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A comparative study on economic analysis of current designs of NPPs

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1. Introduction

Improved designs of nuclear power reactors are constantly being developed internationally. The cost of nuclear projects has increased over the past years, due to more stringent safety and quality requirements, safer designs, and higher construction costs.

The objectives of this paper are to analyze the economics of current designs of nuclear power plants and to provide an unbiased view of recent nuclear costs. To do this, the current designs of nuclear power plants are reviewed. And the key economic parameters are identified and examined. Some of these parameters are construction cost and operation cost. Finally using these key determinants of nuclear economics, the cost of nuclear power reactors will be analyzed and compared.

2. Current designs of nuclear power reactors

2.1 APR1400

South Korea's Advanced Power Reactor 1400 (APR1400) design is an evolutionary ALWR design with enhanced safety and seismic robustness. Design certification by the Korean Institute of Nuclear Safety was awarded in May 2003. It is 1455 MWe gross in Korean conditions, 1350-1400 MWe net (3983 - nominal 4000 MWt) with two-loop primary circuit.

The APR1400 design is based on the actual experience from the OPR1000 design; thus, configuration of the reactor coolant system (RCS) of the APR1400 is identical to that of the OPR1000. Advanced design features and improvements have been incorporated: a pilot operated safety relief valve(POSRV), a four-train safety injection system with direct vessel injection (DVI), a fluidic device (FD) in the safety injection tank, IRWST, an external reactor vessel cooling system, and an integrated head assembly (IHA).

Fuel has burnable poison and will have up to 55 GWd/t burn-up, refueling cycle is 18 months, outlet temperature 324℃. Projected cost at the end of 2012 was US$ 3327 per kilowatt, with 48-month construction time. Plant life is 60 years, seismic design basis is 0.3g. A low-speed (1800 rpm) turbine is applied.

2.2 AP1000

The Westinghouse AP1000 is a two-loop PWR which has evolved from the smaller AP600, one of the first new reactor designs certified by the US NRC, in 2005. Simplification was a major design objective of the AP1000, in overall safety systems, normal operating systems, the control room, construction techniques, and instrumentation and control systems provide cost savings with improved safety margins. It has a core cooling system including passive residual heat removal by convection, improved containment isolation, passive containment cooling system to the atmosphere and in-vessel retention of core damage (corium) with water cooling around it.

It is quoted as 1200 MWe gross and 1117 MWe net (3400 MWt). Westinghouse earlier claimed a 36 month construction time to fuel loading. The first ones being built in China are on a 51-month timeline to fuel loading, or 57-month schedule to grid connection. But the world's first AP1000 third-generation nuclear power plant being built in Sanmen, Zhejiang province, has fallen behind schedule, and questions are being raised over its safety standards.

2.3 EPR

Areva NP (formerly Framatome ANP) has developed a large (4590 MWt, typically 1750 MWe gross and 1630MWe net) European pressurized water reactor (EPR), which was confirmed in mid 1995 as the new standard design for France and received French design approval in 2004. It is a four-loop design derived from the German Konvoi types with features from the French N4. It will operate flexibly to follow loads, have fuel burn-up of 65 GWd/t and a high thermal efficiency of 37%, and net efficiency of 36%. It is capable of using a full core load of MOX. Availability is expected to be 92% over a 60-year service life.

It has double containment with four separate, redundant active safety systems, and boasts a core catcher under the pressure vessel. The safety systems are physically separated through four ancillary buildings on the same concrete raft, and two of them are aircraft crash protected. The primary diesel generators have fuel for 72 hours, the secondary back-up ones for 24 hours, and tertiary battery back-up lasts 12 hours. It is designed to withstand seismic ground acceleration of 0.3g without safety impairment.

2.4 ABWR

The advanced boiling water reactor (ABWR) is derived from a General Electric design in collaboration with Toshiba. Two examples built by Hitachi and two by Toshiba are in commercial operation in Japan (1315 MWe net).

The ABWR is now offered in slightly different versions by GE-Hitachi and Toshiba. 'ABWR' is basically a 1380 MWe (gross) unit (3926 MWt in Toshiba version), though GE-Hitachi quote 1350-1600 MWe net.

The first four ABWRs were each built in 39-43 months on a single-shift basis. Though GE and Hitachi have subsequently joined up, Toshiba retains some rights over the design, as does TEPCO. The design can run on full-core mixed oxide (MOX) fuel. Design life is 60 years. It has a high level of active safety. Unlike previous BWRs in Japan the external recirculation loop and internal jet pumps are replaced by coolant pumps mounted at the bottom of the reactor pressure vessel. Safety systems are active.

3. Key determinants of nuclear economics

There are several important determinants of the cost of electricity generated by a nuclear power plant.

3.1 Capital cost

Construction costs comprise several things: the bare plant cost (usually identified as engineering-procurement-construction cost), the owner's costs (land, cooling infrastructure, administration and associated buildings, site works, switchyards, project management, licenses, etc.), cost escalation and inflation. Owner's costs may include some transmission infrastructure. Recent studies have shown an increase in the capital cost of building both conventional and nuclear power plants.

The term "overnight capital cost" is often used, meaning EPC plus owners' costs and excluding financing, escalation due to increased material and labor costs, and inflation. Construction cost - sometimes called "all-in cost", adds to overnight cost any escalation and interest during construction and up to the start of construction. It is expressed in the same units as overnight cost and is useful for identifying the total cost of construction and for determining the effects of construction delays. In general the construction costs of nuclear power plants are significantly higher than for coal-fired or gas-fired plants because of the need to use special materials, and to incorporate sophisticated safety features and back-up control equipment. These contribute much of the nuclear generation cost, but once the plant is built the cost variables are minor. The OECD Nuclear Energy Agency’s (NEA) calculation of the overnight cost for a nuclear power plant built in the OECD rose from about US$ 1,900/kWe at the end of the 1990s to US$ 3,850/kWe in 2009.

The NEA figures for the 1990s must be treated with caution as they are not in line with some other data sources. The US Energy Information Administration (EIA) calculated that, in constant 2002 values, the realized real overnight cost of a nuclear power plant built in the USA grew from US$ 1,500/kWe in the early 1960s to US$ 4,000/kWe in the mid-1970s. The EIA cited increased regulatory requirements (including design changes that required plants to be back-fitted with modified equipment), licensing problems, project management problems and mis-estimation of costs and demand as the factors contributing to the increase during the 1970s. Its 2010 report "Updated Capital Cost Estimates for Electricity Generation Plants" gave an estimate for a new nuclear plant of US$ 5,339/kW.

There is also significant variation of capital costs by country, particularly between the emerging industrial economies of East Asia and the mature markets of Europe and North America, which has a variety of explanations, including differential labor costs, more experience in the recent building of reactors, economies of scale from building multiple units and streamlined licensing and project management within large civil engineering projects. With few new orders, the data set for new build costs is lacking. The shift to Generation III reactors has added further uncertainty. Other non-nuclear generation technologies also show variation and as do major infrastructure projects such as roads and bridges, depending upon where they are built. However, the variation is particularly crucial for nuclear as its economics depend so much on minimizing its capital investment cost.

By way of contrast, China has stated that it expects its costs for plants under construction to come in at less than $2000/kW and that subsequent units should be in the range of $1600/kW. This estimate is for the AP1000 design, the same as used by EIA for the USA. This would mean that an AP1000 in the USA would cost about three times as much as the same plant built in China. Different labor rates in the two countries are only part of the explanation. Standardized design, numerous units being built, and increased localization are all significant factors in China.

Financing costs will depend on the rate of interest on debt, the debt-equity ratio, and if it is regulated, how the capital costs are recovered. There must also be an allowance for a rate of return on equity, which is risk capital.

Long construction periods will push up financing costs, and in the past they have done so spectacularly. In Asia construction times have tended to be shorter, for instance the new-generation 1300 MWe Japanese reactors which began operating in 1996 and 1997 were built in a little over four years, and 48 to 54 months is typical projection for plants today.

3.2 Operating costs

Fuel costs have from the outset given nuclear energy an advantage compared with coal, oil and gas-fired plants. Uranium, however, has to be processed, enriched and fabricated into fuel elements, and about half of the cost is due to enrichment and fabrication. In the assessment of the economics of nuclear power allowances must also be made for the management of radioactive used fuel and the ultimate disposal of this used fuel or the wastes separated from it. But even with these included, the total fuel costs of a nuclear power plant in the OECD are typically about a third of those for a coal-fired plant and between a quarter and a fifth of those for a gas combined-cycle plant. The US Nuclear Energy Institute suggests that for a coal-fired plant 78% of the cost is the fuel, for a gas-fired plant the figure is 89%, and for nuclear the uranium is about 14%, or double that to include all front end costs.

In June 2013, the approx. US $ cost to get 1 kg of uranium as UO_2 reactor fuel (at current spot uranium price):

Uranium	**8.9kg U_3O_4x$130**	**US$ 1160**
Conversion	7.5kg U x $11	US$ 83
Enrichment	7.3 SWU x $120	US$ 880
Fuel fabrication	Per kg	US$ 240
Total, approx.		US$ 2360

At 45,000 MWd/t burn-up this gives 360,000 kWh electrical per kg, hence fuel cost**: 0.66 c/kWh**.

Fuel costs are one area of steadily increasing efficiency and cost reduction. For instance, in Spain the nuclear electricity cost was reduced by 29% over 1995-2001. This involved boosting enrichment levels and burn-up to achieve 40% fuel cost reduction. Prospectively, a further 8% increase in burn-up will give another 5% reduction in fuel cost.

Uranium has the advantage of being a highly concentrated source of energy which is easily and cheaply transportable. The quantities needed are very much less than for coal or oil. One kilogram of natural uranium will yield about 20,000 times as much energy as the same amount of coal. It is therefore intrinsically a very portable and tradable commodity.

The contribution of fuel to the overall cost of the electricity produced is relatively small, so even a large fuel price escalation will have relatively little effect. Uranium is abundant and widely available.

There are other possible savings. For example, if used fuel is reprocessed and the recovered plutonium and uranium is used in mixed oxide (MOX) fuel, more energy can be extracted. The costs of achieving this are large, but are offset by MOX fuel not needing enrichment and particularly by the smaller amount of high-level wastes produced at the end. Seven UO2 fuel assemblies give rise to one MOX assembly plus some vitrified high-level waste, resulting in only about 35% of the volume, mass and cost of disposal.

Operating costs include operating and maintenance (O&M) plus fuel. Fuel cost figures include used fuel management and final waste disposal. These costs, while usually external for other technologies, are internal for nuclear power (i.e. they have to be paid or set aside securely by the utility generating the power, and the cost passed on to the customer in the actual tariff).

This 'back end' of the fuel cycle, including used fuel storage or disposal in a waste repository, contributes up to 10% of the overall costs per kWh – rather less if there is direct disposal of used fuel rather than reprocessing. The $26 billion US used fuel program is funded by a 0.1 cent/kWh levy.

Decommissioning costs are about 9-15% of the initial capital cost of a nuclear power plant. But when discounted, they contribute only a few percent to the investment cost and even less to the generation cost. In the USA they account for 0.1-0.2 cent/kWh, which is no more than 5% of the cost of the electricity produced.

4. Costs of current NPP designs

4.1 Capital costs

The unit of the capital cost is US$/kWe.

	APR1400	AP1000	EPR1600	ABWR
OECD-NEA (2010) [3]	3,085	2,302 ~ 3,382	3,860 ~ 5,383	3,009
WNA (2011) [4]	3,643	4,363 ~ 6,360	3,400	2,900
Vender data	3,321	2,900 ~ 5,000	2,340 ~ 5,150	4,408

The vender data in the table are from international conferences and press release data.

The capital cost of these nuclear reactors is between 3,000US$/kW to 5,000US$/kW. The capital cost of the reactors built in USA is about 5,000US$/kW. It is higher than the cost of reactors constructed in other countries. These are because the labor costs and material costs in USA are high compared to the developing countries. The capital cost in China and East European countries is relatively low. In case of EPR1600 in Taisan China, the capital cost is 2,340US$/kW.

4.2 LCOE

The unit of LCOE is US$/MWh.

	APR1400	AP1000	EPR1600	ABWR
Fuel Cycle	8.25	9.33	9.33	9.33
O&M	8.39	9.28 ~ 12.89	9.28 ~ 16.00	16.50
LCOE [3]	61.13	54.61 ~ 77.39	54.61 ~ 92.38	76.46

The levelized costs of electricity (LCOE) of these nuclear reactors is between 55US$/kWh to 90US$/kWh. The LCOE of EPR1600 and AP1000 in developed countries is about 80~90US$/MWh. But in China, the LCOE of EPR1600 and AP1000 is lowest to 50US$/MWh.

5. Conclusion

The scope of the paper is a short summary of the economics of current major designs of nuclear power reactors. The cost of NPPs is deeply linked with each country’s economic development. Selecting state of the nuclear technology implies to be paced with higher costs, that can be offset through different parameters; some being intrinsically linked to a country (labor cost, capacity to manufacture components,…), others depending on the project itself (number of units, …).

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