# REVIEW OF COST REDUCTION MEASURES FOR NUCLEAR ELECTRICITY

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## ABSTRACT

The cost of nuclear electricity is strongly dependent on the life-cycle cost of the nuclear power plant itself and of the nuclear fuel cycle. At present, the cost visibility at the front-end of the power plant construction and operation as well as the nuclear fuel is satisfactory and the lessons learned from past good and bad experiences are known. However, this is not the case for the last phase of the life cycle, i.e. decommissioning and waste disposal. Since the investments for the last phase are of the same order of magnitude as the investments needed at the front-end, the duration of the operational life of a nuclear power plant is of paramount importance. This paper presents the implication of the long-life plant approach to the design of a nuclear power plant and to the cost reduction for nuclear electricity.

## 1. INTRODUCTION

Nuclear energy now holds seven percent of the global energy market share. To get nuclear power into a position to keep or increase this share, it requires continuous safe operation of the existing nuclear power plants, resolution of the public acceptance problems and waste management including disposal. One of the key issues, however, is to reduce the cost of the produced electricity. Without cost reduction measures and new approaches to the financing of the nuclear life-cycle activities, it will be very difficult to compete with combined-cycle gas turbine plants where natural gas is available by pipeline, or with other alternatives.

All costs associated with the nuclear electricity production as anticipated over the defined life cycle can be grouped into the following general cost breakdown structure:

- NPP implementation and construction cost (called also capital cost)
- Operation and maintenance
- Front-end fuel cycle
- Decommissioning
- Disposal of the radioactive waste (back-end fuel cycle).

The life-cycle cost profile of nuclear energy is characterised by a capital intensive phase for initial planning and construction of the nuclear power plant, a very low capital requirement for operation and maintenance and front-end fuel supply during the operating life and a capital intensive last period of the life cycle, involving expenditures in the same order of magnitude as at the beginning of the project. This is a typical situation related to the nuclear energy, and no other industrial enterprise shows a similar life-cycle cost profile. The duration of the operational life is of paramount importance to the cost of electricity.

The considerations presented here are more focused on countries having a limited nuclear power program and therefore reprocessing is not considered as an option. Furthermore, this paper is formulated in constant prices to simplify the presentation of the main cost reduction measures.

The publications used as reference are indicated at the end of this paper. Values given are based on these publications as well as on the experience of Electrowatt Engineering.

## 2. OPERATIONAL LIFE OF A NUCLEAR POWER PLANT

Most nuclear plants have been designed for a life of 40 years and several plants are approaching the end of their design life. The experience has shown that it would be possible to extend the operational life to 80 years, provided that the plant is designed to allow for a rapid replacement of the components attaining the end of their design life, such as steam generators or reactor pressure vessel, just to mention the main components. The time necessary to replace a steam generator is of only one month and this does not imply a significant electricity production loss. The experience has also shown that the replacement of instrumentation and control systems, electrical equipment or other mechanical equipment is a common undertaking, due to technological changes, disappearance of the industries that have delivered the original equipment and the difficulties in obtaining spare parts. The massive civil structure, if constructed and maintained in a proper way, could last far more than 80 years - as has been proven for hydroelectric dams or other civil structures. The same is valid for many safety systems that remain idle during plant operation.

There is, from a technical point of view, no reason to object to an operation life of 80 years for an evolutionary type of reactor, provided that the following conditions are met:

- According to the latest developments regarding the mitigation of severe accidents the containment shall be protected in a passive way against a core meltdown to limit the consequences of a severe accident to the plant itself. The design of the European Pressurised Reactor represents one possible solution.
- Diagnostic equipment of and for the primary system is to be improved in respect to current technology, to be able to recognise as early as possible those initiating events that could lead to an accident and to be able to have maintenance strategies based on the actual condition of the equipment.

The main reasons for the addition of the above mentioned mitigation and diagnostic systems, which are already available industrially, are to achieve a considerable reduction of the already small remaining risk to the population to a negligible value. This should also facilitate the renewal of the licensing since the future technological changes are already incorporated into the plant design.

Another concern that an NPP-operator could have is to be assured that he will receive appropriate technical support for 80 years. Many companies have abandoned the nuclear field during the development phase of nuclear energy and this will continue to happen also in the future. Therefore, the choice of reactor type should be limited to the types of reactor that now represent the largest nuclear capacity i.e. the Pressurised Water Reactor and the Boiling Water Reactor. Today, the Pressurised Water Reactor has 79% of the market share. In case one reactor supplier will go out of the nuclear business, it will be possible to substitute him with an other supplier, since the main design principle and main components are similar. The experience has already shown that this is feasible.

The choice for a single reactor technology is based also on the following advantages:

- concentration on a single technology avoids dispersing the capabilities of equipment manufacturers, engineering companies and safety authorities
- an eventual series of identical orders will result in lower price
- concentration on a single technology will facilitate the formation of specialists, required for operation and maintenance, and licensing
- development of standardised manufacturing and inspection procedures is well suited for meeting quality assurance requirements
- preparation of administrative procedures is facilitated.

The effects of the long-life plant approach to the main items of the cost breakdown are discussed in the next chapters.

## 3. NPP-IMPLEMENTATION AND CONSTRUCTION COST

One peculiarity of a nuclear power plant cost structure is the elevated constant costs for the project implementation and construction. These costs—independent of plant size and life cycle duration – concern a) activities of the owner and operator such as site approval, information and public relations, project management and contract verification, training of the operation and maintenance personnel, licensing, b) activities of the supplier, such as engineering including safety analysis, documentation and project management, and c) the activities of the Licensing Authorities. These costs are 30% of the total capital cost of one nuclear power plant of 1,200 MWe. This is the main reason why a small reactor (unit size below 1,000 MWe) is not economical. Typical in this respect is the increase of the plant size of the EPR to an envisaged output of 1,800 MWe. Of course, the plant size must be compatible with the grid capacity.

Other cost reduction measures are related to the number of units to be constructed on a site. For a small country this could be difficult to achieve. The cost reduction is calculated to be 10% for a site with two units and 20% for a site having 4 units provided that the construction interval is less than 2 years.

The experience has also indicated that there is a considerable difference in capital requirements due to the different licensing regimes and requirements, and typical in this respect are the differences between France and Germany. According to the study of the Energy Institute of the University of Cologne, the overnight specific capital requirements for NPPs are

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| France | Price base 1992 | PWR-1400 MWe | 1,360 USD/kW for 4 Units |
| Germany | Price base 1992 | PWR-1250 MWe | 2,666 USD/kW for 1 Unit |

The large difference in costs cannot be explained in terms of multi-unit construction scheme or difference in safety requirements mainly related to the consideration of airplane crash, redundancies and additional emergency heat removal system. The main difference is caused by the duplication of the reviewing process and the complicated licensing procedure as practised in Germany. In this area, considerable reengineering cost reductions are possible, justified by the addition of the passive protection of the containment in case of a severe accident and the visible improvements of the industries in respect to the quality assurance. The verification activities of the Licensing Authorities should be limited mainly to the systems dedicated to the protection of the public and leave to the owner the verification activities related to the systems dedicated to the protection of the investment.

The cost reduction potential is very large and experience has shown that there is no difference in the failure rate between different licensing regimes so that the additional resources spent in this field have had no practical influence on the safety of a plant.

The duration of the depreciable life is, beside the costs of the borrowed money, a key factor in determining the capital cost portion of produced electricity. In addition, different methods of computing depreciation lead to different annual depreciation allowances.

In Germany the allowable depreciable life is 19 years and in France is 30 years. Due to the long-life plant approach we consider the depreciable life of 30 years as prudent since the remaining 50 years of operation are more then adequate for the remaining financial liabilities of the owner. The value of 30 years is also compatible with the value used for hydroelectric plants where the depreciation life is usually 50 years. In fact the material most used per energy unit for both cases is concrete, that has a long lifetime.

The following items of a nuclear power plant have a life period of at least 80 years; their costs represent 58% of the total NPP implementation and construction cost: the civil structures (20%), the many safety systems that are inactive during normal operation (8%), and the constant costs for the NPP implementation and construction (30%). The NPP items, the costs of which make up the remaining 42%, however, have a life period of only 40 years. Therefore, the costs of the “new” power plant is limited to 42% of the original plant costs. These costs are normally accounted for in the operation and maintenance costs; this is an indication of the considerable cost reduction achievable by this approach.

## 4. OPERATION AND MAINTENANCE

The operation and maintenance (O&M) costs are not directly related to long-life approach although the improved and additional diagnostic systems envisaged for such reactors should favour a reduced use of resources for the activities related to the maintenance.

The study of the published data shows that the O&M costs are slowly decreasing as a result of a better cost control discipline and a better load factor. However the difference between good and poor performers is still very large so that cost reduction measures are still possible. The O&M costs have also been affected by the replacement of steam generators and problems related to pressure vessel or pressurizer. These costs are also independent from the total energy produced, and the average values are:

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| USA | Price base 1993 | 80 USD/kW |
| France | Price base 1994 | 52 USD/kW |
| Germany | Price base 1994 | 118 USD/kW |

It is very difficult to compare above costs also when considering the differences in labour costs in different countries. The cost for France would correspond to the cost of US plants in the low-cost quartile and the cost in Germany would correspond to the high-cost quartile.

One cost reduction measure in this respect is the reduction of the plant personnel from 350-400 to a target figure of 300 people as in the case of EDF’ with the possibility of operating all units on a site from one single unit.

The other possibility to reduce the O&M cost is to apply more consequentially a maintenance strategy based on the condition monitoring of the equipment.

The costs of the retrofit included in the O&M costs (replacement of components having reached the end of life) is 21 USD/kW. This value is compatible with the considerations given in chapter 3.

For a single unit plant it is difficult to further be able to achieve a cost reduction substantially below the average price of the US. Assuming 7500 h of full power operation, the average cost contribution of the O&M would be 1.07¢US/kWh, a typical value also found in 1996 in many other nuclear power plants.

## 5. FRONT-END FUEL COST

This paper considers the once-through cycle as the most economic option for the fuel cycle. This option foresees the construction of an intermediate storage of the spent fuel on site. No radioactive transport outside the site fence will occur up to disposal. When choosing this option it is recommended to design the spent fuel capacity inside the nuclear island for 40 years of operation. The fuel storage capacity for the remaining 40 years can be attained with the construction on site of a dry expandable vault storage. In this case, the front-end fuel costs are including the cost of uranium, conversion, enrichment and fuel fabrication. No major cost reductions are to be expected in the future in this field, and according to the OECD-AEN study of 1994 with natural uranium cost of 50 USD/kg U, conversion 8 USD/kg U, enrichment 110 USD/SWU and fuel fabrication of 275 USD/kg U, the fuel costs are 0.47¢USD/kWh. However, this study has shown a major cost reduction in comparison with the previous study published in 1985, mainly due to the decreased price of uranium and enrichment services.

Another minor fuel cost reduction will result from the increased burn-up. The considerations presented here are based on a burn-up of 40 MWd/kg. If this value is increased to 60 MWd/kg, then disposal costs are also reduced considerably since the quantity of fuel to be disposed of is reduced by 50%. The use of the 18-months fuel cycle instead of the 12-months fuel cycle is also a valid cost reduction measure.

The cost for interim fuel storage as well as the storage of the conditioned low and medium waste is estimated to be 133 USD/kW

## 6. DECOMMISSIONING

Decommissioning is the activity carried out after the operation life of the plant. The option of dismantling and total removal (green field) is considered. The non-radioactive material will be disposed in backfill cavities and landscape grounds and radioactive material will be disposed to the final active repository. Since all materials are radioactive, the boundary between what is defined as radioactive and non-radioactive is very important.

The cost visibility for this activity is poor due to lack of experience for a large plant dismantling and this is reflected in the available estimations:

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| OECD | 105 up to 370 USD/kW |
| EDF | 270 USD/kW |
| Germany | 510 USD/kW |

It is important to note that with the long-life approach, the cost of decommissioning per kWh produced is reduced by 50% as compared to the standard solution.

Another advantage is the reduction of low and medium activity solid radwaste volume. During plant operation the target conditioned waste volume production is less than 50 m³ per year, i.e. 4,000 m³ per life cycle. The waste volume resulting from the dismantling of a 1,200 MWe plant is estimated to be between 10,000 and 15,000 m³. From the above data it is evident that the total radwaste volume to be disposed of is dictated by the duration of the life cycle.

The dismantling could be done immediately after the end-of-life or deferred, but the difference in cost is estimated to be of only 6% in favour of the deferred option.

It is premature to discuss here the cost reduction measures for the dismantling but technological progresses are possible in the automatic characterisation of the active waste to limit the total radwaste volume or in dismantling technology. For financing of the decommissioning the value of 370 USD/kW is retained.

## 7. DISPOSAL OF THE RADIOACTIVE WASTES (BACK-END FUEL CYCLE)

At the end of the plant life it is required to dispose of 14,000 to 19,000 m³ of low and medium waste and to condition approximately 1'900 tons of spent fuel for the final disposal.

The costs assuming conditioning outside of the nuclear site are:

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| Transportation and interim storage | 230 USD/kg U |
| Conditioning and final storage | 610 USD/kg U |
| Surface waste repository | 1,800 USD/m³ |

The capital requirement for the final disposal of waste produced during the life cycle of 80 years would amount to 1,630 USD/kW.

To reduce the life-cycle cost, the approach to condition the wastes inside the nuclear site and to combine the dismantling with the conditioning of the spent fuel is recommended. In fact, the total scrap steel quantity for a nuclear power plant is estimated to be 34,000 tons for a 1,000 MWe plant, which could be recycled on site to manufacture the containers for final disposal. The preliminary estimations indicate the requirement of 200 thick-wall containers for the conditioning of the spent fuel. A manufacturing facility for containers with a steel melting plant should be provided at the site and can be combined with the decontamination facility. Such a facility is common for all the units on the site and could be operated by the same personnel of the plant. The cost estimation of a similar facility is 450 USD/kW and its costs are shared by three units. The cost of decommissioning already partially include the manpower for the manufacturing of the containers. The estimation of the missing manpower and expenses is adds 80 USD/kW.

Including the portion costs for the surface waste repository (34.2 MUSD), the high-level waste repository (180 MUSD) and the final spent fuel conditioning facility, a capital requirement of 444 USD/kW is obtained.

Adding to this value the constant cost portion (30%) for the research and development of a final repository, the capital requirement is estimated to be 634 USD/kW.

This approach of avoiding any transport of radioactivity outside the NPP until disposal, results in a considerable cost reduction (approximately 70%) in respect to a strategy with transport of fuel, without recycling a huge amount of scrap steel to be disposed of and an uncoordinated approach between dismantling and conditioning of the spent fuel.

## 8. FINANCING OF THE LAST PERIOD OF THE LIFE CYCLE

The capital requirement according to the proposed approach is estimated to be 1,004 USD/kW. Our proposed solution is warranting a considerable reduction in the total investment required and justifies a new financing scheme.

There are several financial approaches all based on the establishment of a fund managed by the utility and the government. Since such expenses will be incurred in 80 years from the start of plant operation and the life cycle of 80 years is technically achievable for reactors complying with the requirements outlined in chapter 1, it is suggested to start with a fund dedicated to the activities related to decommissioning and disposal of radioactive wastes after the termination of the depreciation. The contribution to the fund should correspond to the depreciation value. Since the capital requirement according to the proposed solution is lower - in terms of constant money - than the initial investment, there is a reasonable assurance to collect the necessary money to finance the last phase in less then 30 years, including the uncertainties due to the poor cost visibility. This would leave an operation time of 20 years for the financing of the next nuclear power plant.

At present, the fund established for decommissioning and final disposal is parallel to the depreciation of the plant adding an unnecessary burden to the financial cost of nuclear electricity. The approach suggested here is a sequential financing: first the construction cost and later the financing of the disposal. With this financial approach the cost of nuclear electricity is controlled by the cost of the initial capital, the operation and maintenance, and the front-end fuel costs.

## 9. COST OF NUCLEAR ELECTRICITY

For the sake of simplicity and for a hypothetical new power plant, the capital requirement is estimated to be 2,475 USD/kW, based on the French data, but with an increase of 30% for interest during a six-year construction period based on a 8.5% interest rate, and a minor escalation.

The load factor is also a key parameter in the cost of electricity. The value of 0.86 (7,500 h full power operation) is achievable. With an average discount rate of 8.5% and a depreciable life period of 30 years a capital cost component of 3.07¢USD /kWh is obtained.

Following the above considerations and including O&M costs (1.07 cUSD/kWh) and fuel costs (0.47 cUSD/kWh), the total energy production cost amounts to 4.61¢USD/kWh.

This value is competitive with large new base-load coal-fired power plants, but presumes the adherence to a strategy as outlined above, to assure that the investment required at the end of the life cycle is lower than the one of the initial phase and to justify the long-life approach.

The important challenge is to control the initial capital cost, where the licensing regime penalises the costs more than the licensing criteria, as long as they are known at the beginning of the design phase.

The crucial phase in nuclear power plant project is the first phase when the licensing criteria are incorporated into the design, especially in respect to the mitigation systems for severe accidents or more effective diagnostic systems.

Although this approach commits to additional systems in respect to the US safety requirements, it results in considerable cost-savings when performing the life-cycle cost analysis of a nuclear power plant.

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## 11. KEY WORDS


Nuclear, electricity, costs, life-cycle analysis, economics.