IAEA-SM-353/8

ECONOMIC COMPETITIVENESS REQUIREMENTS FOR EVOLUTIONARY WATER COOLED REACTORS

C.R. HUDSON
Technology Insights,
Knoxville, Tennessee

E. BERTEL
OECD Nuclear Energy Agency,
Paris

K.H. PAIK, J.H. ROH
KEPCO,
Seoul, Republic of Korea

V. TORT
CEPN,
Fontenay-aux-Roses, France

Abstract

This paper analyses the necessary economic conditions for evolutionary water cooled reactors to be competitive. Utilising recent national cost data for fossil-fired base load plants expected to be commissioned by 2005-2010, target costs for nuclear power plants are discussed. Factors that could contribute to the achievement of those targets by evolutionary water cooled reactors are addressed. The feed-back from experience acquired in implementing nuclear programmes is illustrated by some examples from France and the Republic of Korea. The paper discusses the impacts on nuclear power competitiveness of globalisation and deregulation of the electricity market and privatisation of the electricity sector. In addition, issues related to external cost internalisation are considered.

1. INTRODUCTION

Economic competitiveness is a cornerstone for the successful deployment of any electricity generation source and technology. Although decisions on technologies and energy mixes for electricity generation have to take into account a variety of non-economic issues, including social, environmental and health impacts, decisions taken by utilities are based primarily on the costs of generating electricity from alternative energy sources and technologies available on the market. Therefore, designers and manufacturers of evolutionary water cooled reactors must produce plants whose costs are competitive with other options.

While assessing the competitiveness of alternative sources, the evolution of the policy-making framework for the electricity sector should be taken into account. This evolution creates new challenges and opportunities for different generation technologies, including nuclear power. Deregulation of the electricity market and privatisation of the sector are changing the criteria upon which assessments of competitiveness are based. Private investors will tend to prefer low capital intensive technologies that offer a rapid return on investments. Market deregulation poses challenges for capital intensive technologies, such as nuclear power, because the resulting open competition for supplying electricity will introduce a higher uncertainty on the level of sales by each producer. In order to reduce financial risks, producers will tend to seek more flexible generation strategies that are based upon small size power plants with relatively low investment costs and short pay-back times. Nuclear power will be challenged to retain its competitive position in such a market, owing to the fact that it is a relatively complex technology that requires sophisticated industrial and R&D infrastructures which might be difficult for the private sector to support. On the other hand, the reduction of barriers to bulk electricity exchange via extended networks offers new market opportunities for large units that have stable long term generation costs, such as nuclear power plants.

The increasing awareness of environmental issues and the recognition of broad macroeconomic and social effects arising from technology choices are leading to new approaches and additional criteria in the comparative assessment of different generation options. Cost comparisons of generation technologies can be taken beyond the traditional approach of calculating the direct economic costs to the utility by internalising other costs to society (externalities) insofar as feasible. Internalising externalities might enhance the competitiveness of nuclear power versus coal and gas-fired power plants. Owing to the early recognition of the need to adequately protect the public and environment from ionising radiation, the classic levelised cost assessment already takes into account most of the elements related to health and environmental impacts of nuclear power generation, from mining through electricity generation to decommissioning of the facilities, waste management and disposal. Also, the costs related to the application of safety standards and regulations are embedded in the investment, operation and maintenance costs of nuclear power plants. On the other hand, the liabilities arising from fossil fuel electricity generation (for example, the potential costs of greenhouse gas emissions) are not taken fully into account at present, and their inclusion would increase the costs of fossil fuel based generation relative to nuclear.

This paper addresses the cost economics necessary for evolutionary water cooled reactors to be competitive. Target costs that would allow evolutionary water cooled reactors to compete favourably with alternatives are identified. Factors affecting nuclear power costs are analysed and lessons learnt from past experience are illustrated by examples of cost reduction achieved through the successful implementation of nuclear power programmes in France and the Republic of Korea. The challenges and opportunities resulting from the new economic landscape, and the ways in which they might affect the competitiveness of evolutionary water cooled reactors are discussed. Also, external costs of nuclear power and alternative generation sources are highlighted.

2. TARGET COSTS FOR EVOLUTIONARY WATER COOLED REACTORS

The evolutionary water cooled reactors that are currently being developed will be commercially available for commissioning by 2005-2010. They will compete essentially with state-of-the-art coal-fired and gas-fired power plants. Renewable sources, besides hydropower, generally are not considered for base load generation. For example, in the last OECD study on projected costs of generating base-load electricity [1], participating countries provided cost estimates mainly for coal-fired, gas-fired and nuclear plants.

The data on projected generation costs provided by countries participating in the OECD study show that those costs vary from country to country for similar technologies owing to their specific economic context. However, the levelised lifetime generation costs obtained in the study, using a common framework and generic assumptions, provide a consistent basis for assessing future generation costs at the conceptual level. Cost estimates were provided by participating countries expressed in their national currencies of 1 July 1996; for consistency sake, cost estimate results were converted to dollars of the United States as of 1 July 1996, using the official exchange rate applicable at that date.

On average, projected generation costs for coal-fired power plants are around 41 mill/kWh [1] at 5 per cent per annum real discount rate and around 51 mill/kWh at 10 per cent per annum discount rate. Those costs are based upon coal prices ranging from 1 $/GJ to 2.8 $/GJ in 2005 - year of commissioning of the plant - and increasing at an average escalation rate of 0.3 per cent per annum. For gas-fired power plants, the average projected generating costs are 40 mill/kWh and 43 mill/kWh at 5 per cent and 10 per cent discount rate, respectively. The gas prices assumed vary between 1.6 $/GJ and 5.4 $/GJ in 2005 with a 0.8 per cent per annum average escalation rate. In the same study, the average generation costs for nuclear power plants are 32 mill/kWh and 49 mill/kWh, respectively at 5 per cent and 10 per cent discount rate.

Table I. Projected levelised generation costs (1996USmill/kWh)

	At 5 per cent discount rate			At 10 per cent discount rate		
Country	*Coal*	*Gas*	*Nuclear*	*Coal*	*Gas*	*Nuclear*
Canada	29.2	30.0	24.7	37.0	33.0	39.6
Finland	31.8	35.9	37.3	39.1	41.1	55.9
France	46.4	47.4	32.2	59.5	53.3	49.2
Korea	34.4	42.5	30.7	45.0	47.0	48.3
Spain	42.2	47.9	41.0	54.7	54.4	63.8
Turkey	39.8	30.7	32.8	48.7	33.9	51.8
United States	25.0	23.3	33.3	34.7	23.6	46.2
Brazil	35.4	28.5	33.1	43.2	32.7	46.7
China	31.8	n.a.	25.4	40.0	n.a.	39.0
India	33.0	n.a.	32.8	40.2	n.a.	51.0
Russia	46.3	35.4	26.9	55.3	39.0	46.5

Table I summarises the results obtained in the OECD study for the reference cases, i.e., 40 year lifetime and 75 per cent load factor, in the eleven countries that provided cost data for nuclear power and at least one alternative. All those countries, except China and India which did not provide data for gas-fired plants, reported cost estimates for coal-fired, gas-fired and nuclear power plants. In cases of multiple plant submissions in the study, only the cheapest power plant for each technology/fuel is shown.

At 5 per cent discount rate, levelised generation costs for coal-fired power plants range from 25 to 46 mill/kWh, the average value being around 36 USmill/kWh; for gas-fired power plants, the range is 23 to 48 USmill/kWh, the average value being around 36 USmill/kWh; and for nuclear power plants, the range is 25 to 41 USmill/kWh and the average value is around 32 USmill/kWh. At 10 per cent discount rate, levelised cost ranges are 35 to 60 USmill/kWh, 24 to 54 USmill/kWh and 39 to 64 USmill/kWh for coal-fired, gas-fired and nuclear power plants, respectively, with the average values around 45, 40, and 49 USmill/kWh, respectively.

In the eleven countries where coal and nuclear options are considered, the ratios between projected costs of nuclear and coal generated electricity range from 0.58 to 1.33 at 5 per cent discount rate and from 0.83 to 1.43 at 10 per cent discount rate. In the ten countries where gas and nuclear options are considered, the ratios between projected costs of nuclear and gas generated electricity range from 0.68 to 1.43 at 5 per cent discount rate and from 0.92 to 1.96 at 10 per cent discount rate. In the same countries, the ratios between projected costs of coal and gas generated electricity range from 0.76 and 1.24 at 5 per cent discount rate and from 0.68 and 1.04 at 10 per cent discount rate.

As indicated above, the ranges of generation costs for each technology/energy source are quite broad, underscoring the observation that competitiveness should be assessed on a case by case basis at the country and utility level, based upon specific technical and economic conditions applicable in each case. Nevertheless, the average generation costs given above provide an indication of target costs in order for evolutionary water cooled reactors to be competitive.

Owing to uncertainties on projected cost elements and to the conceptual level of detail inherent within international studies based upon generic assumptions, small differences in generation costs are not significant. Differences higher than 10 per cent, however, may be considered indicative of the relative competitiveness of alternative options in each country. Within the eleven countries that provided data for nuclear power and at least one other option, at 5 per cent discount rate, nuclear is the cheapest by a margin of at least 10 per cent in five countries, coal is the cheapest by a margin of at least 10 per cent in one country and gas is the cheapest by a margin of at least 10 per cent in one country. At 10 per cent discount rate, nuclear is the cheapest option by a margin of at least 10 per cent in no country, coal is cheapest option by a margin of at least 10 per cent in one country and gas is the cheapest option by a margin of at least 10 per cent in five countries. As would be expected, as the discount rate increases, technologies with lower capital intensity fare better.

3. KEY FACTORS FOR ENHANCING EVOLUTIONARY WATER COOLED REACTOR COMPETITIVENESS

The historical cost experience of nuclear power has been quite varied. In some countries, nuclear power has become the primary source of economic baseload generation. In other countries, particularly in the United States, the cost results of nuclear power have been inconsistent, with some facilities producing low cost electricity and other facilities closed before the end of their design life due to economic non-competitiveness. The causes of this inconsistency are beyond the scope of this paper, but the lessons learned from these events are very relevant to the future of nuclear power.

A number of studies have been undertaken to "learn from the past" and improve the economics of nuclear power. In 1990, the NEA investigated means to reduce capital costs of nuclear power used in different Member countries [2]. In the United States, the Electric Power Research Institute (EPRI), in co-operation with the utility industry and the U.S. Department of Energy, has developed a set of utility design requirements for next generation nuclear plants [3]. The EPRI Utility Requirements Document (URD) consists of a comprehensive set of design requirements for future LWRs. As a part of the URD, several key elements that are necessary to achieve deployment success have been defined. Many of these factors bear heavily on the potential economic competitiveness of new plants and are presented below.

Simplification – Nuclear power is, inherently, a relatively complex undertaking. Nevertheless, plant designs can seek to minimise the number of systems, valves, pumps, etc., consistent with essential functional requirements. A particularly important aspect of simplification is with respect to plant operations. Improved man-machine interfaces, simplified protective logic and actuation systems, and system designs which minimise operator demands will lead to higher plant availability and less accident risk.

Regulatory Stability – The requirements necessary to obtain regulatory approval must be clear and stable if costly redesign and plant modifications are to be avoided. In the United States, the Nuclear Regulatory Commission has developed rules to further define and improve the licensing process through a "one-step licensing process". Early dialogue between plant designers and regulatory bodies can lead to improved understanding of the regulatory requirements and how the plant design can meet them.

Standardisation – A key mechanism to achieve low costs is designing and constructing a standardised plant. A standardised approach creates efficiencies in engineering, construction, and schedule. With a standardised plant, the bulk of design and engineering activities can be performed once and the costs amortised over many units, licensing time and costs will be reduced, and construction techniques will become more refined, reducing both cost and schedule. Operation and maintenance costs will be reduced through reduced operator error and improved maintenance efficiencies.

Improved Constructibility – By incorporating the items identified above, the construction duration will be kept to a minimum, which will greatly influence the plant capital cost. In addition to the above items, improvements in construction will also be made when there is a large fraction of the design complete before construction begins. As an example, the EPRI URD requires that ninety percent of the design be complete (i.e., 90 percent of design drawings must be 100 percent complete) before plant construction starts. Another aspect of improved constructibility relates to modularisation, whereby segments of a plant can be fabricated and assembled in a factory environment and shipped to the site for placement and interconnection. The factory setting provides a better work environment as activities tend to have greater quality control with the potential for greater automation and higher productivity. Modular construction also reduces site congestion and improves construction schedule as module production can take place away from and in parallel with site specific activities.

An additional factor that can influence economic competitiveness is the use of multiple unit sites. In addition to the sharing of the site land cost, site licensing costs can also be shared among multiple units. During the construction phase, considerable efficiencies and associated savings can be gained from phased construction and rolling the various craft teams from one unit to the next. Also, by construction repetition, there is craft labour learning that reduces the time to perform a given task and correspondingly reduces both construction labour cost and schedule. Finally, common facilities such as administration and maintenance buildings, warehouses, roads, and guard stations can be shared by multiple units at a common site.

4. FEED-BACK FROM EXPERIENCE

As over half of the total generation cost of a nuclear plant is related to capital cost, reducing the plant capital cost is a prerequisite for enhancing the competitiveness of nuclear power. As mentioned in the previous section, a study carried out by the NEA in 1990 **[Error! Bookmark not defined.]** analysed means to reduce the capital cost of nuclear stations, identifying as the most significant: plant size, multiple unit sites, design improvement, standardisation, modularisation and performance improvement. A second study, to be completed by the end of 1998, is revisiting the issue drawing from experience acquired in Member countries.

The French experience is of interest in this connection since its large nuclear power programme, based upon standardised units and large series orders, led to competitive nuclear generation costs as compared with fossil fuels. The impacts of unit size and number of units constructed on the same site, according to French data, are illustrated in Table II.

Also, in the French case, the effect of series order is estimated to have been significant. The "first-of-a-kind" (FOAK) initial cost may be between 15 per cent and 55 per cent higher than the cost of a series unit depending on the differences between a new design and previous reactors. When a series of reactors is ordered, additional cost reductions resulting from productivity effects are possible from the third unit on. With a 2 per cent productivity gain for each new unit after the second one, the capital cost of the eighth unit in the series is 10 per cent lower than the capital cost of the first unit.

The Korean nuclear power programme is characterised by standardisation and technology self-reliance. Since 1987, Korea has developed the Korea Standard Nuclear Power Plant (KSNP), a 1000 MWe PWR. Today, one KSNP unit is in operation and five more units are under construction. The capital costs of subsequent KSNPs, based on contracts, are illustrated in Table III.

The most noticeable cost reductions were achieved in Nuclear Steam Supply System (NSSS) equipment, turbine plant equipment, and design and engineering. The cost reduction in NSSS and turbine equipment results from enhanced technology self-reliance and increased productivity in manufacturing through construction repetition and design evolution. The largest beneficiary of

Table II. Overnight costs of nuclear power plants, normalised to 1.0 for 1 x 1000 MWe unit

1 x 300*	2 x 300*	1 x 650*	2 x 650	**1 x 1 000***	2 x 1 000	1 x 1 350	2 x 1 350*
1.82	1.44	1.22	1.0	**1.0**	0.84	0.87	0.75

* *Reactor size in MWe*

Table III. Capital costs of subsequent KSNPs, normalised to 1.0 for 1st & 2nd units

	1st & 2nd units	3rd & 4th units	5th & 6th units
Direct cost	1.0	0.9	0.9
Indirect cost	1.0	0.9	0.73
Contingency	1.0	0.9	0.85
Total capital cost	1.0	0.9	0.85

standardisation could be design and engineering costs. Another factor that influenced the cost reduction significantly is phased construction of continuing projects.

In addition to KSNP, Korea has started a programme for the development of the Korea Next Generation Reactor (KNGR), a 1 300 MWe PWR. The key objective of the KNGR development programme is to enhance safety and economics. The expected cost reduction as compared with existing KSNP and influencing factors were estimated in an economic viability study on KNGR, the results of which are shown in Table IV.

5. ADAPTATION TO THE NEW ECONOMIC LANDSCAPE

Deregulation of the electricity market and privatisation of the sector are changing the criteria upon which assessments of competitiveness are based. Private investors will tend to prefer low capital intensive technologies that offer a rapid return on investments. Market deregulation poses challenges for capital intensive technologies, such as nuclear power, because the resulting open competition for supplying electricity will introduce a higher uncertainty on the level of sales by each producer.

To reduce financial risks, producers will tend to seek more flexible generation strategies that are based upon small size power plants with relatively low investment costs and short pay-back times. In order to retain a competitive position in such a market, designers of nuclear power plants should aim towards streamlined concepts, requiring less sophisticated industrial and R&D infrastructures, including consideration of smaller size modular units more adapted to uncertainties on future demand.

Competitive markets may raise the discount rate used by electric utilities because commercial risks for utilities will increase. Nuclear power plants that have high up-front capital costs would, thereby, have a handicap as compared with low capital intensive gas-fired units.

However, the reduction of barriers to bulk electricity exchange via extended grid networks offers new market opportunities for large units that have stable long term generation costs, such as evolutionary light water reactors.

Table IV. Expected capital cost reduction compared with KSNP and influencing factors

Influencing factor	Expected cost reduction
Standardised design	4.9%
Simplified design	> 4%
Capacity upgrade	8%
Reduced construction period	4%
Total capital cost reduction	> 16.9%

6. EXTERNAL COSTS

Beyond, direct levelised generation costs, as described above, there are external costs or benefits related to the production of electricity that are not directly borne by producers or consumers. Costs and benefits to society that generally are not incorporated in direct costs of electricity generation include: macro-economic impacts such as job creation, price stability and balance of payments; strategic factors such as security and diversity of supply; resource management and sustainability; and health and environmental impacts of residual emissions.

Ensuring diversity of supply and preserving energy security are undoubtedly of concern to policy makers. However, empirical and analytical studies aiming at assessing the value of energy diversity and security differ enormously in their results and conclusions that depend largely on country specific contexts. It is clear that nuclear power introduces diversity and reinforces security of energy supply, but the extent to which this might be reflected in generation costs and prices is questionable.

Environmental impacts are potentially the most significant external cost of electricity generation. The increasing awareness of global impacts on the environment and the broad acceptance of the concept of sustainability are leading analysts and decision makers to aim towards incorporating these parameters either explicitly or implicitly in the comparative assessment process.

Since nuclear power plants of the current generation already have very low external costs related to both normal operation and off-normal situations, greater internalising of externalities might enhance the competitiveness of nuclear power relative to coal- and gas-fired power plants.

A study carried out under the auspices of the European Commission concluded that external costs for fuel cycles are essentially country/technology specific and that large uncertainties on physical damages and their monetary values are large enough to make comparisons between alternative generation options very sensitive to local conditions and assumptions made in estimating those costs. However, the external cost ranges derived from the study (cf. Table V) indicate clearly that nuclear power externalities are lower than those of coal or gas, primarily due to the greater environmental emissions of fossil-fired plants.

The assessment of the external costs related to the operation of a nuclear reactor is based on monetary valuation of the associated health impacts, for both public and workers. Concerning the public, these impacts are associated with the radioactive releases from the nuclear power plant into the environment. Occupational health impacts include potential health effects of ionising radiation exposure as well as occupational accidents.

For a current 1 300 MWe French reactor, the cost associated with the health impacts of the electricity generation routine operation varies between 0.017 and 0.04 mill/kWh for a 3 per cent discount rate, depending on the site, with an average of 0.022 mill/kWh (without discounting, this cost reaches 0.57 mill/kWh, owing to long term impacts) [4]. This cost can be compared to the monetary

Table V. External cost estimates for electricity generation technologies*

Source	Lower estimate	Higher estimate
Coal	7	60
Gas	3	14
Nuclear	1	3
Biomass	1	12

* *Normalised to 1 for nuclear power lower estimate. [Source:* [1].*]*

value of 0.026 mill/kWh reported for a 900 MWe French PWR, which represents an older generation of reactors. For normal operations, it is important to note that, despite the differences existing in the characteristics of the sites and the releases, the differences between the two kinds of PWR are essentially insignificant. Moreover, if the construction and the decommissioning impacts are taken into account, the average value becomes 0.08 mill/kWh for both PWR types.

7. CONCLUDING REMARKS

Nuclear power is a capital intensive technology. As such, owner risks are greater for this technology in a changing or unstable business environment than for a technology with lower capital cost. With the global utility industry undergoing deregulation and privatisation, the market is not the most attractive for highly capital intensive technologies. In a free market, relative cost will have a great influence in the selection process. Evolutionary water cooled reactors must, therefore, project a very competitive total cost in order to be successfully deployed. In terms of broad application, this may be difficult to accomplish globally as fossil-fuel prices are currently low and are projected to rise only modestly. However, there are, and will continue to be, markets where indigenous fossil fuel supplies are scarce, and in these areas, nuclear power may have the economic advantage.

Nuclear power plant costs can be minimised if certain conditions exist at the outset. These conditions include design simplification and standardisation, clear and stable regulatory requirements, a high fraction of design completion before construction, use of multiple unit sites with phased construction, and use of modular construction.

A factor that may influence the competitiveness of nuclear power in the future is externality costs. National policy issues of energy security and diversity of supply may modify the selection process from one of pure relative internal cost. In addition, the global environmental impacts of various power generation technologies are not completely internalised at present. Should this occur, nuclear power will likely have an improved economic ranking worldwide. It is not clear, however, when and if such recognition will take place. Therefore, evolutionary water cooled reactors must be competitive at this time solely on the basis of their direct, internalised costs. This paper has identified some of the factors necessary for this to occur.

REFERENCES

[1] **International Energy Agency, Nuclear Energy Agency,** Projected Costs of Generating Electricity: Update 1998, Paris (1998)

[2] **Nuclear Energy Agency,** Means to Reduce the Capital Cost of Nuclear Power Stations, Paris (1990)

[3] Advanced Light Water Reactor Utility Requirements Document, Electric Power Research Institute, NP-6780-R1 (December 1995)

[4] **European Commission,** Externalities of Energy, Brussels (1995)