Chapter 12
Plant Economics and Project Schedule

Introduction

A nuclear power plant makes an ideal baseload generator because its cost of electricity (COE) is mostly fixed. Of the total cost of electricity produced by an advanced nuclear plant, the capital costs are about 70%, O&M costs are 15% and fuel costs are also about 15%. The experience of recent years is that O&M costs are essentially fixed. Moreover, nuclear fuel costs have been remarkably stable over time and, in fact, have declined in real terms (after inflation is subtracted.) Thus, approximately 85% of the COE of a nuclear plant is fixed for the lifetime of the plant. Contrast this with a combined cycle plant for which the COE depends heavily on prices of natural gas (Table 12-1).

	Nuclear	Natural Gas
Fixed Costs	85%	20%
Variable Costs	15%	80%
Fuel Costs	stable	volatile

Table 12-1. Fixed and Variable Costs

A stable, low cost source of electricity is important to countries with growing economies. It supports economic growth and it makes the cost of products produced for export more competitive in world markets. Moreover, for countries which import large amounts of fossil fuels, the use of nuclear energy decreases vulnerability to changes in the supply and price of oil and gas.

During the development of the ABWR, a good deal of emphasis was placed on ensuring that it would be economically competitive. Table 12-2 provides a comparison between key economic parameters of the ABWR and those of existing U.S. BWRs.

Capital Costs

The capital cost of any nuclear plant depends upon a number of key variables. For example, the cost of

	ABWR	U.S. BWRs	
		Average	Best of Class
Capital Costs, $/kW	1600	3000 to 5000	2000
Construction schedule, years	4	10-15	5
Capacity Factor, %	90	80	90
Production costs*, c/kWhr	1.10	2.0	1.5
Outage length, days	25	50	< 30
Staffing, people per unit	375	800-1000	500

* O&M and fuel costs

Table 12-2. Economic Comparison

labor, equipment, and commodities in the host country—and the amount of local content—are important determinants of overall costs. So, too, are financing costs and escalation rates, which vary not only from country to country but depend upon how the project itself is structured.

To understand a cost estimate, therefore, it is important to know what assumptions have been made (as opposed to a firm price quotation in which all costs are known). Table 12-3 contains the following key assumptions:

Host Country:	*United States*
ABWR Design:	*Design Certified or U.S. version*
No. of units:	*Single, stand-alone unit on existing site*
Rating:	*1350 MWe net*
Costs:	*U.S. labor rates and productivity figures* *U.S. material and equipment costs (expressed in 1998 dollars)*
Not included:	*Owner's cost, escalation and financing costs*

This last set of assumptions, namely, what is not included, is in keeping with industry practice. In particular, because financing and escalation are so project dependent, the industry prefers to report capital costs in so-called "overnight costs"; that is, as if the plant could be built instantaneously. Potential owners of an ABWR use the overnight cost to determine the as-constructed cost by applying escalation and financing costs appropriate for their situation.

There are two more assumptions that are of particular importance for the ABWR— engineering costs and contingency:

Design engineering costs:	$0
Owner's costs:	10%
Contingency costs:	8%

As a result of the ABWR projects in Japan and Taiwan and the First-of-a-Kind Engineering (FOAKE) program sponsored by U.S. utilities and the U.S. Department of Energy, the ABWR design is fully engineered. This represents a significant accomplishment that has immediate benefit for new ABWR projects. There are no engineering or development costs that must recovered (only site engineering is required) and none have been included in this estimate. In addition, the labor man-hours, material quantities and equipment specifications are known in exacting detail.

At the conceptual design stage, the contingency is normally 20% to 25%. Most of this contingency is associated with the uncertainty in the basic design at this stage of its development. Later, the design concept is frozen, the engineering is completed in detail and, when a project commences, equipment and construction drawings are prepared to procure hardware. At this point, the contingency reflects mostly the uncertainty in financial considerations such as escalation and exchange rate.

As the direct result of the experience with two projects, the contingency costs associated with the ABWR are minimal.

GE has developed an extensive computerized cost database which includes over a half million entries for plant quantitative data and another half million entries for plant cost data. This database is derived from the POWRTRAK system, which is used for both the FOAKE and Lungmen detailed designs. The quantitative database includes detailed design data from the POWRTRAK 3D model, as well as data from P&IDs, control system schematics, electrical system wiring diagrams, etc. contained in the POWRTRAK system. The cost database includes cost data obtained from competitive pricing quotations for K-6&7, FOAKE, and Lungmen. The GE cost estimating database for the ABWR is the most extensive and up-to-date cost estimating database ever compiled for a nuclear plant design prior to start of construction. The capital cost of the ABWR is given in Table 12-3.

ABWR NUCLEAR PLANT COST BREAKDOWN

Average capital cost of next two ABWR units if built in the U.S.

EEDB* Account	Direct Costs	
21	Structures & Improvements	430 $MM
22	Reactor Plant	520
23	Turbine Plant	230
24	Electrical Plant	150
25	Miscellaneous Plant	45
26	Main Heat Rejection System	**45**
	Total Direct Costs	*1420 $MM*
	Indirect Costs	
91	Construction Services	250 $MM
92	Engineering Home Office	70
93	Field Office Services	**190**
	Total Indirect Costs	*510 $MM*
Total Direct and Indirect Costs		1930 $MM
Contingency		125
Owner's Costs		200
Total Overnight Capital Cost		**2255 $MM**
Total Capital Cost in $/kW		*$1611 $/kW*

**Engineering Economic Database Code of Accounts*

Table 12-3. ABWR Capital Cost Summary

Achieving a Competitive Capital Cost

The design of a nuclear power plant is a key factor in determining its capital cost. Design simplification, in particular, pays large dividends. The design effort, however, is certainly not the only source of cost reductions and maybe not even the most important. Managing capital costs is an on-going effort that spans the entire life of the design and construction of a plant. Table 12-4 summarizes all of the opportunities for reducing the capital costs.

Several of these items will be discussed.

Design Features

Design simplification and the use on new technology has reduced the amount of equipment and construction quantities in the ABWR compared to the previous generation of BWRs. For example, the ABWR uses reactor internal pumps (RIPs) mounted directly to the reactor vessel to recirculate core flow. Pump speed is controlled by adjustable speed motors or drives (ASDs).

Use of RIPs and ASDs eliminates the large external recirculation loops found in previous BWRs. This has many cost benefits. The large recirculation pumps, flow control valves, jet pumps, piping and pipe supports have all been eliminated. Also, the containment and Reactor Building are more compact, thereby reducing the amount of material quantities need to construct them. Finally, because there are now no large nozzles below the top of the core, the safety systems can keep the core covered with water with less capacity. For example, the low pressure systems

Opportunities to Reduce Costs	Sources of ABWR Cost Reductions
Design features	Simplification, compact buildings, less equipment and quantities
Complete engineering before start of construction	FOAKE, Kashiwazaki, and Lungmen engineering
Shorter, predictable schedule	Construction experience, advanced information management system (IMS)
Institutional changes	One-step licensing
Construction techniques	Modularization, productivity, lessons learned
Learning curve	Transfer experience from projects
Standardization	Complete project engineering, advanced IMS
Global sourcing	Competitive equipment and component costs

Table 12-4. ABWR Capital Cost Reductions

of the ABWR have a flow capability of 19,000 gallons per minute compared to 29,000 gpm for BWR/5 and BWR/6, a 35% reduction. This is an example of improving safety and reducing costs.

The design of the control rod systems has also been simplified. Fifty percent of the hydraulic control units (HCUs) in the control rod drive systems have been eliminated. Because the new Fine Motion Control Rod Drives (FMCRDs) discharge water directly into the reactor during a scram, the scram discharge volume and the accompanying piping have also been eliminated.

The use of new technology further reduces the amount of plant equipment and construction quantities. The use of fiber optic networks, which carry substantially more information, instead of copper cabling, has eliminated 1.3 million feet of cabling and 135,000 cubic feet of cable trays. Use of microprocessors and solid-state devices in the control networks has reduced the number of safety system cabinets in the control room from 17 to only 3.

The ABWR containment is a Reinforced Concrete Containment Vessel (RCCV). This technology was first introduced in a limited number in Mark III containments. The advantage of re-introducing this technology is that the containment can be made more compact, especially in comparison with the free-standing steel version of the Mark III design. The ABWR containment volume is over 50% less compared to that design.

Shorter, Predictable Construction Schedule

Use of the RCCV has another important advantage – it reduces the construction schedule. Use of this containment and modular construction techniques reduces the overall construction schedule by an impressive seven months.

In constructing steel containments, the containment vessel is completed first, then the outer biological shield is erected, and, finally, the Reactor Building is constructed. For the RCCV, however, the construction of the containment vessel can take place concurrently with the construction of the floors and walls of the Reactor Building so that the entire construction schedule of the whole plant can be shortened. Also, RCCVs can be built in any shape. In the case of the ABWR, this is generally a right circular cylinder, which was chosen because it is easier to construct.

The use of fiber optic cabling also reduces the construction schedule, in this case by one month, simply because there is less cable to install.

It is perhaps not generally appreciated that the ABWR has been designed for extensive use of modular construction, in particular large modules. The entire control room (400 tons), the steel lining of the containment, the reactor pedestal, the turbine generator pedestal, and the upper drywell structure with piping and valves are notable examples.

Several studies have shown that the length of the construction period does not materially affect capital costs, provided the schedule is met. It is when construction takes longer than expected that capital costs, namely interests costs, become significantly higher. In other words, spreading the costs over a 5-year instead of a 4-year period does not incur substantially more interests costs if properly managed. Falling behind on the schedule, however, will cause interest costs to soar. Utilities appreciate this too, since it means they will have the electricity when expected and won't have to use, or purchase, expensive replacement energy.

This harsh economic reality means that construction schedules must be predictable. GE has teamed with Black & Veatch (B&V), a leading engineering company and power generation project developer, to develop an exceptional information management tool that will do much to ensure predictable schedules. For its fossil fuel plants, Black & Veatch has developed an information management system called POWRTRAK. With the aid of POWRTRAK, B&V has built plants in several months less time than the industry average. Capital costs are also correspondingly less than the industry average and B&V's plants operate at higher capacity factors as well, a testimony to the quality of the construction. GE and Black & Veatch are adapting POWRTRAK for nuclear applications.

Experience

There is no substitute for experience. The Lungmen ABWRs are being supplied by a team of worldwide suppliers, led by GE, that were also involved in the supply of the Japanese ABWRs. This team and the supporting network of equipment sub-suppliers is accustomed to working on an international stage and can readily transplant its experience and know-how to a new host country. This is the basis for the "learning curve" effect, which reduces capital costs by about 10% with each new unit.

Global Sourcing

One of the most important tasks in the delivery of a nuclear plant is the establishment of a dependable, cost competitive source of suppliers. This is by no means an easy task and, once established, this network is an extremely valuable asset for future projects. ABWR projects are supported by a worldwide network of suppliers. Those with the larger scopes are listed Table 12-5 but represent only the tip of the iceberg. GE and its sub-suppliers work closely together to deliver a cost effective, high quality product, using such collaborative tools as Six Sigma used throughout the General Electric Company.

Hitachi	Japan
Toshiba	Japan
Foxboro	U.S.
Weir	Scotland
KSB	Germany
Seimens	Germany
Atwood & M.	U.S.
Target Rock	U.S.
STN Atlas	Germany
Local supply	Taiwan

Table 12-5. Key Lungmen Sub-Suppliers

Production Costs

Once the plant is built, capital costs are basically sunk costs; there are, however, the occasional costs of capital addition that occur during the life of the plant. The on-going costs of producing nuclear electricity are the fuel cycle costs and the costs of plant operation and maintenance (O&M), the sum of which are referred to as the production costs. In theory, production costs are variable with the amount of electricity produced. For a base-loaded nuclear plant, however, the reality is that, in *total dollars*, O&M costs are largely independent of how much electricity is actually generated in given operating cycle.

The ABWR production cost is about 1.10 cents per kWhr, which would place it in the best-of-class category for U.S. operating BWR plants.

A typical figure for the ABWR fuel cycle cost is about 0.45 to 0.50 cents per kWhr. As such, it represents only about 15% of the total cost of electricity (COE). The overall nuclear electricity cost then is not sensitive to changes in fuel prices. For example, if the cost of uranium were to *double*, the total COE would only increase by 3%.

The ABWR is designed to use the same standard bundle designs that are used in the rest of the worldwide BWR fleet. For this reason, the fuel cycle costs for the ABWR are substantially similar to other BWR types, although the higher power density, the larger water gap and the enhanced spectral shift capability tend to make these costs slightly lower.

A bottoms-up estimate of the O&M cost is 0.65 cents per kWhr. In the 1990's, the nuclear industry made a concerted effort to contain and then reduce O&M costs, which had risen to a level high enough to threaten the economic viability of operating plants. Many good practices came out of that effort, which demonstrated that capable plant management — people with know-how and skill — are the key to low O&M costs. A nuclear plant designed for ease of maintenance can help but not replace this essential element.

Ease of Maintenance

The ABWR is designed for ease of maintenance. The ABWR design benefitted in this respect by the direct involvement of TEPCO during the development stages. TEPCO not only emphasized the importance of designing the ABWR to accommodate maintenance activities, but its engineers brought their personal experiences to bear on the design.

For example, inside the containment, equipment at all levels is accessible by stairs and platforms which encircle the vessel. Monorails are available to remove the equipment, such as a main steam isolation valve, to a conveniently located service room via an equipment hatch. Removal of the RIPs and FMCRDs has been automated. Handling devices, which in the case of the FMCRD are operated remotely from outside the containment, engage and remove the equipment. The pump or drive is laid on a transport device and removed through the equipment hatch. Just outside the hatch are dedicated service rooms, one for the RIPs and another for the FMCRDs, where the equipment can be decontaminated and serviced in a shielded environment. The entire operation is done efficiently and with virtually no radiation exposure to the personnel.

Staffing

The estimated staffing level for an ABWR unit is 375 people, or about 0.3 people per MWe. This is an achievable target and indeed many operating plants have reached this level already. Some reasons why the ABWR design will have less staffing needs are presented in Table 12-6.

Maintenance staff

- Less maintenance requirements
- Maintenance made easier
- Shorter outage lengths
- Fewer major repairs

Technical support staff

- Standardized, pre-licensed design
- Electronic Configuration Management (POWRTRAK)
- Standardized training, operator and maintenance procedures

Operating staff

- Self-diagnosing C&I systems
- Plant automation
- Fewer technical specifications

Table 12-6. Reducing Staffing Levels

Capacity Factor

The ABWR can operate with a cycle length up to 24 months. ABWR design improvements and current operating experience indicate that the ABWR should experience no unplanned scrams or other types of forced outages. The capacity factor, in this case, will be determined primarily by the length of the refueling outage. The top quartile of operating BWRs routinely run for 24 months with no scrams and refuel in less than 30 days, in some cases as low as 20 days. The Olkiluoto BWRs located in Finland and operated by Teollisuuden Voima Oy have consistently performed refueling outages in 10 days or less and have achieved a lifetime capacity factor of over 90%.

The expected capacity factor for the ABWR is 90% based upon an outage length of 25 days on a 24-month operating cycle.

The design of the ABWR lends itself to these short outages. The ABWR has three redundant divisions of safety systems, complete with high and low pressure pumps and a dedicated diesel generator, and four divisions of protection systems. By taking advantage of this and the ample fuel margins, the ABWR's operating technical specifications will permit on-line maintenance. This has two important results. First, there will be more preventative maintenance programs, which keep major refurbishments off the critical path of the refueling outage. Secondly, it permits utilities to shuffle fuel. Currently in the U.S., the entire core is off loaded because all of the safety systems are out of service for inspection and maintenance. However, by performing this activity while the plant is operating, one safety system can be kept in service during the refueling outage.

Total Cost of Electricity

The total cost of electricity (COE) is the sum of the capital, fuel and O&M costs. At a 90% capacity factor, the ABWR COE is expected to be about 3.7 cents per kWhr (1998 dollars), as summarized below:

Capital	2.57
Fuel	0.46
O&M	0.65
COE	3.68 cents/kWhr

Project Schedule

The ABWR project schedule consists of a 48-54 month construction schedule, as measured from when first structural concrete is poured to commercial operation. This is preceded by a two-year period during which the plant is licensed and the site is prepared for construction, including about a three-month excavation period.

Figure 12-1. Kashiwazaki ABWR Under Construction

The Kashiwazaki units were built in record time for a nuclear power plant (part of the reason was the extensive use of large construction modules, as shown in Figure 12-1). From first concrete to fuel loading, construction of the plant took only 36.5 months, all the more impressive because these were first-of-a-kind units. The overall construction schedule was 48 months. The Lungmen units are being built on a more contracted basis in accordance with the owner's plans.

This experience can be duplicated elsewhere, especially since several ABWRs now have been licensed and constructed and the necessary licensing, manufacturing and construction documents are available. However, since each project has its own unique conditions and issues, it may be more prudent to assume a 54-month construction schedule for purposes of conservatism.

The project schedule, with its key milestones, is given in Table 12-7.

Milestone	Months from Authorization to Proceed	Months from First Structural Concrete
1. Issue Tender	-15	-
2. Bidders Prepare and Submit Bids	-9	-
3. Owner Evaluate Bids and Award Contract	-1	-
4. Owner Issue Authorization to Proceed (ATP)	0	-
5. Start Eng. and Licensing Documents	0	-
6. Place Order for RPV	4	-
7. Site Clearing and Grading	6	-
8. Owner Complete and Submit PSAR	12	-
9. Start Excavation	12	-
10. Continue Eng. and Receive Construction Permit (CP)	24	-
11. First Structural Concrete (FSC)	24	0
12. Start Equipment, Piping and Others	33	11
13. Deliver RPV	50	26
14. Civil work Required to Support RPV Set	51	27
15. Start RPV Set	51	27
16. Pre-Operation Testing	56	32
17. Complete and Submit FSAR	58	34
18. Primary Hydrotest RPV	60	36
19. Main Control Room Ready	62	38
20. Receive Operating License (OL)	70	46
21. Fuel Loading (FLD)	70	46
22. First Turbine Roll	71	47
23. First Synchronization	72	48
24. Commercial Operation (CO) and Plant Turnover	78	54

Table 12-7. Project Schedule