste disposal costs should be dealt with.

2 THE MAIN VARIABLES AND ISSUES IN FORECASTING THEM

The disagreement about whether nuclear power is cheap comes partly from the large number of complex variables needed to make a full estimate of the cost of nuclear power. It also comes from the methodological and ethical issues raised because of the unique features of nuclear power, in particular, the long time period over which costs and benefits from nuclear projects are incurred. In addition there are a number of other practical factors that make forecasting difficult.

As well as these practical, methodological and ethical issues, there is a significant difference between the corporate and public viewpoints. This arises because nuclear power is viable only in countries that have implicitly or explicitly accepted the role of underwriting the risk associated with clean-up and waste disposal and the cost arising from significant accidents so this cost is borne by the public and is not relevant to corporate investment decisions. This complexity means that apparently authoritative cost estimates can be seriously inaccurate if inappropriate assumptions are chosen. However, the complexity of the calculations needed means that few observers will be able to identify the source of the inaccuracy, which may be embedded deeply in a complex computer model.

2.1 PRACTICAL ISSUES

The main practical issues include:

- Cost estimates are from organizations with a prior position for/against nuclear power;
- Methodological issues for dealing with long-term costs, e.g. accounting for decommissioning;
- Existence of explicit subsides, for example, the limits on liabilities for companies owning nuclear power plants or implicit subsidies, for example, the implicit guarantee that the state will pay for decommissioning and waste disposal if commercial arrangements fail;
- Lack of experience with key processes or operations means cost estimates are necessarily no more than educated guesses, for example, waste disposal;
- Lack of reliable information on the cost of particular elements, for example, few utilities publish reliable data on the operation & maintenance cost of nuclear plants;
- Lack of recent experience with some elements, for example, few nuclear plants have been completed in recent years and only a small proportion have reliable construction cost data;
- Vulnerability to major events at other nuclear plants, such as safety related issues;
- Lack of information about future regulatory standards;
- Vulnerability to environmental changes, for example, increases in sea level
- There are significant project specific costs, for example, the arrangements for the sale of power will determine how risky financiers will perceive the project to be and hence this will determine the cost of borrowing;
- There are significant site specific costs, e.g., the civil engineering cost will depend on factors such as cooling method, geology of the site and distance from the transmission network;
- Experience and capability of the work force, for example, the first plant in a country is likely to be more expensive than subsequent plants because of the need to build the necessary skills, regulatory capacity and industrial facilities and plants built in low wage economies are likely to be cheaper than those built in developed countries;

- Some elements are difficult to quantify, particularly enabling decisions and cost guarantees but are clearly vital to the viability of the project;
- Some elements are often omitted from cost estimates.

2.2 THE MAIN VARIABLES

For the purposes of analysis, the variables can divided into four: those that are relevant to the pre-construction phase, those relevant to the construction phase, those relevant to the operation phase and those relating to the post-operation period.

2.2.1 PRE-CONSTRUCTION PHASE

Variable

TABLE 3 PRE-CONSTRUCTION PHASE VARIABLES

Source of difficulty of estimation	R&D	Site acquisition & approval	Safety regulatory approval
Existence of subsidies	✓		✓
Significant project specific costs		✓	
Difficult to quantify	✓	✓	✓
Omitted from cost estimates	✓	✓	✓

Source: Author's research

The variables associated with the pre-construction phase are diverse, ranging from the cost of getting site approval to R&D on the design (see Table 3). In terms of the overall cost of nuclear power, these elements are relatively small but they represent important enabling decisions where the support of government, particularly in facilitating planning approval and safety approval, have huge value. In terms of their impact on the cost of power, this is likely to be small under conventional accounting.

2.2.2 CONSTRUCTION PHASE

The main variable for the construction phase is the basic construction cost itself. In addition, there are the site specific costs, such as cost of connection to the transmission network and any additional costs resulting from the geology and method of cooling (see Table 4). The cost of capital will also be determined at this stage. While there are few variables determined at this stage, because the cost of power from a nuclear power plant is dominated by the fixed costs associated with the cost of construction (Areva has estimated that two thirds of the cost of a kWh of nuclear electricity is determined by these fixed costs), these variables are the most important in determining the expected economics of a nuclear power project using conventional accounting methods.

Variable

TABLE 4 CONSTRUCTION PHASE VARIABLES

Source of difficulty of estimation	**Construction cost***	**Site specific costs**	**Cost of capital***	**Construction time***
Biased estimates	✓		✓	✓
Existence of subsidies	✓		✓	
Lack of reliable information or data	✓			
Lack of recent experience or data	✓			✓
Vulnerability to events at other plants	✓	✓		
Experience and labor costs	✓			✓
Country issues			✓	✓
Arrangements for power sales			✓	
Omitted from cost estimates		✓		

Source: Author's research

Notes: Variables marked '*' are likely to have a significant impact on the cost of nuclear power

2.2.3 OPERATING PHASE

Most of the variables that have to be forecast arise from the operational phase (see Table 5). Of particular importance is the reliability of the plant. This will determine how much saleable output the plant produces, which in turn will determine how thinly the fixed costs can be spread. Generally, estimates of fuel cost include the cost of the entire fuel chain from uranium mining to spent fuel disposal, including enrichment, fuel fabrication and fuel storage. For these purposes, spent fuel disposal is dealt with separately because the characteristics of this process are very different to those of the other parts of the fuel chain – the process is unproven and the costs not known.

In most cases, spent fuel disposal is expected to be through direct disposal of the spent fuel. In a few cases, the spent fuel is reprocessed to isolate potentially re-usable plutonium, leaving a large additional amount of lower level waste to be disposed of as well as high level waste (the constituents of spent other than plutonium).

Variable

TABLE 5 OPERATING PHASE VARIABLES

Source of difficulty of estimation	Fuel cost*	Operations & maintenance cost*	Plant load factor (%)*	Plant output (MW)*	Mid-life capital investment*	Insurance+	Operating waste disposal cost+	Plant lifetime (years)*	System costs*
Biased estimates	✓	✓	✓		✓		✓	✓	
Existence of subsidies	✓					✓	✓		
Lack of experience					✓		✓	✓	
Lack of reliable data	✓	✓			✓				✓
Vulnerability to events at other sites		✓	✓	✓	✓				
Uncertainty about future standards				✓	✓		✓	✓	
Experience and skills of workforce		✓	✓						
Omitted from estimates					✓	✓			✓

Source: Author's research

Notes: Variables marked '*' are likely to have a significant impact on the cost of nuclear power and variables marked '+' raise significant methodological and ethical issues

Variable

TABLE 6 POST-OPERATING PHASE VARIABLES

Source of difficulty of estimation	Decommissioning phase 1	Decommissioning phase 2	Decommissioning phase 3+	Spent fuel disposal+	Intermediate and low-level waste disposal+	Site security
Biased estimates	✓	✓	✓	✓	✓	
Methodological issues			✓	✓		
Existence of subsidies			✓	✓		
Lack of experience			✓	✓	✓	✓
Vulnerability to events at other sites					✓	
Vulnerable to changes in regulation	✓			✓	✓	✓
Vulnerability to environmental changes	✓			✓	✓	
Experience and capability of workforce			✓		✓	
Omitted from estimates						✓

Source: Author's research

Notes: Variables marked '*' are likely to have a significant impact on the cost of nuclear power and variables marked '+' raise significant methodological and ethical issues

2.2.4 POST-OPERATING PHASE

These are the most problematic variables to forecast, partly because they are expected to arise so far in the future and partly because they often involve processes for which there is little or no commercial experience (see Table 6). Decommissioning is conventionally divided into three processes with very different technological characteristics: phase 1 mainly comprises the removal of the fuel, which is a process that has been carried out throughout the life of the plant; phase 2 mainly comprises the demolition of uncontaminated or lightly contaminated structures and therefore has much in common with normal demolition jobs; and phase 3 includes the cutting up and disposal of the significantly contaminated parts of the plant.

Phase 3 is a technologically demanding process for which there is little experience. In practice, phase 1 is carried out soon after the closure of the plant because once the fuel is removed, there is no risk of a criticality in the reactor and this allows the operating staff to be run right down. Phase 2 can also be carried out promptly although the process of discounting may mean there is an incentive to delay this. Phase 3 is likely to be delayed for decades, partly to allow decay of some of the radioactivity and will be much the most expensive element. Phase 3 is therefore by far the most important variable and most problematic to estimate because of the lack of experience and the long delay before it is carried out. At the end of phase 3, it is expected that the land is clean enough to be released for unrestricted use – so-called green-field status.

3 THE INDIVIDUAL VARIABLES

3.1 THE PRE-CONSTRUCTION PHASE

The activities carried out in the pre-construction phase are vital enabling activities, particularly site approval and regulatory approval, and the role of government in facilitating these approvals is crucial. However, the monetary cost of the activities is, in comparison with other cost elements, small and, for some, the costs are sunk, for example R&D, so is not relevant for investment decision making. These variables are therefore not considered further in detail.

3.2 THE CONSTRUCTION PHASE

3.2.1 CONSTRUCTION COST

This variable, along with cost of capital and plant load factor, determines most of the fixed cost and these are therefore the most important in determining the commercial case for nuclear power. To allow fair comparison between different projects, construction cost is usually quoted in dollars per kilowatt of installed capacity, so a 1000MW plant costing $2 billion would have a construction cost of $2000/kW. Conventionally, finance costs are not included in this and such estimates are known as the ‘overnight cost’ (i.e., the cost if the plant had been built ‘overnight’). This includes the relatively small cost of the first fuel charge.

There are a range of issues that mean getting reliable estimates of cost is extremely problematic. In general, the actual cost of projects is a much better indicator of future costs than cost estimates. Cost estimates have always been a poor indicator of actual costs for nuclear power, almost invariably being a significant underestimate of actual costs. However, while cost estimates ahead of construction are easy to find, reliable outturn costs are much more difficult. Companies building nuclear plants are not generally required to publish accurate, audited costs and have a strong incentive to present their investments to their shareholders, customers and regulatory bodies in a good light. Only in the USA do the regulatory requirements mean that utilities are obliged to publish accurate cost figures – companies’ regulated profits are based on the amount they invest and if companies underestimate their investments, this will reduce their profits.

Throughout the commercial history of nuclear power, real construction costs have continued to rise. There has been an intuitively reasonable expectation that, as with any normal technology, factors such as learning, scale economies and technical progress would mean that real costs would begin to fall. However, even after a commercial history spanning more than half a century, there is no sign that the nuclear cost curve is going to turn downwards. Indeed, it seems likely that the Fukushima disaster will give a further twist to this cost spiral. There is no clear analytical explanation for this unlikely increase in real costs.

This issue has been illustrated in the past decade by the increase in expected cost of the current generation, Gen III+, of nuclear designs. The categorization of designs by generation is not rigorous. Generally, it is expected that such designs should be less complex and incorporate more ‘passive’ safety than their predecessors and, since the 9/11 attack, must be designed to withstand impact by a civil airliner. Understandably, vendors self-categories their designs as being of the latest generation, even though some have few passive safety features and few if any are less complex than their predecessors. The main designs that are usually categorized as Gen III+ and which are undergoing generic design assessment are: the Areva EPR PWR (European Pressurized Water Reactor); the GE ESBWR (Economic Simplified Boiling Water Reactor); the Toshiba/Westinghouse AP1000 PWR (Advanced Passive); updated versions of the (ABWR) Advanced Boiling Water Reactor supplied by both Hitachi-GE and Toshiba and the Mitsubishi APWR (Advanced Pressurized Water Reactor). Only the EPR and the AP1000 have firm orders and these are still in the construction phase or earlier. Other designs are discussed, for example, the Areva Kerena BWR and the Areva/Mitsubishi ATMEA, but these are not sufficiently developed to undergo generic design assessment.

When these were first being discussed, there were confident predictions that these could be built for $1000/kW or less. Current estimates for these designs are at least $5000-6000/kW. Over a period of a decade, general price inflation would have increased prices by about a third so this means real price estimates have increased about 4-fold and all experience suggests outturn prices will be even higher. Whether the forecasts of $1000/kW were solidly based is highly debatable – the estimates were far below the actual costs of the few plants completed in the 1990s – but they achieved their desired objective of convincing governmental policymakers, for example, in the USA and the UK, that this new generation of nuclear power plants would provide power as cheaply as the cheapest alternative, gas. By the time it was clear how inaccurate the promise of $1000/kW was, the UK and USA had made political commitments to nuclear power that they have not had the courage to reverse

The scarcity of new orders over the past 20 years, particularly from countries which publish useful cost figures, has meant that there is little recent cost data. None of the latest generation of nuclear plant designs, Gen III+, has been completed yet so for the designs that are orderable in the West, there is no complete construction experience.

Further practical problems of forecasting include:

- Cost estimates from different times must be corrected to take account of inflation;
- It is not always clear what published costs include: e.g., finance costs, fuel, transmission costs etc., making comparisons difficult;
- Cost estimates in currencies other than dollars have to be converted to dollars and this can lead to distortions because of the instability of currency exchange rates;
- The differing cost and skills of the local labor force will have a strong influence on its cost.

3.2.1.1 SOURCES OF DATA

The assumptions used in forecasting exercises have little value in themselves as was clearly shown by the $1000/kW claim that was taken up in several influential forecasts (Thomas, Bradford, Froggatt & Milborrow, 2007). If they are based in real experience they may be more reliable but clearly it is preferable to go to the source data. Outturn costs have historically been the best predictor. However, the near absence of plant completions in the past two decades in countries where cost information is reasonably reliable and the absence of any outturn information on the latest plant designs means this is not an option. The next best option is actual bids in competitive tenders. The vendors will not be held to these costs if things go wrong[2], but they must be credible enough to convince the utility. Bids are not generally published, but the trade press, for example, Nucleonics Week, is usually able to get a good indication of the costs bid. Another useful option is the cost estimates made by US utilities. The economic regulatory system in the USA means it would be highly risky for a utility to make a forecast of the cost of a new facility (of any type) that proves to be substantially inaccurate.

However, the majority of nuclear orders in the past decade and probably for the next decade have not been supplied by Western vendors. In some cases, they are offering designs that could not be offered in the West, for example, China, Korea and India. In others, their licensability has in the West has not been tested, for example, Russia. In most case, these orders are for home markets, are not competitively bid and no useful price information is available. Even for the exports, useful price information is not usually available because the bids are not competitive.

The main designs are: the Chinese CPR1000 (PWR) which is based on the 900MW design built by France in the 1970s and 1980s (itself based on a 1960s design licensed from Westinghouse); the Indian version of the Candu (heavy water cooled and moderated) design, based on a design from the early 1960s and imported from the Canadian vendor, AECL, now available as 200MW, 500MW and 700MW sizes; the Korean APR1400 (PWR), licensed from Combustion Engineering and using a 1990s design, System 80+; and the Russian NPP2006 (a Russian version of the PWR (WWER)).

China has only exported two small reactors to Pakistan but is now seen as a possible supplier to South Africa and even the UK. India has not exported any reactors and is unlikely to be able to export its Candu technology. Russia, when the Soviet Union still existed, exported reactors to Soviet Republics and East European satellite countries. In the 1990s, Russia also sold reactors to India and China and in the past few years, it has won orders in Turkey and Vietnam and is competing in most tenders. It is reported to have ambitions to export reactors to South Africa and the UK. Korea has recently entered the world market, winning orders for four units for the UAE in 2009 and competing in South Africa.

Japan began to enter the world market offering Gen III+ designs from around 2009 onwards and was reported to have won an order for Vietnam. However, following the Fukushima disaster, it is not clear whether Japanese vendors will continue to compete in world markets.

3.2.2 COST OF CAPITAL

Nuclear power plants are usually financed by a mixture of equity, usually self-financing and borrowing. The cost of equity is generally higher than the cost of borrowing, perhaps double, because essentially the company is asking shareholders to allow some of the money that could have been paid to them as dividends to be reinvested in the business. If the investment is not successful, the shareholders will lose this money. The proportion of debt to equity in the total finance is variable. Shareholders may prefer a high proportion of borrowing, while banks may prefer a higher

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[2] Even if the cost bid is a 'turnkey' or fixed prices cost - these are extremely rare because of the risk the place on the vendor - as has clearly been illustrated with the Olkiluoto plant in Finland, the vendor will not necessarily honour the fixed price. Here Areva bid €3bn as a turnkey contract but when costs began to escalate, they refused to honour the fixed price deal and the matter is now being settled in a court of arbitration

level of equity so the company has a larger stake in the success of the project. The cost of capital is calculated as the weighted average of the two sources, the Weighted Average Cost of Capital (WACC). So, for example, if debt accounts for 66 per cent of finance and the cost of debt is 6 per cent, and the rest is supplied by equity at a cost of 9 per cent, the WACC is 7 per cent.

The cost of borrowing will be determined by how risky the lending institute perceives the project to be. In part, this will be determined by general factors such as the country where the plant is located. Companies in a very economically stable developed country with a high credit rating will find it much cheaper to borrow than a comparable company in a less stable country. Large companies with a strong economic record will find it much cheaper to borrow than weaker companies.

On the project specific risks, there will be a technology risk. Nuclear power plants have a history of seldom being built to time and cost whereas, for example, combined cycle gas turbine plants are usually built to time and cost and are often supplied under fixed cost terms. The reliability of nuclear power plants is much more variable than, for example, combined cycle plants. So nuclear power is perceived to be a much riskier technology than other generation technologies.

The impact of these technology factors will be determined by the commercial arrangements, particularly the arrangements for sale of the power. If the plant has a long-term power purchase agreement that allows full cost recovery – under this, whatever costs are incurred can be recovered from consumers via the electricity tariff – it will be much less risky than one that has to compete in a market. The technology specific issues are much less important for plants with full cost recovery because lending institutions know the utility will have its costs covered no matter how badly it performs. For a plant that must compete in a market or where the power sale contract terms do not allow full cost recovery, the perception of how economically risky the technology is will be crucial.

The structure of nuclear costs also works against it in competitive markets. A high proportion of nuclear costs are payable whether or not the plant operates. Thus, if the market price is low, few of the nuclear plant costs can be saved by not operating the plant. By contrast, for fossil fuel plants, the dominant cost is the cost of fuel and if the plant is not operated, this cost can generally be saved. Thus, in times when the market price is low nuclear plants will struggle to survive economically, while fossil fuel plants are much less at risk. For example, in 2002, the British nuclear power company, British Energy went bankrupt in a period of low wholesale electricity prices because its costs were higher than revenue from electricity sales.

The cost of capital is entirely project specific and it is therefore impossible to generalize. In the past, when electricity supply was a monopoly business with effective guarantee of full cost recovery, finance for nuclear power plants was not an issue. Banks were sure of recovering their costs and were therefore willing to lend money for nuclear projects at rates appropriate for very low risk projects. However, this changed when markets were introduced and, in regulated markets, where regulators were less willing to allow full cost recovery from consumers. No nuclear plant has been built or ordered for operation in a system where it is fully exposed to market risk and it is highly questionable whether a nuclear power plant built to survive in a competitive electricity market is financeable.

3.2.3 SITE-SPECIFIC COSTS

These costs are highly variable, seldom included in generic forecasts of nuclear power and are highly variable. A nuclear power station proposed for a site with existing nuclear capacity and transmission links will require little expenditure to link it to the grid. However, a reactor on a new site, remote from the existing grid could impose significant additional costs and, because transmission lines can cause public opposition, could raise additional difficulties.

For cooling, there are two basic methods: cooling tower or cooling using water from the sea or a river. The cooling tower method is more expensive and consumes more power than the other method and is used where there is insufficient water available. Sea-water cooling is generally the cheapest and least environmentally problematic because any change to the temperature of the sea is relatively small, although the corrosiveness of salt water does require the use of more expensive materials. River cooling is more problematic if the water returned to the river is too warm and this will damage the local ecology and may require reductions in power when ambient temperatures are high. In extreme cases of drought, the river level may drop so much that the inlet pipe is above the water line and the plant then has to be shut down and this has happened in recent years at a number of French plants. There are no systematic sources for site-specific costs and separate estimates are seldom published.

3.3 THE OPERATING PHASE

3.3.1 FUEL COST

The extent of uranium reserves has been a concern, on and off, throughout the history of nuclear power. In the early 1950s, the expectation was that uranium reserves were so limited that fast reactors, which can use effectively all the uranium rather than just the 'fissile' isotope, which makes up only 0.7 per cent of naturally occurring uranium would be required. There remains a strong lobby for fast reactors despite their very high costs, the poor technological record of prototype and demonstration plants and the issues of weapons proliferation their use of plutonium as the fuel raises. Indeed of the six technologies identified as being strong candidates for the generation of reactors (Gen IV) to replace Gen III+, five are fast reactors. However, a mixture of the discovery of large additional sources of uranium and the fact that the use of nuclear power has been far less extensive than expected has meant that availability of uranium has never been a significant influence on nuclear investment decisions. There are clearly large amounts of uranium resources, but many of these are not recoverable at costs that would make them viable for use in nuclear power plants. For example, there is a large amount of uranium in sea water but extracting it would almost certainly require more energy than the uranium would produce in a nuclear power station.

The uranium market is difficult to evaluate. Exploration has been in short spurts peaking when there was a perception of significantly increased demand for uranium and increased spot prices sharply, for example, after the first oil crisis and when the credibility of the 'Nuclear Renaissance' (the expected boom in ordering Gen III+ designs was expected to bring) was high. When demand failed to materialize, prices dropped sharply and exploration levels declined. It is far from clear therefore how well estimates of uranium reserves represent the actual amount of economically recoverable uranium.

The uranium commodities market can also give misleading signals. Its liquidity (the proportion of sales of uranium that take place in the visible spot market) is low with most uranium purchased under long-term contracts at prices not connected to the spot price. Thus, the spot price could increase sharply due to a small increase in demand, with little or no impact on most uranium users.

The cost of fuel conventionally includes all stages from uranium mining, through conversion, enrichment, fuel fabrication and temporary spent fuel storage to final spent fuel disposal (or reprocessing and disposal of the resulting waste). It is expected to account for perhaps 5 per cent of the cost of a kWh of nuclear electricity. The last two stages are dealt with separately in this report. The most expensive of the other stages is enrichment, which is done via a centrifuge process or gaseous diffusion technology. These technologies are highly sensitive because they provide a route to nuclear weapons. The location of commercial enrichment facilities is therefore limited to a few countries with weapons programs and facilities are often old and fully depreciated. Whether the market price of enrichment is an economic one is open to question.

Even if the price of uranium or the price of enrichment was to increase significantly, the impact on the cost of nuclear electricity would be small. However, if the price of uranium rose sharply, this would probably be associated with the exploitation of poor quality reserves. This would increase the energy requirement to produce it, it would also lead to a large increase in the amount of land that would have to be mined to produce it and it would also result in much larger volumes of hazardous mining wastes.

Most companies do not provide full details of their fuel costs, but US utilities, because of the economic regulatory requirements, do give an accurate figure for fuel costs. It is of the order 0.5c/kWh. The only issue with these figures is that the US government is committed to take the spent fuel for disposal at a nominal fee of 0.01c/kWh, a cost expected to be far below the actual disposal cost, so the fuel cost for US utilities is artificially low

3.3.2 OPERATIONS AND MAINTENANCE COST

The operations and maintenance (O&M) cost is generally perceived to be low – nuclear power stations are seen as expensive to build but provide essentially free power once they are built. In terms of fuel, nuclear power plants are much cheaper to run than fossil-fuel plants but in terms on non-fuel O&M costs, they are much more expensive. This is for a number of reasons: for safety reasons, plants with equipment problems that do not prevent the operation of the plant are much less tolerable than with a fossil fuel plant; the cost of carrying out maintenance is much higher because the radioactivity makes access to parts of the plant much more difficult and expensive; equipment and materials used in nuclear plants generally have to be of a higher specification.

O&M costs can be highly variable, depending on the extent of any repairs required and are also highly dependent on the reliability of the plant. The cost of maintenance does not vary much according to utilization so is largely fixed and, as with construction costs, with a reliable plant these costs can be spread more thinly than with an unreliable plant. As with fuel costs, the best source of data is US plants, which report accurate O&M figures. Few other utilities report reliable O&M cost figures. They are generally of the order 1.5c/kWh.

3.3.3 PLANT LOAD FACTOR

The plant load factor (or capacity factor in US parlance) is calculated as the number of units of output produced in a given period (usually a year or the life-time to date of the plant) as a percentage of the output that would have been produced had the plant operated uninterrupted at its full design output rating. Load factor can be calculated on a gross basis, using the design gross rating and output, i.e., including power used on site or a net basis, i.e., power supplied to the grid. While the net basis is clearly the more useful because this represents the power actually sold, in practice, the difference between the figures is small enough that either basis is accurate enough.

This is a key variable for overall costs as it determines how thinly the fixed costs can be spread. For example, let us assume the overall cost of a kWh of nuclear electricity was 9c/kWh if the plant operated at a 90 per cent load factor and two thirds (6c) of this cost was accounted for by the fixed cost. If the load factor is only 60 per cent and all other costs were unchanged (in practice they would tend to be higher) the fixed element would go up to 9c/kWh and the overall cost to 12c/kWh.

Particularly up to the mid-1990s, annual load factors were highly variable with the global average below 65 per cent in some years, far below the promises of 85 per cent or more made by the nuclear industry. Some plants, particularly in some European countries such as Switzerland and Finland had consistently better results than this, mid-80s or better. Since then, performance has improved and in many countries, plants achieve load factors of 85 per cent or more.

Figure 1 shows the historical development of the net load factor for the world fleet of nuclear power plants.

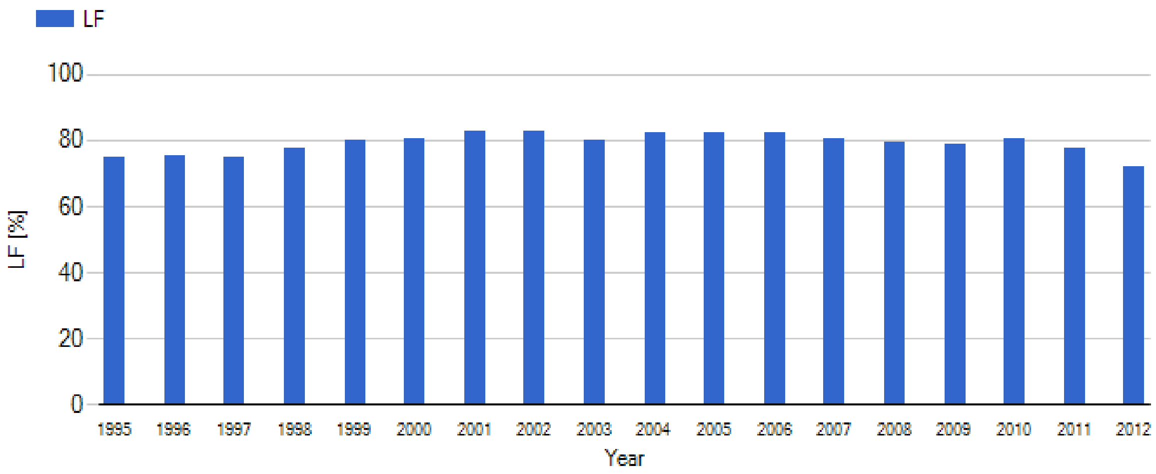

FIGURE 1 RECENT LOAD FACTORS WORLDWIDE

Source: IAEA, PRIS database. http://www.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=341

All civil power reactors report the performance of their plants in detail to the IAEA which publishes this in its PRIS data base (International Atomic Energy Agency (2013), including the duration and cause of all plant outages (shutdowns) and the number of kWh generated. So there is ample available data from which to make forecasts.

3.3.4 PLANT OUTPUT RATING

In some cases, particularly with early designs, reactors proved unable to operate at the level they were designed for because of design faults, for example, the use of inadequate materials. For example, none of the British Advanced Gas-cooled reactors is licensed to operate at its design rating because of design and safety issues. Operating reactors may have to be down-rated for safety reasons or because of problems with equipment, particularly as they begin to age. Reactors may also be up-rated, for example, by the use of more efficient turbines or by operating the reactor at higher coolant temperatures and/or pressures. For example, the Olkiluoto BWRs in Finland were designed to produce 658MW (net) but has been progressively uprated to 880MW by 2010. Practice on uprating varies widely from country to country and while Finland has substantially uprated all four of its operating reactors, Japan has always operated all its reactors at no more than the design rating. The rating a plant is licensed for is published and included in the IAEA statistics noted above so there is no problem of data availability

3.3.5 MID-LIFE CAPITAL INVESTMENT

This is a variable that is seldom included in forecasts of nuclear costs. It covers investments in the plant over and above routine maintenance and repair including major equipment replacement or upgrade. This may be done to replace worn out equipment (or equipment too old to satisfy regulatory requirements), to upgrade the plant, or to meet new, higher safety requirements. The cost of such upgrades could be very high but is very variable. For example, in the Candu reactor design, the fuel is contained in a large number of pressure tubes. After about 20 years, these have worn to the extent that their integrity cannot be guaranteed and they must be replaced, involving, essentially a rebuilding of the reactor costing billions of dollars.

With increasing pressure from the nuclear industry to allow reactors to operate for 60 years or more instead of the 30-40 years they were designed for, mid-life capital investment will have much greater significance, especially for plant being life-extended.

There is little systematic data available on the extent of mid-life capital investment and the figures will be highly variable depending on the design, the operating history of the plant and the occurrence of external events that might cast doubt on the safety of existing plants.

3.3.6 INSURANCE

In the USA, it was recognized from the start of the nuclear era that civil nuclear power plants would not be commercially viable if plant owners were liable for the damages caused by a nuclear accident. As a result, the Price-Anderson act was passed by Congress in 1957, limiting the liability of a utility to $60m. This amount has been progressively increased to take account of inflation and now stands at $300m. Other countries either have national legislation comparable to Price-Anderson or are parties to international conventions: either the Paris Convention, passed in 1960 (and the supplementary Brussels Convention of 1963), or the Vienna Convention originally passed in 1963. These conventions limit utility liability to comparable sums to the Price-Anderson Act. The sums for which the utilities can be liable are clearly tiny compared to the cost of a major nuclear accident – likely to be in the order of hundreds of billions of dollars for Chernobyl and Fukushima.

Japan has national legislation to cover liability but it seems that it was not adequate to protect the utility owning Fukushima, TEPCO, from the consequences of the disaster and Japanese taxpayers are now being required to provide TEPCO with tens of billions of dollars to protect it from bankruptcy.

Putting a price on the value of these limits on liability is very difficult, because it is clear that if these limitations were removed, the nuclear industry would immediately collapse. Utilities are liable for damage to the plant itself resulting from an accident but this is orders of magnitude less than the external damage and can be covered by commercial insurance. Some information on the price for this cover is available but the sums involved do not have a major impact on nuclear economics.

3.3.7 OPERATING WASTE DISPOSAL COST

The operating waste (excluding the spent fuel) is mainly low-level or intermediate level waste arising from the routine operation and maintenance of the plant. Where major replacement of equipment that is exposed to radiation takes place, for example, steam generators in PWRs and pressure tubes in Candus, the activity of the waste could be higher and disposal much more expensive. Most, but not all, countries have waste disposal facilities for low-level waste albeit these facilities are now old, nearing capacity. Finding acceptable sites and building new facilities would generally be highly contentious and the costs much higher than for existing facilities. Some data exists on the cost of low-level waste disposal.

3.3.8 PLANT LIFETIME

Nuclear power plants have typically been designed to have a life of up to 40 years. Clearly, all things being equal, the longer the life of a nuclear power plant, the cheaper the electricity it produces. In practice and especially with a high discount rate which means the value of future benefits is an investment appraisal, there is little difference in the economics whether a lifetime of 40 years or 60 years is assumed.

The life of nuclear power plant is determined by a number of factors: as regulatory standards increase, it may be impossible or prohibitively expensive to satisfy those standards; if a life-limiting component, that is one for which the cost of replacement would be prohibitive (e.g.,, a PWR pressure vessel), is no longer serviceable the plant may have to be retired; and if the maintenance and repair costs increase so much that it may be cheaper to retire the plant and replace it with new capacity.

In practice, other, political, considerations may influence lifetime. Once a nuclear reactor is retired, the expensive and problematic process of decommissioning must start. So it may be cheaper overall to retain a loss-making in service than to retire and have to start decommissioning it with no income stream to counteract the losses. Some governments may wish to keep loss-making plants in service simply to avoid the strong negative signal on nuclear power that being forced to acknowledge the poor economics would give.

Despite the common current expectation that BWRs and PWRs can be retained in service for 60 years or more, there is negligible experience of operating plants over 40 years. Virtually all the plants commissioned before 1971 have already been closed for various reasons

3.3.9 SYSTEM COSTS

These are seldom evaluated. Like all power plants, a nuclear power plant has to fit in with the requirements of an integrated power system. This means that there must be sufficient power available to meet demand should the unit fail. As a result, in most systems, there has to be at least as much power on 'spinning reserve', that is, with the plant hot and ready to generate in seconds. Nuclear power plants are almost always the largest units in the system with the smallest available modern reactor design providing about 1200MW, whereas typical gas and coal units are 600MW or less. So the cost of spinning reserve is almost always higher in a system with nuclear plants than one without.

The rule of thumb is that in a given system, for system stability, the largest single generating unit should be no larger than 10 per cent of the total system capacity so a modern nuclear reactor needs to be in an integrated system of at least 12,000MW. Where there is more than one reactor at a site, that increases the risk, for example, if the transmission links from the site fail, the electricity system could lose all the power from the nuclear site.

These costs and risks have been clearly illustrated in South Africa where its two nuclear reactors, both of about 920MW, are sited in the Cape Town region, where they meet the majority of demand. The South African system is very large, about 40,000MW, but interconnections to the Cape are weak and if one of the units breaks down when the other is undergoing maintenance, not an unlikely sequence, it will be difficult to maintain electricity supplies in the Cape. In the last few years, there have been regular black-outs (system failures) and brown-outs (deliberate cutting off of districts to prevent the whole system collapsing) there because of the unavailability of one or both reactors.

3.4 THE POST-OPERATION PHASE

3.4.1 DECOMMISSIONING

The cost of decommissioning is the dominant cost for the post-operation phase, but, as shown above, in economic evaluations of nuclear power, using conventional accounting it has little impact on the cost of nuclear power. There is negligible experience of decommissioning large reactors of modern design that have operated for long enough to become significantly contaminated to green-field status. The IAEA lists 135 reactors as being permanently shut down but only 15 of these are PWRs or BWRs of 800MW or larger. Seven of these are in Germany, all except one of which was shut post-Fukushima and the other plant was only in commercial service for one year. One of the 15 is in Italy but it only had six years of commercial service and decommissioning is not far advanced there. The other seven are in the USA where most experience of decommissioning exists.

One is the wrecked Three Mile Island plant, which only operated for a year and on which little decommissioning work has been done and the work needed there will not be representative of a normal decommissioning operation. The Shoreham plant was only critical for a matter of days so there was no useful experience. The other five plants were in service for between 14 and 25 years.

Of these, Rancho Seco (913MW, 14 years operation) has now been fully decommissioned since 2009 except for 3 hectares of land where waste is stored. At the Trojan site, (1180MW, 16 years of service) decommissioning was completed in 2006, but the reactor pressure vessel, the most contaminated part of the plant, was transported to the Hanford disposal site where it was buried intact, not an option likely to be available elsewhere. At Maine Yankee (860MW, 24 years of service), decommissioning was completed in 2005 and the land released except for 5 hectares of land where waste is stored. Zion 1 and 2 (both 1085MW, 14-15 years of service) are in so-called 'safe store' with phase 3 not started.

In the UK and France, there are 28 and 10 respectively, reactors permanently closed, mostly small gas-cooled reactors of limited relevance to PWR and BWR decommissioning, but at none of the UK and French sites has phase 3 work started.

Frequently, forecast decommissioning costs are quoted as a percentage of the construction cost. This is meaningless on two grounds. First, the construction cost for new reactors is not well-established so this does not help estimate the decommissioning cost and second, since the cost of decommissioning has only the weakest of relationships with the cost of construction, it indicates that no serious cost estimates have been undertaken.

3.4.1.1 DECOMMISSIONING PHASE 1

This phase is the simplest and cheapest and involves an operation, removal and storage of the fuel, which has been carried on throughout the life of the plant. The cost should therefore be easy to establish. The conventional rule of thumb is that the cost of phase 1 accounts for a sixth of the total undiscounted cost of decommissioning. However, even though it is the cheapest phase of decommissioning in undiscounted terms, because it is usually carried out immediately after plant closure and the other two phases are expected to be delayed by a decade or more, it is the most expensive phase in discounted terms It is therefore the most significant contributor to the cost of nuclear power using conventional accounting. There is some evidence that these costs are distorting decisions on retirement. For example, the UK Magnox reactors were kept in service for many years despite the fact they were losing large amounts of money. There must be suspicions this was because the work of decommissioning was too expensive to start.

3.4.1.2 DECOMMISSIONING PHASE 2

Phase 2 is also a technologically well-proven and cheap process, being essentially demolition of largely uncontaminated buildings and disposal of the resulting waste. The conventional rule of thumb is that phase 2 accounts for a third of the total undiscounted cost of decommissioning. However, it is generally expected to be done well ahead of phase 3 so has a higher weight in a project appraisal.

3.4.1.3 DECOMMISSIONING PHASE 3

This is the most expensive and technologically challenging phase of decommissioning and, as shown above, there is little relevant experience of cutting up, dismantling and disposing of highly radioactive structures. Particularly if the plant has had a long life, this could require robots because the level of radioactivity is too high to use people. Most utilities plan to decommission within a couple of decades of plant closure but when they actually have to take the decision, it is likely they will find it economically advantageous to delay.

3.4.2 PROVISIONING FOR DECOMMISSIONING

The widely accepted 'polluter pays' principle requires that users of a facility should pay for its clean-up and, in theory, this has for a long time been the position for nuclear power plants. In conventional accounting, future liabilities are recorded as accounting provisions and effectively exist as the assets of the company. When the liability comes to be discharged, it is paid for either by selling assets or from income from these assets. This has proved far too unreliable a method of paying for liabilities that might fall due more than 150 years after start of construction. The probability that a company will be intact in 150 years with assets available to pay for decommissioning is minimal.

Currently, best practice is to make provisions in a segregated funs, that the company owning the plant contributes to but cannot access for any purpose other than decommissioning. Funds are invested conservatively in very low risk investments, which will earn commensurately low returns. Whilst this is a superior method of provisioning to conventional accounting with unsegregated provisions, the sum of money will only be sufficient if:

- The plant operates for as long as it is expected to;
- The plant owner is able to make decommissioning provisions throughout its life;
- The funds consistently earn as much interest as expected;
- The cost of decommissioning is accurately forecast;
- The timing of the phases of decommissioning does not have to be brought forward;
- The plant does not suffer a major accident substantially increasing the decommissioning cost.

If these conditions are not all met, a future generation will have to meet some or all of the cost of decommissioning from its own resources as well as actually carrying out this hazardous task. This is in clear violation of the 'polluter pays' principle. No method of provisioning can ultimately provide complete assurance that all the needed funds will be available whatever happens - a global catastrophe or a major war could easily wipe out the value of investments. However, to reduce this risk, a number of additional measures can be taken.

To account for the risk that the plant is closed early, it might be possible for the utility to take out a financial instrument, effectively an insurance policy, which would pay the balance of funds needed. This might be necessary if the plant is uneconomic or suffers a significant technical issue, or the design is found to be deficient and continued operation is not prudent. Similarly, it might be possible to take out a financial instrument that would insure the fund against the failure of the company that owns the plant. In 2002, this occurred with the bankruptcy of the British nuclear electricity company, British Energy. The plants continued in service but all payments into the decommissioning fund were stopped and decommissioning will now be paid for by future British taxpayers

To reduce the risk that interest payments might not be as large as expected, it would be prudent not only to invest in the lowest risk investments but also to not assume any real capital growth of the fund after plant closure. This would mean that if the fund was not accumulating rapidly enough during its life, its owner could make larger contributions to compensate. If no capital appreciation is assumed after plant closure, this would mean that when the plant was closed, all the funds needed would already be available. This would also deal with the risk that some decommissioning operations have to be carried out earlier than expected, for example, because of sea water level increases, the decaying of skills and structural problems with the buildings. From an ethical point of view, it would also allow a future generation to carry out decommissioning with no financial penalty when they choose, not when the current generation believes would be the best time.

The estimated real cost of decommissioning has been increasing rapidly since serious estimates began to be made. For example, in 1992, it was estimated that the cost of decommissioning a British Magnox plant would be about £250m (in money of the day). By 2012, the estimated cost had increased to about £1.5bn, even though no phase 3 work had been started. To deal with the risk that the expected cost proves to be an underestimate, cost estimates need to be frequently updated with careful auditing of the cost estimates to ensure their credibility.

If a serious accident occurs the decommissioning cost could increase many-fold because of the raised levels of radioactivity and the increase in volume of material that has to be disposed of. At the Chernobyl and Fukushima sites, the priority for the foreseeable future will be keeping the site safe with no thought of decommissioning. At the Three Mile Island site, no serious decommissioning has started more than 30 years after the accident and the funds available are grossly inadequate. It is not clear whether this risk is insurable.

3.4.3 SPENT FUEL FINAL DISPOSAL

In principle, the method by which spent fuel would be disposed of has long been known. Spent fuel or high level waste arising from reprocessing, would be packaged in multiple layers and stored in a deep repository for the 250,000 years needed for it to have decayed to a level where it presented no risk. The repository would have to be very geologically stable with negligible water flow and packaging would have to be robust enough to survive for that long. The dilemma of whether to make the waste retrievable or not remains unresolved. If the material is retrievable, it can be subverted by a future generation for weapons use. If it is not retrievable, if the process goes wrong, it will be very difficult to deal with the problem.

Despite knowing in principle how spent fuel/high-level waste disposal would be done, there have been no practical steps to actually do this. The USA is the only country to have selected a site, the Yucca Mountain site, for their repository but after lengthy arguments, the site was abandoned in

2008 with no replacement site. It is therefore likely that the earliest spent fuel disposal can take place anywhere in the world is several decades away. This means the cost estimates for high-level waste can only be, at best, speculative guesses.

3.4.4 INTERMEDIATE AND LOW-LEVEL WASTE DISPOSAL

The process of low-level waste disposal is highly contentious and new sites are likely to be bitterly opposed. However, in technical terms and in comparison to intermediate and high-level waste disposal, the challenge is feasible. Material must be kept isolated from the environment for several decades before the radioactivity has decayed to a level where it presents no risk. However, for intermediate-level and low-level waste containing long-lived isotopes, the first facilities world-wide are only now being built. Their cost will be highly variable depending on the sites available, so cost estimates are still at an early stage. A significant proportion of the cost of decommissioning is accounted for by waste disposal so if the cost of waste disposal turns out to be much higher than expected, this will have an impact on decommissioning costs.

3.4.5 SITE SECURITY

Especially with very extended decommissioning timetables, under which the plants would be left in ‘safe- store’ for long periods. Security measures would have to be in place to monitor the condition of the plant as well as preventing any intrusion on to the site.

4 ECONOMICS OF LIFE-EXTENDED PLANTS

For life extension, we are talking about extending the life of a plant by decades, perhaps 20 years, rather than a few years. For these purposes, we assume that all life-limiting components, for example, the pressure vessel, are expected to be serviceable for the period of life-extension expected.

Life-extension is a particular current issue for the USA because of the age of its reactor stock and for France because of the short period of time over which most of its plants were built. A concern is the lack of precision on decommissioning costs. Expected costs for decommissioning all of France's nuclear facilities (including reactors, research facilities and fuel cycle plants) and disposing of radioactive wastes are estimated to be €79.4 billion. However these estimates are fragile due to the lack of firm decommissioning costs and lack of final disposal plans. A massive increase in future costs would have significant impact on the annual cost of production(World Nuclear Association (2012). Life extension may mean that pressure to forecast accurately and in detail will be less and increases the incentive to life-extend.

It has been very aggressively pursued in the USA and by March 2012, 71 of its 104 operating reactors had already been granted a 20 year life-extension with a further 15 applications being processed. France, because of the large number of reactors installed from 1977 onwards (22 between 1977 and 1982) has to plan much earlier than other countries because of the large amount of capacity that would be lost if plants were retired at a fixed age. The countries with four or more reactors with at least 35 years of operation are Canada, Japan, Switzerland, Sweden and UK. However, Canada and UK use very different technologies to those used in the rest of the world, where water cooled and moderated reactors dominate, and this means that very different considerations apply on plant life-times. Canada uses Candu reactors which use heavy water as coolant and moderator and the fuel is contained in a large number of pressure tubes rather than a single pressure vessel. Canada has life-extended some of its plants and, as discussed above, this requires a major investment because of the need to replace the fuel-containing pressure tubes. The UK uses carbon dioxide cooled, graphite-moderated reactors and the integrity of the graphite moderator determines the lifetime of such plants. Eleven of the 50 reactors Japans still officially had in service in May 2012 have 35 years or more of operation, but the issues that will determine how long these remain in service are much broader than just their age. It seems unlikely that Japan will seek to life-extend many of its plants. In Switzerland, three out of five of its reactors have more than 35 years of service, but Switzerland has decided, in the wake of Fukushima, to operate its existing reactors for up to 50 years but not to replace them. Sweden has had a policy of phase-out of nuclear power since 1979 but has done little to achieve this and four out of ten of its operating reactors are more than 35 years old. Swedish utilities have invested significantly in a number of the older plants presumably with a view to extending their life.

The economic aspect of a decision to life-extend a nuclear plant should be taken purely on marginal cost grounds, in other words, considering only the costs and benefits that would accrue because of the life-extension. Any costs that would have to be paid whether or not the plant is life-extended, for example, paying off any loans already taken out, are not relevant to the decision. This means that any costs arising from the pre-construction and the construction period should not be considered.

Most of the operating costs will tend to increase the older the plant is with only ‘system costs’ and waste disposal costs unlikely to be much changed. The plant rating may be reduced to reflect concerns about component wear, but this may be counterbalanced by uprating resulting from the installation of more efficient components. O&M cost will tend to be higher the older the plant is and plant load factor will tend to be lower reflecting the need for more maintenance and repair. This might increase fuel cost if the plant becomes less reliable and, if more on-site spent fuel storage has to be built because the existing stores are full, this will require mid-life capital investment to build new fuel storage capacity. Insurance costs may also tend to increase.

The impact on post-operating costs is mixed. Phases 1 and 2 of decommissioning and security costs should not differ significantly for a plant with 60 years’ service compared to one with 40 years. Spent fuel disposal costs will be incurred for the additional fuel used and additional low and intermediate level waste will be produced. Decommissioning phase 3 costs will tend to be higher because the plant will be more intensely irradiated the longer it operates, generating more waste and increasing the difficulty of the job but if the decommissioning fund is already adequate, funding the additional cost will probably not be a major burden.

However, the fixed costs from construction account for, say, two thirds of the cost of a kWh of nuclear electricity, and these will not be incurred once the plant reaches the end of its planned life because these costs will have been paid off. So an increase of even, say, a half to the operating cost would still mean that the marginal cost for a nuclear life-extended plant would be only about half the full cost of the plant before its construction cost was paid off.

The key issue is therefore the need for capital investment, partly to replace equipment that would not be serviceable for the period of the expected life-extension and partly to satisfy contemporary safety requirements. If the decision to try to life-extend is known of well in advance, the need to replace old equipment can be met by enhanced maintenance and repair. Enhanced maintenance and repair over several years should mean that there is not a large volume of work to be done at the end of the planned life of the plant.

The major unknown is the extent of any upgrading required by the regulatory authority. Any plant reaching retirement age will inevitably fall far short of meeting current standards and the design would be unlicensable as a new plant. It is also highly unlikely the plant could be retrofitted with sufficient new and additional systems so that current standards can be met. However, regulators have tended to apply less stringent standards for existing plants than they would to new plants and none of the US plants applying for pile-extension has been turned down. These standards will be susceptible to events at other plants. For example, it is clear that the Fukushima disaster will lead to a requirement for additional safety measures to be taken at existing plants, especially if they are to be re-licensed for a decade or more. If these requirements are extensive enough, the scale of investment may be prohibitively high.

5 CREDITS FOR LOW-CARBON SOURCES

Given the overwhelming priority now to reduce the use of fossil fuels to try to mitigate climate change, there is pressure from some governments to give favorable treatment to nuclear power because of the low emissions of carbon dioxide associated with nuclear power. There is some disagreement about the level of carbon dioxide emissions associated with nuclear power because of the energy intensity of the fuel chain process from mining to fuel fabrication, much of which requires fossil fuels at present. If the quality of ore exploited falls, the energy input to the fuel will increase.

In Europe, there is a market for carbon so that anyone burning fossil fuels must buy permits from the carbon market to allow them to burn fossil fuels. In theory, the price of carbon should reflect the additional cost needed to generate electricity using the cheapest non-fossil fuel sources. In practice, this market has never worked well and the market price has continued to fall and is now well below the level needed to make renewable sources viable. In May 2012, it was standing at about €6/tonne of CO2 emitted, compared to a level of more than €30/tonne soon after the market was introduced in 2005. The volatility and low level of the carbon price means it is not likely to be an effective incentive to investment in low-carbon technologies

In the UK, as an attempt overtly to give greater certainty to investment in low carbon sources, the British government, in its 2011 budget, set a floor for the carbon price £16/tonne in 2013 rising to £30/tonne (€36/tonne) in 2020. Under this scheme, low-carbon sources would be certain to receive this floor price whatever the market price was. In practice, this measure was widely seen as an attempt to improve the economics of nuclear power and it was probably no coincidence that a price of €36/tonne was calculated to be the level at which nuclear power would be competitive with fossil fuel sources in the UK government's White Paper on nuclear power in 2008.

More recently, four countries, France, the United Kingdom, Poland and the Czech Republic, were reported to have written to the European Commission Presidency requesting that nuclear power be given the same status as renewable sources with respect to subsidies. Subsidies for renewables are legal under EU law but they would be categorized as unfair state aid for nuclear power. The four countries named have denied making this request. There also exists a joint communion of 12 EU member states who want to pursue nuclear energy and who meet annually, in 2013, in London(Mitchem, 2013).

6 SCENARIOS OF NUCLEAR POWER COSTS

6.1 RECENT FORECASTS OF NUCLEAR POWER COSTS

In the years after the nuclear renaissance began to be discussed, from 2002-06, a number of influential forecasts of nuclear power costs emerged, for example by a high-level team from MIT(Deutch, Moniz, 2003) and reports commissioned by the Finnish, UK and US governments. These all forecast very low kWh costs from nuclear power plants, typically of the order €20-50/MWh. Thomas analyzed 12 of these forecasts and found that, even then, the assumptions they were based on were extremely optimistic (Thomas, Bradford, Froggatt, Milborow, 2007). He found that most assumed a construction cost of between $1000-2000/kW and a real cost of capital of 5-10 per cent. The Olkiluoto order, priced at more than $2000/kW exposed the high level of optimism embodied in these forecasts. As delays and cost escalation at Olkiluoto began to arise and forecasts from US utilities wanting to build plants and who, for economic regulatory reasons, had to forecast realistic prices, by 2008, utility forecasts of construction cost and bids for nuclear tenders had begun to cluster around $5000/kW. This did not stop the UK government assuming a construction cost of only £1250/kW (less than $2000/kW) in its 2008 White Paper on nuclear power, which formed the basis of its policy to re-launch nuclear ordering in the UK (Department of Business, Energy & Regulatory Reform, 2009), whilst an update in 2009 of the influential MIT study of 2003 still assumed a construction cost of only $4000/kW (Deutch, Forsberg, Kadak, Kazimi, Moniz, Parsons, 2009).

Costs have continued to escalate since then and forecasts of nuclear costs now have little credibility unless those who are making the forecast have a strong reason to be as accurate as possible, for example, a utility or a vendor projecting a price that needs to be accurate for commercial reasons. As the lessons from Fukushima filter through to the new designs, the real cost of new plants can only increase so forecasting nuclear costs is trying to hit a moving target and the forecast presented in the next sections must be regarded as no more than a snap shot of the position at time of writing.

Forecasts of nuclear generation costs by the major international organizations have a very poor record historically, generally being based on unreasonably optimistic assumptions. The International Atomic Energy Agency (IAEA), which has as one of its main duties the promotion of nuclear power unsurprisingly, is particularly unrealistic. It has not published a forecast in recent years and in a 2012 presentation, relied on a 2010 IEA/NEA cost analysis (Rogner, 2012). As discussed below, the range for key variables was as wide as to worthless.

The International Energy Agency (IEA) with its sister organization, the Nuclear Energy Agency (NEA), publishes regular forecasts of generation costs using different technologies. Its most recent forecast was in 2010. A recurring problem with IEA/NEA forecasts are that the data on which its forecasts are based are submissions from member governments which it would not be politically appropriate to question. For example, in their latest forecast (IEA/NEA, 2010), the construction cost for a nuclear power plant was given a range of less than $2000/kW to more than $8000/kW. Unsurprisingly the conclusion is that at the lower end of the scale, nuclear might be competitive and at the upper end, it would not be.

The World Nuclear Association (WNA) is also consistently over-optimistic on nuclear costs and its most recent forecast was made in 2005 (WNA, 2005) and updated in 2013 (World Nuclear

Association). However, like the IAEA, WNA relies on the 2010 IEA/NEA study for its cost estimates so these forecast contain little or no independent information.

The Global Energy Assessment (GEA) was carried out by the International Institute of Applied Systems Analysis (IIASA) and published in 2010 (IIASA, 2010). However, it assumed a construction cost range for nuclear power of only $1800-2500, about a third of the figures from actual calls for tender and from serious utility estimates. It also assumed an unreasonably low discount rate of only 5 per cent. The results of their analysis therefore have no credibility.

Where those forecasting are closer to a real investment decision, they are more likely to make realistic cost estimates. According to the US Department of Energy and Nuclear Energy Institute the cost of electricity from the new nuclear power plants in the USA would be 12.1 US cents/kWh. This would be the most expensive electricity source in the US (Nucleonics Week, 28 February 2013).

The planned Akkuyu nuclear power plant (four Russian reactors each WWER 1200MW) in Turkey would cost $20 bn. According to a 15-year Power Purchase Agreement, the power from Akkuyu NPP is to be sold at a weighted average price of 12.35 US cents/kWh, with a ceiling of 15.3 cents/kWh (Nucleonics Week 2012).

6.2 LEVELISED COST OF ELECTRICITY

A common way to compare the costs of power from different forms of generation is to compute the levelized cost of electricity. This methodology estimates all the costs and benefits of the plant over its entire product life from start of construction to completion of decommissioning. It 'discounts' costs and benefits to 'present' values and from this calculates the average cost of power. As argued in detail elsewhere, the concept of discounting is intuitively reasonable and is based on the idea that a cost or benefit incurred or received in the future is worth less than the same cost today. In simple terms, if cash can earn a real annual rate of interest of 2 per cent, a benefit of £102 received in one year is only worth £100 today because that £100 could be invested to grow to £102 in a year's time.

The cheapest option might not always be the most economical option because electricity is supplied by an integrated system and to make a proper judgment, it would be necessary to look at what the impact on the cost of running the whole system would be of adding a new plant. For example, if a system has plenty of 'base-load' capacity (plant that can operate continuously which tends to have low running costs, but, perhaps, high fixed costs) but not sufficient 'peak-load' plant it is likely to be more attractive to add a peaking plant than a base-load plant because the peaking plant will reduce the overall cost of supplying the system than a base-load plant. In practice, the system simulation models needed to make this assessment are immensely complex and require large numbers of assumptions that are difficult to make accurately. Calculations of the levelized cost also require assumptions that are difficult to make accurately but the number of assumptions is much lower and the impact of varying these assumptions is easy to illustrate.

The cost of nuclear power is very strongly determined by just two variables, the construction cost and the discount rate and there is huge uncertainty about both of these. Estimates of the real construction cost have increased by a factor of more than five in only a decade, while the discount rate will vary hugely depending on the commercial circumstances. For example, in the USA, loans for the proposed Summer and Vogtle plants, which account for 80 per cent of the projected cost, are covered by Federal loan guarantees and state regulators have given strong assurances of full cost recovery. In this circumstance the risk to a bank lending for such a project is minimal and the cost of borrowing is close to the Federal lending rate. In such circumstances, a discount rate of less than 5 per cent might be appropriate.

In the UK in 2006, the government announced a new nuclear power program but with no public subsidies, implying that new nuclear power stations would have to survive in the wholesale electricity market competing on equal terms with other forms of generation. This would have been a massively risky investment and the government has effectively abandoned this attempt, but if they had tried to follow this approach, the cost of capital and hence the discount rate could easily have exceeded 15 per cent, had borrowing been feasible. The impact of high discount rates is to give little weight to costs or benefits accruing more than 20 years in the future. Using a 10 per cent discount rate, a cost incurred 20 years in the future will have a weight of only about 15 per cent of its nominal value while after 50 years, the 'present' value is less than 1 per cent of the nominal value. Even if the discount rate is only 3 per cent, after 50 years, the value of a cost incurred in 50 years is reduced by about 80 per cent. Conversely, anything that goes wrong in the early years, for example, poor reliability and cost overruns will have a very strong impact on the levelized cost. This means that decommissioning cost at any plausible cost estimate and at a low discount rate would still make a very small contribution to the cost of a kWh of nuclear electricity.

Further levels of uncertainty are created by variability in exchange rates and in the cost base year. The three main currencies are the US dollar, the Euro and the pound sterling. Our calculations are in Euro and for 2012 prices, the exchange rates used are €1=$1.35, £1=€1.20 and £1=$1.60.

Given this level of uncertainty, it is clearly hard to justify anything other than a very simple model. We identify one central case and for each variable investigate how credible changes to the assumed value of this variable affect the outcome. As is good practice for project appraisal, for our central case, we try to identify central estimates, that is, estimates that are as likely to be too low as they are to be too high. For many variables, the distribution of probable outcomes is far from symmetrical around this central estimate. For example, the probability of construction cost or time being less than the target value is minimal but the probability of the cost or time being double the target value (or more) is significant.

7 DATA SOURCES

For the key data items, construction cost, discount rate and load factor and for costs of unproven operations, such as operating life, decommissioning and waste disposal, we make our own cost estimates. For other cost items, where possible we use US cost data. The US system of economic regulation of electricity means that in most states utilities can only recover costs they can demonstrate have been incurred. The tendency for utilities to underestimate costs therefore does not apply there and the data, for example on O&M costs should be relatively reliable. Otherwise, we use cost estimates carried out by consultants, Parsons Brinckerhoff (Brinckerhoff, 2011) in 2011 and by Mott Macdonald (Macdonald, 2012) in 2010 for the UK government. These provide cost estimates for a First of a Kind (FOAK) and for an Nth of a Kind (NOAK) plant. It is assumed that a FOAK will be more expensive than an NOAK because there will be set up costs that will not be repeated for subsequent plants. In practice, the likelihood of any Western nuclear power program being large enough to achieve the NOAK scale economies assumed is small so we use the FOAK values.

8 COSTS AND VARIABLES RELATED TO THE PRE-OPERATION PHASE

8.1 DISCOUNT RATE

This is one of the most crucial variables but also one of the most difficult to forecast. There is no 'correct' answer in the sense that there is a value that, with hindsight, represents the best estimate as for example, there might be with, for example, construction costs. Each project will have its own discount rate that will reflect the specific conditions of that project. These include the credit-worthiness of the country in which it is being built and the utility, the power purchase terms in particular how predictable the price is and how far extra costs can be passed on to consumers. At one end of the spectrum, the nuclear plants being proposed for construction start in 2013 in the USA, Summer and Vogtle, have all the loans, 80 per cent of the construction cost, guaranteed by the US Federal government and the state in which the plant will be built is guaranteeing full cost recovery from consumers. This represents a very low risk loan for the financiers. The risk is no less than for other projects but is being entirely borne by US taxpayers and electricity consumers in the state concerned. In this situation, it might be arguable that the appropriate discount rate would be very low, perhaps 5 per cent. Equally, if a nuclear power plant was being built in a country with a low credit rating and/or where the price that would be paid for electricity was determined by a competitive market, financiers would view the investment as highly risky. Whether finance would be available at all would be a moot point but if it was the cost of capital would be very high, perhaps 15 per cent or more. It is worth noting that when the UK electricity market was opened up, gas-fired power plants, a relatively proven technology given 15 year contracts with full indexation to the price of gas, were widely reported as being appraised at a discount rate of 15 per cent so assuming 15 per cent for a nuclear project is far from being a worst possible case.

8.2 PRE-CONSTRUCTION COSTS

Some costs are incurred before construction starts, for example, design, licensing etc. There are also infrastructure costs such as transmission links. These are highly variable depending on a variety of factors, but relatively small compared to the construction cost. In 2010, the UK consultant Mott MacDonald in an estimate produced for the UK Department of Energy & Climate Change estimated these as in their central estimate as £180/kW or about €220/kW (Macdonald, 2010). Given their relative size, there seems little point in choosing a high and low case. For simplicity, these costs are added to the construction cost in the first year.

8.3 CONSTRUCTION COST AND TIME

These are the most widely debated variables and it makes sense to consider them together for these purposes. It is hard to imagine a time overrun that does not also involve a cost overrun and vice versa. For these purposes, the cost should be the cost per kW of capacity and should be an 'overnight' cost. This excludes finance charges during construction but includes the cost of the first fuel charge. For simplicity it is assumed that the construction cost will be distributed evenly over the construction period so, for example, if the construction period is five years, 20 per cent of the cost will be incurred in each year. The actual cost profile is probably rather different but the impact of this simplification will be relatively small

The conventional activity that marks the construction period as starting is the pouring of first structural concrete and completion is marked by the declaration of commercial operation. At this point, the plant has completed and passed its operating tests and control of the plant is handed over from the vendor to the utility/operator. In most case, commercial operation usually occurs a few months after first criticality and connection to the grid.

The 'Nuclear Renaissance' first talked about around 2000 was based on a promise that the new generation of reactors being considered then and now would have an overnight cost of no more than $1000/kW. Since then estimated costs have continued to escalate and in January 2013, it was reported that EDF and the UK government had agreed a construction of £7bn for each Areva EPR (1600MW). This equates to €5250/kW ($7000/kW). On the one hand, EDF will want to negotiate as high a price as possible but on the other, given that few of the modifications that are likely to be required as lessons from Fukushima emerge have yet been identified, this can be taken as a reasonable central estimate. Given the experience of the past decade, and the likely impact of the Fukushima disaster, it is hard to see how costs could fall in real terms. However, if we assume that other designs will be cheaper than the EPR and that larger orders will be cheaper, we could envisage a low scenario of a reduction of 10 per cent, i.e., €4750/kW. The upper bound will be much wider and 20 per cent seems reasonable, i.e.€6300/kW. For construction time we assume six years with a lower bound of five years and an upper bound of eight years. Again, given experience at Olkiluoto and Flamanville, this appears, as with construction cost, to be far from a worst case scenario.

9 COSTS AND VARIABLES RELATING TO THE OPERATION PHASE

9.1 PLANT LIFETIME

There are four main factors that determine how long a nuclear power plant will remain in service:

- The physical life of the components especially those that cannot economically be replaced;
- The economic life of the plant, in short how long it remains a competitive source of power;
- Its licensability, in short how long the national safety regulatory body is prepared to allow it to operate; and
- There are also potentially political factors, for example, if there is a nuclear phase-out policy, plants that could otherwise remain in service might be closed.

Most debate recently has been about life-extension with the USA leading the way and extending the licensed life of most of the operating plants there from 40 to 60 years. In the UK, in December 2012, the UK safety authorities extended the life of the oldest operating plants, originally given a design life of 25 years, to nearly 50 years. Design life, particularly in the early days of the nuclear industry was a very imprecise measure because there was no experience of testing the durability of materials to long term exposure to radiological exposure as well as heat stress. Materials might not last as long as expected and in January 2013, it was still not determined whether two reactors in Belgium, both about 30 years old, would be allowed to return to service following the discovery of flaws in the pressure vessel.

In practice, many items in a nuclear power plant, not all, can be replaced so the cost of generation may determine the life of the plant. In the early 1990s in the USA, it was calculated that for a small number of nuclear plants, it would be cheaper to shut them down and pay the cost of building and operating new gas-fired plant than to pay the cost of just continuing to operate these nuclear plants. As a result the nuclear plants were closed. In 2002, income to the UK nuclear generator, British Energy, fell below their variable costs and the company went bankrupt. In this case, the British government chose to use taxpayer money to rescue the company by subsidizing it. However, the government could have chosen to close some or all of British Energy’s reactors.

The life of the plant may also be determined by safety considerations. If the safety regulator is no longer prepared to license the plant and upgrades that would make the plant licensable are prohibitively expensive, the plant must be closed. This is likely to be an issue with plants of designs involved in serious accidents for example, the Chernobyl design or the Fukushima design.

Nuclear phase-out policies are an increasing trend in Europe and several countries, including Germany, Sweden, Spain and Belgium have policies to limit the life of their nuclear plants, while Italy and Austria have chosen not to operate nuclear plants.

In practice, the normal assumption of life-time is 40 years with an increasing number of forecasts assuming 60 years. 40 years may be too optimistic for a central estimate and given that few nuclear plants have operated beyond 40 years and many have been retired before 40 years, a more appropriate central estimate might be 35 years with a low case of 30 years and a high case of 40 years.

The assumption on plant lifetimes is not likely to be critical. If we choose a discount rate of 10 per cent, the value of any cost or benefit incurred at 30 years will be discounted by 94 per cent, so no matter how profitable a plant is that can operate for more than 30 years, it will have little impact on the overall economics.

9.2 OPERATIONS & MAINTENANCE COST

Conventionally, for forecasting, this is split into fixed costs, that is, those that will be incurred regardless of whether the plant operates in the short-term, and variable costs. The fixed costs dominate and include staff, and are usually expressed as €/kW of capacity per year. Variable costs are those directly related to production including consumable items and some waste disposal and are usually expressed as €/MWh. The common perception is that nuclear O&M costs are low and while in general construction costs dominate overall cost estimates for nuclear power, O&M costs are not necessarily trivially low especially for unreliable plants. Because fixed costs dominate, more than 90 per cent of O&M costs, the O&M costs per kWh will be very sensitive to the load factor. If the load factor is about half that expected, the O&M costs will be double that expected. This is because the low level of output means there are fewer than expected units of output over which to spread the fixed O&M costs.

Parsons Brinckerhoff estimates the fixed O&M costs for a FOAK unit as £72,000/MW/year (€86,400/MW/year, $115,200/MW/year) and the variable cost as £0.6/MWh (€0.72/MWh, $0.96/MWh/). If we assume the load factor is 80 per cent, a notional 1MW nuclear power plant would produce 7000MWh per year and the fixed cost per MWh would be £10.3/MWh (€12.33/MWh, $16.44/MWh) giving a total non-fuel O&M cost of £10.9/MWh (€13.04/MWh, $17.39/MWh).

This can be benchmarked against the actual O&M costs of the 33 US plants that reported their costs to the US Federal Energy Regulatory Commission in 2009.[3] The average non-fuel O&M cost for that year was $15.8/MWh (Nucleonics Week, 2011). The average load factor for US plants in 2009 was 87.65 per cent, so if the load factor had been 80 per cent as we assume, the O&M costs assumed by Parsons Brinckerhoff would have been almost exactly the same as the outturn US costs.

9.3 FUEL COST

The cost of fuel including all stages of the fuel cycle from uranium mining to final disposal of spent fuel is a relatively small element of the cost of power. The first parts of the fuel cycle, mining, processing, enrichment and fuel manufacture are relatively cheap. The latter parts, especially final disposal, are totally unproven and therefore subject to major uncertainty. However, final disposal is unlikely to take place until many decades, perhaps 100 years, after the fuel was taken from the reactor. So, even with high costs and low discount rates, as for decommissioning, disposal costs would be expected to have little weight in cost calculations. In practice, while these disposal costs are incurred in the post-operation, they are accounted for in the operating phase.

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[3] All nuclear power plants in states where the price is regulated rather than set by the market must report their costs to the FERC. In the past, this covered all US nuclear power plants but by 2009, the most recent year for which data has been published, only 33 units reported their costs.

Parsons Brinckerhoff uses the fuel prices derived in the predecessor study by Mott Macdonald of £5/MWh (€6/MWh, $8/MWh). Average fuel costs in the USA in 2009 were US$6/MWh. However, this includes only the nominal fee paid to the US government for spent fuel disposal so the fuel cost is in line with actual fuel costs in the USA in 2009.

9.4 INSURANCE

Parsons Brinckerhoff estimate insurance costs as £10,000/MW/year (€12,000/MW/year, $16,000/MW/year). For simplicity, this is added to the fixed O&M costs in the model.

9.5 LOAD FACTOR

The annual load factor, calculated as the output in kWh per year as a percentage of the output that would have been produced had the unit operated uninterrupted at full design rating for the whole year, is a key economic factor. Because nuclear power plants are capital intensive and it is difficult and undesirable to vary output levels, nuclear power plants are almost invariably operated on base-load at the highest level of output that it is safe to operate at. Only in France is nuclear capacity such a high proportion of total generation capacity that nuclear power plants have to 'load follow' and even here it is restricted to a small number of plants and has little impact on the overall load factor.

Load factor determines how much output there is to spread the high fixed costs over. Ideally the load factor should be calculated on a net basis, i.e., units of output supplied to the grid excluding own use and based on the net output rating, i.e., rating net of station own use. However, in practice, there should be little if any difference between load factors calculated on a net or a gross basis.

As discussed elsewhere, in the past load factors have been far below the levels of more than 85 per cent forecast by the nuclear industry and in 1980, the world average was only 60 per cent. However from the late-1980s onwards, load factors have improved and the world average is now about 80 per cent. The level may be a little lower in the first year or two and may decline in later years as maintenance periods have to be lengthened to replace worn out equipment or reliability levels decrease. A reasonable estimate of life-time load factor would be 80 per cent with high and low cases of 90 per cent and 70 per cent respectively.

Parsons Brinckerhoff uses three assumptions, low, central and high, of 88.2 per cent, 90.2 per cent and 92.2 per cent based on an assumption of the likely breakdown rate and the length of routine refueling and maintenance outages. It assumes that whenever the plant is on-line, it is operating at 100 per cent of its design rating. These assumptions appear unreasonably optimistic given the experience of reliability to date and the range is far too narrow so these assumptions are not used.

9.6 LICENSED OUTPUT RATING

The net output rating of the plant, the maximum level at which the plant is licensed to operate has, in the past, fallen short of the design level. For example, in the UK, most of the first generation plants, the so-called Magnox reactors, had to be 'down-rated' by about 25 per cent because operating at full power would have led to serious corrosion of some of the components. The next generation, the Advanced Gas-cooled Reactors also were not able to operate at design rating because of design issues. However, in the past three decades, nearly all the plants coming on line elsewhere have reached their design rating. Upgrades to some components, such as the turbine or operating the plant at higher temperatures and pressures have even allowed some plants to operate at beyond their design rating.

The most extreme examples are the two Olkiluoto BWRs in Finland which were commissioned in 1978. Their original design rating was 660MW (net) but this was uprated to 710MW in 1984, 790MW in 1997, 840MW in 1998, 860MW in 2006 and 880MW in 2010. This means that the load factor on licensed rating of 880MW of 94.1 per cent in 2011 would be a 125.5 per cent on a design basis. Given that the economic case is based on the design rating, it is this measure that should be used to calculate load factors.

As the technology gathers more experience, the risk of down-rating and equally the possibility of up-rating is likely to decline so the central estimate is that the licensed rating will be the design rating.

10 COSTS AND VARIABLES RELATING TO THE POST-OPERATION PHASE

10.1 DECOMMISSIONING COSTS

The existing data for costs of decommissioning of nuclear facilities, disposal of spent fuel and radioactive waste are limited and plagued with big uncertainties. For example future costs for decommissioning all of France's nuclear facilities (including reactors, research facilities and fuel cycle plants) and disposing of radioactive wastes are estimated to be €79.4bn. However these estimates are fragile due to the lack of firm decommissioning costs and lack of final disposal plans. A massive increase in future costs would have significant impact on the annual cost of production (World Nuclear Association, 2012).

In the USA Nuclear Regulatory Commission regulations require sites of nuclear power plants to be fully decommissioned to a greenfield state within 60 years of permanent shutdown. In May 2013 the Kewaunee nuclear power plant (a PWR with capacity 583 MW commissioned in 1974) in Wisconsin was finally shutdown due to lack of customers for its electricity. Decommissioning of the Kewaunee nuclear power plant is expected to cost a total of about $900m (Nucleonics Week, 9 May 2013).

Decommissioning costs are very large, expected to be several billion Euro for a large reactor, but given the minimal experience of carrying out decommissioning, they are very hard to estimate accurately. Many cost estimates are expressed as a percentage of the construction. Given that there would appear to be little logical connection between the construction cost and the decommissioning cost and the high level of uncertainty about construction costs, this illustrates the uncertainty and the lack of detailed engineering based cost estimates. Nevertheless, because these costs are likely to occur perhaps 100 years or more after plant start-up, even a very high decommissioning cost estimate will have little impact on the levelized cost. We have no better basis for forecasting than an arbitrary percentage of the construction cost and, we take 50 per cent as a central case, that is, €2600/kW.

We assume that all the funds should be available at the end of the operating life of the plant, (we assume a 40 year life-time and for these purposes we do not vary the lifetime for decommissioning funds). The discount rate for decommissioning funding has to be different to the one applied to other costs and benefits. It can be estimated as the real rate of interest that can be assumed for a period of operation. The UK Treasury recommends a real discount rate for long term liabilities incurred 31-75 years in the future of 3 per cent (HM Treasury, 2011). For even longer timescales, it reduces the rate to 1 per cent for liabilities more than 300 years in the future.

Best practice is that decommissioning provisions should be collected from consumers throughout the life of the plant and kept in a fund that the utility has no access to (segregated funds) and invested in very low risk assets, for example, bonds issued by a very stable government.

For simplicity we assume that all the funds should available on the day the plant closes and for simplicity, we add the discounted decommissioning cost to the final year construction cost. The discounting factor for 40 years at 3 per cent is 0.306, so the discounted value of the decommissioning cost is €800/kW. To reflect the huge uncertainty about this figure, we take the high case as 50 per cent higher, €1200/kW and the low case as half the central figure, €400/kW.

There is also the issue of how to ensure that the risk that funds will not be sufficient when required, which on the basis of failings with existing provisioning schemes is very high. The main factors leading to this risk arise from:

- Risk that the fund earns less interest than expected;
- The cost estimate proves to be too low;
- The plant does not operate for as long as expected. Decommissioning takes place earlier than expected and consumers do not provide as much provisioning as expected;
- The operator goes out of business and is unable to make the required payments to the fund.

A logical way to deal with these risks would be to require the owner of the plant to take out a financial instrument (essentially an insurance policy) that would make up any shortfall in the decommissioning fund. However, there is no precedent for such an instrument, nor any certainty that the market would be willing to provide such an instrument. If an estimate could be made, this cost could be added to other insurance premia.

11 COSTS OF POWER AND SENSITIVITIES

Under the base case assumptions listed in Table 7, the cost of power would be €140/MWh. We do not develop a high case and a low case as is normal for cost projections because it is not realistic to assume that all variable go about 10-20 per cent than better or worse than forecast. However, we do develop an 'Olkiluoto' scenario where construction costs are double the expected level. Whilst this may prove to be an abnormal outcome, it will be one that will concern financiers. In this case, the construction cost would be €10,500/MW or €955/year

TABLE 7 BASIC ASSUMPTIONS

Variable	Base	Pessimistic	Optimistic
Pre-construction cost (€/MW)	220	220	220
Construction cost (€/MW)	5250	6300	4750
Construction time (years)	6	6	6
Plant lifetime	40	40	40
Fixed O&M (€/MW/year)	86,400	86,400	86,400
Insurance (€/MW/year	12,000	12,000	12,000
Variable O&M (€/MWh)	0.72	0.72	0.72
Fuel cost (€/MWh)	6	6	6
Load factor	80	70	90
Output rating (per cent of design)	100	100	100
Decommissioning cost (€/MW	2600	3900	1300
Discount rate (%)	10	15	5

Source: Author's calculations

TABLE 8 COST PROJECTIONS (LEVELISED COST EURO PER MWH)

Case	Optimistic	Pessimistic
Base case	140	
'Olkiluoto'	230	
Construction cost	110	160
Load factor	120	150
Discount rate	80	210

Source: Author's calculations

In the base case, the levelized cost is €140/MWh but this goes up €230 if the construction costs double, the Olkiluoto case. Table 8 shows the key variables are the discount rate, the construction cost and the load factor.

12 CONCLUSIONS

Despite more than 50 years of commercial experience there is little clarity about the cost of electricity from nuclear power plants. The main factors behind this uncertainty are lack of experience and knowledge; existence of subsidies that are difficult to quantify; project specific costs; and limitations of conventional project appraisal techniques. In addition, the normal technology trajectory, under which costs go down and performance improves, due to factors such as learning, scale economies, have not applied to nuclear power and forecasts based on assumptions of such factors will inevitably be too optimistic. Despite the large number of significant variables, in practice, assumptions on the construction cost and the cost of capital are much more important than any other assumptions in determining the cost of power from a nuclear power plant.

As the existing fleet of plants ages and reaches the end of its expected life, utilities are looking more at the option of life-extending the plant. This is a much less risky option than building a new plant. How economically attractive it is depends on what additional investment is required to bring the plant up to a standard that will satisfy safety regulatory authorities.

Applying assumptions that are based on current costs via a simple model to calculate the cost of power from a nuclear power plant underlines that the key assumptions are those on construction cost and cost of capital. While the results vary widely according to the assumption, they underline that nuclear power is not a cheap source of power, and has costs of the same order as the most expensive renewables. However, whilst for these, the cost curve is going down, for nuclear it is still going up and as the lessons from Fukushima are fed into the safety requirements, there seems little prospect in the medium terms that costs will begin to fall.

LIST OF ABBREVIATIONS

ABWR: Advance Boiling Water Reactor
APWR: Advance Pressurized Water Reactor
AP1000: Advanced Pressurized water reactor
EPR: European Pressurized water Reactor
ESBWR: Economic Simplified Boiling Water Reactor
FOAK: First Of A Kind
GE: General Electric
IAEA: International Atomic Energy Agency
kW: kilowatt
kWh: kilowatt hour
MW/MWh: MW is 1000kW
NOAK: Nth Of A Kind
O&M: Operations and Maintenance
PWR: Pressurized Water Reactor
R&D: Research & Development
TEPCO: Tokyo Electric Power Company
WACC: Weighted average cost of capital
WWER: Vodo-Vodyanoi Energetichesky Reactor (Russian version of PWR)

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