THE JAMES A. BAKER III
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NEW ENERGY TECHNOLOGIES:

A POLICY FRAMEWORK FOR MICRO-NUCLEAR TECHNOLOGY

ECONOMIC AND MARKET POTENTIAL OF SMALL INNOVATIVE REACTORS

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Introduction

Present projections make it clear that a large global increase in the market for electric generating plants is ahead. What isn't clear is the degree to which nuclear power will serve this market, particularly for developing countries where the growth projections are relatively high and the limited electric grids call for small unit power output plants. As a recent report(1) on long term nuclear energy supply R&D by the DOE Nuclear Energy Research Advisory Committee (NERAC) succinctly put it: "How much of a contribution nuclear power can make in the future depends on the economic competitiveness of new plants."

The economic driving forces that led to the rapid expansion of orders for large nuclear power plants in the 1970s have changed radically. The lessons learned from these changes can help to assess the economic and market potential of small innovative reactors in future markets where the driving forces are very different. Such an assessment suggests that much broader and diverse economic criteria should be considered than in the past, particularly for small reactors.

Historical Driving Forces in Nuclear Power Economics

Three primary economic driving forces were dominant in the 1960s and early 70s when commercial commitments caused the surge of construction of nuclear power plants, leading to most of the present nuclear generation capacity.

- The market for new electric generating capacity was strong with forecasts of a continuing growth in demand at a 7% annual rate, or a doubling in capacity requirements per decade.

- The primary competitive driving force in this market was to achieve the lowest total bus-bar cost per unit of nuclear power electricity output as compared to alternative base-load generation. Many factors were favorable to nuclear power in this quest:

- ✓ Investment risk was minimal under rate regulation.
- ✓ Size of investment was not a deterrent; large investments were advantageous to the regulated utility since regulators provided, through the ratepayers, a reasonable rate of return on the utility investment.
- ✓ Production costs from nuclear plants were lower than all alternatives except hydro.
- ✓ Nuclear fuel promised greater price stability than fossil fuel.
- ✓ Peaking generation, i.e., low capital cost/high fuel cost generators such as gas turbines, were not seriously considered as an alternative for base load applications.
- ✓ All externalities were not included in the power cost, e.g., there were no charges for the disposition of spent fuel, no advance provision for decommissioning costs, and incomplete provision for severe accident mitigation.

- ➢ The primary means of reducing nuclear electric generator bus bar cost was to achieve economy of scale in systems, components, and structures through higher unit power output. The early commercial nuclear plants had a modest competitive cost advantage at their 600 Mwe unit size but no advantage at <500 Mwe. The competition led to market offerings at unit sizes of 1000 Mwe and larger. This move was facilitated by the following favorable conditions:
  - ✓ Demand growth was strong and steady, indicating little uncertainty in long-term demand forecasts.
  - ✓ Inflationary trends were modest and there was a dependable supply chain of equipment and construction materials, suggesting long term price stability.
  - ✓ Public acceptance of nuclear power was comparatively favorable, paving the way to timely completion of large nuclear plants with multiyear construction schedules.

Economies were also achieved beyond that of the systems, components, and structures. Reductions in costs per unit output were realized in site qualification and acceptance costs and time, reactor licensing costs and time, operational staff size, and management overheads.

The move to higher unit power output caused a loss of the small and medium generator plant market in the 600 MWe range and below. Smaller utilities generally did not opt for the large nuclear plants because they occupied too great a percentage of their grid capacity. Although the market for units of 600 MWe or less was substantial, its loss was tolerable to reactor suppliers because the surge of large plant orders was taxing their engineering and manufacturing capacity.

A driving force that affected economic evaluations indirectly was the quest for a greater level of energy independence, a strong influence in countries with limited indigenous fossil fuel resources. In effect, a premium in price was afforded nuclear power because the logistics of purchasing, transporting and storing nuclear fuel were much less demanding compared to those entailing the immense quantities of fossil fuel.

The Change in Today's Economic Driving Forces

The trend toward rate-deregulation of the generation market is removing many of the earlier advantages of capital-intensive nuclear generation units: The large investment is no longer protected by the regulator's assurance that an appropriate rate of return on the investment will be provided by the ratepayers. All externality costs have now been essentially included in nuclear power generation causing significant increases in cost. Yet, costs have not been fully internalized in fossil-fueled power generation. Although air pollution and greenhouse gas emissions from fossil-fueled plants have not been internalized, the issue has increased the uncertainty regarding the long-term profitability of new coal capacity.

The uncertainties in long-term projection of power demand for plants of large unit power outputs have proved to be substantially greater than anticipated. A sudden large increase in oil costs was precipitated by OPEC cartel actions and the Iran revolution in the 70s, causing a radical drop in electricity demand growth (from the traditional 7% per year to less than 2%). A more recent example is the supply crisis presently being experienced in California because of unanticipated strong demand growth, and sharp gas price rises coupled with inadequate in-state electricity generation capacity.

The strong focus on rapid return on investment, particularly in this age of the Internet entrepreneur, has militated against the longer time it takes to achieve the return on a large nuclear plant investment.

Many of the anticipated benefits of nuclear plant investment did not eventuate, even under the regulated market, as the construction of the large plants was carried to completion in the 1980s. Some key reasons for this were:

- The OPEC/Iran actions caused fossil fuel prices to rise so sharply that the utilities were allowed to pass on automatically to the rate-payer the incremental fuel costs of their fossil fueled generators, diminishing the stable nuclear fuel cost advantage. The sharp increases in fossil fuel prices in turn caused a reduction in demand, removing the need for the new capacity under construction. That excess capacity was reduced, but not fully removed, by plant cancellations and construction postponements, many of which were for nuclear plants. As a result, prudency disallowances on the utilities' investments in new plants forced a substantial write off to the disadvantage of their stockholders.

- The Three Mile Island accident caused a sharp drop in availability/capacity factor for the operational nuclear power plants.

- Major additional capital investments were required for post-TMI safety improvements in both operating plants and those under construction.

Significant difficulties arose in completing the large plants in the 1980s in addition to the regulatory changes that had to be implemented: Inflation increased to a two-digit level, causing major unanticipated increases in construction cost. Slowdowns in the pace of construction were initiated because of the reduction in electricity demand and this led to inefficient construction management and higher interest charges during construction.

With longer-term operation, corrosion degradation of materials, component/system malfunctions, and inadequate operational training were revealed, reducing revenue below expectations.

Other factors arose. The Three Mile Island and Chernobyl accidents and concern over delays in the disposition of nuclear waste increased public opposition to nuclear plants. This led to intervener obstruction and litigation delays and costs. Natural gas-fired generation became a direct competitor to nuclear power in the base load generation market because of the unusually low prices of natural gas combined with low capital cost and rapid construction time.

Even the quest for energy independence was quelled. The price setting strength of OPEC declined, more optimistic prospects for a cooperative global economy grew, and it was demonstrated that decisive action could be taken to forestall a sudden threat to Mid-East oil supplies such as was mounted by Iraq.

Positive changes also occurred. Investment is now avidly sought in the rate-deregulated market for old nuclear plants where the so-called “stranded asset” has been written off and amortization costs are low. The capacity factors of the existing U.S. nuclear plant fleet have increased to historically high levels and on the average their production costs presently beat the economic competition from all fossil fired units.

In addition, the regulatory framework has been improved by the U.S. Nuclear Regulatory Commission (NRC) in two important respects: first, a standardization policy was adopted that provides the opportunity to seek a site-independent design certification and a separate early site permit. Contingent on meeting compliance conditions, a nuclear power plant operator can apply for a combined construction and operating permit before the major investment is made in plant equipment and construction. Secondly, a risk informed, performance based approach is being put in place and the subjective oversight of plant safety performance has been changed to utilize objective performance criteria for such oversight. These improvements are providing a more effective and stable regulatory process.

The Net Outcome Among the Economic Driving Forces

In summation, the advantages of large unit output nuclear plants as perceived in the 60s and 70s have diminished. Two strong cards still remaining are economy of scale and stable competitive fuel cost, two substantial advantages. But these do not presently make a good enough economic case for private investment in new nuclear plants in a rate-deregulated market while natural gas prices are low.

A summary of the present economic competitive position of nuclear plants as compared to the alternative electricity generators in the de-regulated market is shown in Tables A-1 through A-3 in the Appendix, derived from Electric Power Research Institute (EPRI) data[(2)]. A single source has been chosen to assure a common basis for purposes of comparison.

The cost picture of the existing U.S. nuclear and fossil electricity generating plants is shown in Table A-1. The nuclear generators are all large plants in the range of 500 to 1300 Mwe. The power production costs, (i.e., operating, maintenance, and fuel costs but not the amortization costs on the investment) of the nuclear plants are presently lower than coal, gas, and oil, confirming the positive change cited above. Only large hydroelectric generators have lower production costs. Renewables, except for hydro, are presently operating with substantial subsidies, and their cost projections are covered later. It is only recently that nuclear plant production costs have shown a small advantage over coal. This present market advantage for nuclear exists because the capital investments in most existing nuclear plants have for the most part been written off as part of the move to de-regulation. That advantage would leap if all the externalities of coal were internalized in their costs, as is now the case for nuclear.

On the other hand, since the investment in a new large conventional nuclear plant cannot be written off, its relative economic advantage disappears because of its high amortization cost. That picture is portrayed in Table A-2, which compares the capital costs of new conventional nuclear, coal, and gas-fired plants, and in Table A-3 a variety of renewables, all for plant start-up dates between 2010 and 2020. It is seen that gas-fired plants at $400/Kwe and wind-powered plants at $800/Kwe have a substantial advantage in capital cost as compared to coal at $1,000/Kwe, nuclear at $1480/kWe, and renewables ranging from $1,400/Kwe to $2,550/Kwe.

Table A-3 combines the amortization costs on the capital investment with the production costs to give a total cost of electricity for these generator types. It is seen that gas-fired plants are projected to maintain their economic advantage on the assumption that gas prices will follow normal escalation trends. (When these estimates were made, the sudden price rises in gas that have particularly afflicted California had not occurred.) The cost of electricity from gas-fired plants continues to be the market benchmark that all the alternative generators are striving to meet. That will be the case until it is clear that an above normal escalation of gas prices has set in for the long term, a price trend which history has shown to happen sooner or later. Coal and wind plants are the closest competitors but neither has been fully internalized: for coal, environmental impact and for wind, the need for back-up power because of its intermittence. Nuclear power has a significant gap to make up and the other renewables even more so.

A final word needs to be said on the uncertainties inherent in these estimates. EPRI(2) has also estimated uncertainty ranges for the total cost of electricity from gas, coal, nuclear, and wind plants in the projected year 2020. Gas costs range from 2.1 to 4.3 cents/Kwh; coal from 2.2 to 4.0 cents/Kwh and nuclear from 3.1 to 5.2 cents/Kwh. It can be seen that the uncertainty bands of each are substantial and overlap each other. If externality costs were included in the gas and coal cases, the top of their bands would increase to 5.3

cents/Kwh and 6.0 cents/Kwh, respectively, raising their mid-point cost estimates considerably. Such an uncertainty analysis highlights the importance of energy portfolio planning and having available a diverse set of electricity sources.

The cost data in Table A-1 make it clear that the present nuclear operating plants have benefited from rate de-regulation, but that the higher capital cost of new nuclear plants is now a major barrier to market entry. The entire investment evaluation process has also changed in the rate-deregulated market. Not only the rate but also the rapidity of return on investment is important. The investment risk is more heavily weighted, including adequacy of demand forecasts, stability of safety and environmental regulation, ability of a plant to achieve profitable capacity factors, competitive production costs, and minimal re-fueling and forced outage times. Consideration is also given to potential value added features such as emissions trading.

The Advanced Light Water Reactor (ALWR) Program(3) made substantial progress in reducing capital costs, even while adding costly features to improve safety and reliability. ALWRs with passive emergency core cooling features were developed to counter the economy of scale so as to make them economically competitive at 600 MWe. Significant reductions in construction time and capital costs were gained from the simplifications resulting from substitution of natural emergency cooling processes for the conventional powered emergency cooling systems.

Yet, the progress is not enough to compete economically with gas-fired generation at low natural gas prices. Therefore, effort is continuing on all ALWR designs to identify further capital cost reductions. Substantial interest has also arisen in innovative nuclear reactors of small unit power output as an alternative. The question then becomes: what are the prospects for countering economy of scale and achieving economic competitiveness of small reactors in an economic environment giving more weight to lower capital costs?

The Potential Cost Competitiveness of Innovative Small Plants

There is currently a paucity of quantitative economic data on small commercial nuclear power plants in the 50 to 150 Mwe range. Development of small units for special functions such as ship propulsion, research reactors, and experimental reactors of water-cooled and gas-cooled types established the technical feasibility of such systems but did not show sufficient economic promise for electric generation applications.

The International Atomic Energy Agency has for many decades fostered the development of small plants for commercial service in developing countries to fulfill the technology transfer obligations of the Non-Proliferation Treaty. But these efforts were unsuccessful in making up for the loss of economy of scale achieved on larger plants and thus could not penetrate the market. There is a renewed worldwide interest[(4),(5)] in small, modular plants but the detailed design, engineering, demonstrations, and licensing have not yet reached the point that dependable quantitative economic estimates can be made.

Small modular light water and liquid metal cooled nuclear power plants are being developed through DOE's Nuclear Energy Research Initiative (NERI). A light water cooled version, the International Reactor and Secure Nuclear Power System (IRIS)[(6)] seeks its capital cost reduction through an integral nuclear steam supply system design incorporating the steam generators within the reactor vessel. The integrated design is a further advance on the integrated concept for LWRs pursued in earlier R&D on small reactors. Lower production costs are projected from ultra long-lived fuel (8 to 10 years between refueling).

Two small modular high temperature helium-cooled nuclear plants are also under development, the Pebble Bed Modular Reactor (PBMR)[(7)] and the Modular Gas Reactor (MGR)[(8)] The South African utility ESKOM has taken the lead in developing the PBMR and is being financially supported by both Westinghouse/BNFL and the U.S. utility Exelon. The MGR is under joint development by General Atomics and Russia's Minatom, with support by Framatome.

The technical characteristics of these two small reactor systems are covered in some detail in other papers provided for this forum. So this paper will only cite the key innovative features that promise major capital cost reductions. A key innovative feature of both the PBMR and MGR designs is that the helium heated in the reactor core is pumped directly to the gas turbine. This is a major change from the traditional high temperature gas-cooled reactor (HTGR) design that incorporates a secondary coolant circuit so that the helium transfers the heat from the core to steam generators that feed a steam turbine. Elimination of the secondary coolant system reduces the capital cost of the plant significantly. Further reductions in capital cost are anticipated by eliminating the conventional containment or confinement systems; depending on a fuel form of sufficient reliability and integrity that radioactivity is contained within the fuel elements throughout the life of the plant. In addition, all HTGRs have the advantage of higher efficiency (~40%) versus present commercial LWRs (~30%).

The primary difference between the PBMR and the MGR is in the fuel form. The PBMR utilizes TRISO-coated fuel particles incorporated in billiard-ball sized graphite “pebbles” that continuously flow into and out of the reactor core zone. The MGR uses similar fuel particles incorporated in fixed graphite blocks. Both systems utilize high integrity triple-coated fuel particles, very similar in composition and based on many years of fuel material testing and manufacturing experience carried out during the development of the conventional HTGR of large unit power output.

Bus-bar generation cost estimates are given in Table I for the two small modular plants, PBMR and IRIS, each in a multi-modular 1000 MWe complex and compared to two larger ALWRs: the Westinghouse/BNFL AP-600, with passive safety features and an up-rated (1091 MWe) version of that design, the AP-1000. These examples have been chosen because cost estimates were available on all of them from the same source, Westinghouse/BNFL[(9)], so that some degree of evaluation consistency would be expected among them. Point estimates are given in Table I for simplification and a discussion is given later of the possible variations in cost that would apply. The cost estimates are given in 1990 dollars; an after tax discount rate of 8% and a finance period of 20 years are assumed; fuel cycle and operations costs are representative of the actual top quartile performance of plants with Westinghouse NSSS designs.

Since none of these plants have yet entered the market, it is well to establish a capital-cost reference base from experience on plants that have been deployed. An appropriate reference is the 1380 Mwe ABWR, developed by GE/Toshiba/ Hitachi, an ALWR that has been built, is in operation in Japan, and has been granted design certification in the U.S. The overnight capital cost of the ABWR is reported(11) by OECD's Nuclear Energy Agency (NEA) to be 1582 $/Kwe in 1997 $, giving a breakdown of the capital costs (in millions of U.S. dollars) into 1,253 in direct costs, 191 in indirect costs, and 613 in other costs, (consisting of owner's cost, spare parts, initial fuel costs, contingencies), for a total of 2,057.

These comparative projected cost estimates indicate that both the PBMR and the IRIS at a total bus-bar generation cost of ~2.5 cents/Kwh have a potential economic advantage over the ALWRs, which range from 3 to 4 cents/Kwh. It is of course not unusual that the cost estimates for plants at a relatively early stage of development are more a reflection of the economic goals than of an accurate knowledge of plant costs. In particular, the plants that have been built are estimated as the costliest, those with design certification as next most costly, and those with neither experience as the least costly.

Table I: Bus-Bar Generation Costs
(cents/Kwh)

Plant Type:	AP-600	AP-1000[(a)]	IRIS	PBMR[(b)]
Power (Mwe):	2x600	1x1090	3x333	10x110
Bus-bar Cost (cents/Kwh):				
Capital	2.6	1.8	1.4	1.7
O&M	0.8	0.55	0.6	0.3
Fuel[(c)]	0.6	0.6	0.35	0.47
Decommissioning	0.1	0.1	0.1	0.1
Total:	4.1	3.05	2.49	2.63
"Overnight" Capital Cost ($/Kwe)	1485	1075	636	1004

(a) GE is developing a 1000 Mwe passive BWR, called the ESBWR, which shows similar economic potential.
(b) ESKOM has reported[(10)] total bus bar cost estimates ranging from 1.7 to 2.4 cents/Kwh
(c) Includes 0.1 cents/Kwh for used fuel disposition.

To reflect this picture more quantitatively, Westinghouse/BNFL has estimated[(9)], for all four of the cases in Table I, the impacts on bus-bar costs for potential variations in plant construction costs and the cost impact of the time to construct; for production costs (operating costs, fuel and fuel disposition costs), for the key performance factors that influence production costs (plant availability, plant capacity factors, and plant life); for financing costs (interest rate and finance period), and for decommissioning costs. The cost impacts have not been estimated for "unknowns."

The following general observations, except for two outliers, can be derived from these analyses: The ranges in bus-bar cost are generally greater (~10 to ~15%) for the IRIS and PBMR than for the AP-600 and AP 1000 (~2 to ~6%). The ranges in power output are smaller for the ALWRs, showing a greater potential for power up-grading of the small modular reactors. The ranges in plant availability and capacity factors are greater for the small modular reactors, implying greater uncertainty in achieving top performance. The two outliers are:

1. The interest rate variation in all cases results in a bus-bar cost range of about 30%.

2. The construction cost variation results in a small (~3%) bus-bar cost range for the ALWRs but a large (~40%) range in for the small modular plants.

Although the ranges analyzed are greater for the smaller modular reactors than for the ALWRs, they still reflect a reasonable level of confidence in the economic forecasts. On the other hand as mentioned above, the analyses do not include the cost impact of "unknowns" which are principally the technical uncertainties in the designs. Here, the ALWRs have the clear advantage because the technology employed is proven, the NRC has already certified their basic design and the cost of most of the plant content is known from actual fabrication, installation, and construction experience.

On the other hand, the PBMR direct helium cycle and the level of fuel integrity needed to eliminate containment have not been proven. No total system of the kind contemplated has ever been built or operated. Thus, the actual ranges of cost uncertainty in the PBMR are substantially greater than for the ALWRs. The same comment applies to cost projections for the MGR. Similarly, the IRIS design requires the incorporation of the steam generators and related circuits into the reactor vessel, a step considered over the years for commercial application but never been taken. The primary reason is that there has been continual need to inspect, repair, and replace steam generators, maintenance operations that are exceedingly more difficult in the high radiation environment in the interior of the reactor vessel. A challenge also exists for IRIS to be able to extend fuel life far beyond the present level of proven fuel endurance. The successful completion of in-depth design, testing, and demonstration for both concepts will be necessary to reduce the technical and related financial risks to an acceptable level.

The major contributions to the lower capital and production costs of the PBMR come from the three aforementioned features: the direct coolant cycle, no containment, and higher efficiency, as is the case for the MGR. The lower capital and production costs of the IRIS come from the integral layout and the ultra long-lived fuel. None of these features is unique to unit-power output size, although there may be difficulties in achieving their full advantage at much higher unit power output. This consideration gives rise to the possibility that economy of scale might lead to large unit power output designs of these innovative systems.

Such an evolution did in fact occur in the ALWR Program. In its early phases, innovations in the form of passive emergency cooling features were introduced to effect major simplifications, reflected in capital cost reduction, which would make mid-size ALWRs in the 600 Mwe range economic. But, as this program matured and low natural gas prices made gas fuel-fueled electricity generators more economic than had been anticipated, the need for further capital cost reduction of the ALWRs became evident. Design studies showed that the passive safety features could be scaled up effectively. As a result, the passive ALWR designs in the 1000 Mwe range emerged. Modular construction, which had been emphasized in the 600 Mwe effort, was also applied to the larger sizes. The simplifications for both the AP-600 and AP-1000 are summarized(12) in Table II.

Table II: Reductions in Material Content in "Passive" ALWRS

	AP-600	AP-1000
Fewer ASME* valves:	50%	50%Less
ASME pipe:	80%	83%
Less cable:	70%	87%
Fewer pumps:	35%	36%
Less seismic building volume:	45%	56%

*Comply with American Society of Mechanical Engineers Standards
Similar simplifications have been effected in GE's ESBWR(13), rated at 1190 Mwe.

The small, modular gas-cooled and water-cooled systems such as the PBMR, MGR, and IRIS are subject to this same evolution. If no major difficulties appear in scaling up these systems then it is probable that economy of scale will once more show capital cost savings.

What Does The Shift in Economic Driving Forces Portend for the Market Prospects of Smaller Nuclear Plants?

The key issue is whether small nuclear plants in the 50-150 MWe electric range can beat the economy of scale through other economic advantages unique to their size and design. The developers of small plants cite significant number of economic advantages that can contribute to this end, including the following:

- Flexibility in nuclear plant capacity planning can be achieved since demand forecasts will encompass shorter time periods, making the prediction of power demand more accurate, and short term adjustments can be made in capacity expansion schedules at minimal cost.

- High content of factory fabrication will result from a large number of duplicate units, providing several advantages: Factory fabrication and assembly is less costly. Quality is more assured and less expensively implemented in factory conditions. Complete small modular units can be more readily and relatively inexpensively shipped from the factory to the field and entail a minimum of field assembly steps. A high degree of standardization can be effected among the modules. "Learning curve" cost reductions in manufacture and maintenance can be gained from repetition and standardization

- Shorter construction times can be achieved through modular factory fabrication that reduces component and systems costs and construction times, and through smaller units reduce the complexity of site assembly and construction and minimize the potential for construction delays. The shorter construction periods will result in interest charges during construction and less chance of a sudden surge in inflation over the shorter period.

- Incremental costs of first-of-a kind engineering in a multi-modular system can be absorbed in the first modular unit. None of the cost estimates shown in the previous tables include first-of-a-kind engineering. If those costs were absorbed in a single AP-1000 plant, the overnight capital cost would be in the range of 20%. Small modular designs such as PBMR and IRIS will have lower first-of-a-kind costs for a multi-modular 1000 Mwe complex such as portrayed above since these costs will be expended only on the first module. No quantitative estimates of first-of-a-kind engineering are available for PBMR and IRIS, but a "ball park" estimate, probably on the low end of the range, can be made by using the percentage increase for first-of-a-kind-costs cited above for the AP-1000. In that case the incremental increase on the first module would be of the order of 2% of the overnight capital cost of the 10-unit PBMR complex or about 5% for the four unit IRIS.

- Reduced financial risk and lower financing rates can occur because of the smaller investment required and the ability to make demand forecasts over shorter time periods, which make the prediction of power demand more accurate. Further, public acceptance might be favorably influenced by small plant size.

- The generation plant market for small modular units becomes larger because it is opened up to many small users.

- National or regional market prices may offer better returns on investment where premium prices are available for smaller units.

- Small users can gain ancillary economic benefits since their transmission network does not have to be greatly expanded in a short time and the vulnerability of their electric grid need not be threatened by the concentration of a high percentage of their capacity in one plant.

- Small modular plants lend themselves to "packaging": Some concepts lend themselves to constructing the entire plant in a factory or shipyard facility with even greater cost reductions than for the case of modular factory manufacture. Barge mounting can be employed, providing not only reduced manufacturing and assembly costs but also shipment of the complete generation system to a site and the potential for mobile generation units. The potential exists to provide a total generating service, not just the generation plant, providing expertise that is costly for small users to develop for themselves.

- Infrastructure costs could potentially be reduced. Experience has shown that infrastructure needs for nuclear power generation are substantially greater than for fossil-fueled generation, e.g., operator and maintenance personnel training, in-service inspection capability, waste storage/disposition facilities and transportation, national safety regulatory compliance, and IAEA/NPT compliance. For large utilities and countries, the costs to provide this infrastructure can be pro-rated over multiple nuclear plants. But for small countries, these requirements would have to be absorbed in the cost of one plant and setting up the infrastructure to meet and sustain them would be a major challenge. A complimentary approach is also of importance in waste management through the development of regional facilities for used fuel disposition that would remove the need for small users to build and operate their own facility.

It should be noted that many of the advantages of small nuclear plants outlined above also apply to small fossil-fueled plants. But application of these advantages in nuclear power has the potential of allaying the impediments that presently keep nuclear power plants out of the small unit-size generation market.

The Need for Full Scope Economic Quantification

There are three groups of economic criteria that encompass the full scope of economic evaluation. The first group comprises the costs of the power plant content (bill of materials, manufacturing, construction, first-of-a-kind engineering, capacity factor). This group lends itself to quantitative cost estimating once significant knowledge is gained of the technical and operating features of the given system, corroborated by extensive testing, and licensing approval. These estimates are the focus of engineering attention during the development and detailed design of the system. Recent efforts[14] to evaluate existing nuclear plants for purposes of acquisition or disposition have led to the inclusion of performance indicators in their economic analysis. This trend may well be extended to the evaluation of investment decisions on new plants in the future.

The second group bears on the financing of the plant (interest rate, rate of return on investment, length of investment pay- back, construction time, investment risk, market clearing price, and public acceptance. It is this group that may well dominate investment decisions, assuming that the first group falls in the ball park of competitive costs. To estimate the initial cost estimates in the first group, the engineer assumes a financing rate, but quantification of the many features that influence financing rates and the investor will demand investment risk. This is not an easy task and cannot be tied down fully by the technology.

The third group contains the ancillary benefits to small users that may well be the unique economic appeal of single nuclear units in the range of 50-150 MWe. Yet these features have not been quantified economically. An effort to do so could not only show economic value added to small systems for small users but could provide more specific guidance in the development and marketing programs in achieving the maximum value added.

Although difficult to achieve, this broadening of the scope of economic quantification is fully in keeping with the continuing movements toward full system evaluation---not just for the power plant but also for the entire system in which it operates.

Table III: Global Primary Energy Consumption Growth Between 1990 and 2050
(Giga-tonnes of oil equivalent)

	1990	A	B	C
OECD Countries	4.2	6.3	5.6	3.0
Economies in Transition	1.7	3.7	2.4	1.7
Developing Countries	3.1	14.4	11.8	9.5
TOTAL	**9.0**	**24.8**	**19.8**	**14.2**
Contribution from Nuclear Power	0.5	2.9	2.7	0.5 to 1.2

Global Market Potential for Small Plants

There is a major potential global market for small nuclear power plants, as can be surmised from a review of the latest World Energy Council (WEC/ IASA) projections(15) of energy growth through 2050. Table III shows that from 1990 to 2050 global primary energy consumption is projected to grow by 175% in the "high economic growth" scenario A, by 120% in the "moderate economic growth" scenario B and from zero to 60% in the "ecologically driven" scenario C. Energy consumption from nuclear power sources, assumed to be primarily through electricity production, is projected to grow by 480% in scenario A, by 440% in scenario B, and from zero to 140% in scenario C. The contribution of nuclear power to global consumption ranges grows from 5.5% in 1990 to 12% in scenario A, to 14% in scenario B, and from 3.5% to 9% in scenario C. Table IV shows a similar growth pattern in electricity consumption for all three scenarios. The projected increases in electricity consumption do not fully reflect the continuation of the historic shift in the electricity fraction of primary energy that today is 38% but is projected by EPRI(16) to reach as high as 70% by 2050. This shift would imply an even greater future contribution for nuclear power.

Table IV: Global Electricity Consumption Growth Between 2000 and 2050
(10^{12} Kwh)

	2000	A	B	C
TOTAL	**15**	**42**	**31**	**23**

To better differentiate the market, WEC/IASA has projected the changes in the distribution of energy consumption among the OECD countries, countries whose economies are in transition, and developing countries, shown in Table V.

These projections portray a radical change, from 1990 to 2050, in the distribution of total primary energy consumption among the three market sectors.

Table V: Global Distribution - Primary Energy Consumption
(%)

	1990	A	B	C
OECD Countries	47	27	28	21
Economies in Transition	19	15	12	12
Developing Countries	34	58	60	6

OECD countries drop from about one-half to less than one-third in the higher growth scenarios and to one-fifth in the low growth case. The share of the economies in transition drops slightly from 19% to the range of 12-15% in all the scenarios. Of particular interest to this forum, the share of the developing countries shifts from one-third in 1990 to two-thirds in 2050 for the low growth case and to about 60% in the higher growth cases. The potential users of nuclear power in the developing countries will primarily be small consumers of electric power and will want small nuclear power plants, as will some of the countries whose economies are in transition. This radical shift will be ameliorated from a supplier's perspective by the need to replace old capacity with new in the OECD countries and some of the countries in economic transition. The need for capacity replacement will add to the total increases shown in Table IV, making for a substantial challenge to the capital market and to all suppliers, as well as nuclear ones, to fulfill the overall need.

The fundamental question remains: Can small modular systems be sufficiently economic to take advantage of this large potential market? There seems a reasonable chance that they can in the form of multi-modular units in the 1000 Mwe range, although within the nuclear power alternative they will face substantial competition with the single large unit ALWRs.

But it will be difficult for large single unit or multi-modular plants, simply because of their size, to meet the alternative energy source competition in important sectors of the dominant growth market in the decades ahead: the countries in economic transition and the developing countries. There is of course uncertainty as to whether single-module units in the 100 Mwe range will be sufficiently economical to do so. Penetration of this market will depend on successful completion of the R&D on these innovative plants as well as demonstration of the added value of financing and ancillary benefits through more quantitative economic analyses. Success in this overall endeavor can provide nuclear power with unit size flexibility to serve the full global market.

It will be difficult for large single unit ALWRS or multi-modular plants in the 1000 Mwe range, simply because of their size, to meet the alternative energy source competition in the decades ahead in the dominant growth market sectors: the countries in economic transition and the developing countries. The single module units in the 50-150 Mwe range satisfy the size needs of these market sectors. But, penetration of these markets will depend upon the successful completion of research, fabrication, and demonstration of these innovative plants, as well as realizing their financing enhancements and ancillary benefits by broadening the scope of economic quantification. Success will provide nuclear power with unit size flexibility to serve the full global market.

A Potential Course of Action

These economic considerations and the economic lessons learned from past experience suggest several lines of action:

- Perform the research, development, design, and demonstration that will provide the option to deploy small innovative plants.

- Minimize the investment risk caused by technical uncertainties by implementing an in-depth program of component and materials testing, followed by integrated demonstration plants, confirming the capital cost projections and construction schedule, establishing an operational regime of the highest standards of excellence including key performance indicators, and assuring licensability.

- Develop a broad economic framework with which to assess the potential enhanced value of small nuclear plants.
  - ✓ Lower interest charges
  - ✓ Reduced investment risk
  - ✓ Greater environmental advantages
  - ✓ Eased fuel supply logistics
  - ✓ Relative robustness against contingencies in fuel supply and power demand projections
  - ✓ Ancillary benefits from reduced infrastructure requirements
  - ✓ Regional market clearance enhanced opportunities
  - ✓ Facilitation of the investor(s) commitment
  - ✓ Flexibility of power capacity planning
  - ✓ Utilization of performance indicators

- Such a change in economic framework will require commensurate actions of a political nature to support the changes in approach. Such actions would be to:

- ✓ Foster the expansion of international collaboration to share development, testing, and demonstration facilities and costs
- ✓ Develop an international basis for safety, environmental, and proliferation resistance standards,
- ✓ Promote the consideration and utilization of value-added economic criteria, and
- ✓ Establish regional facilities for used fuel and radioactive waste management.

This course of action would be a significant break from past practice by encompassing at the outset of development essentially all the considerations that would go into the decisions to finance a nuclear plant.

This is a substantial challenge but is worth the try in view of the prize being sought: providing nuclear power with the flexibility to serve essentially all the energy markets in the world.

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Appendix

Table A-1: Average Electricity Production Costs
(cents/Kwh, 1999 dollars)

Year	Nuclear	Coal-fired	Gas-fired	Oil-fired
1995	2.10	2.05	2.93	4.12
1996	2.04	1.94	3.59	4.40
1997	2.36	2.17	3.63	3.95
1998	2.18	2.12	3.37	3.31
1999	1.83	2.07	3.52	3.18

Source: Nuclear Energy Institute, UDI

Table A-2: Overnight Construction Costs of Coal, Nuclear, Natural Gas, and Renewables
($/Kwe)

	Year of Startup			
Type	**2005**	**2010**	**2015**	**2020**
Nuclear	1600	1480	1400	1380
Coal	1080	1000	900	860
Natural Gas	450	400	380	360
Wind	800	800	800	800
Photovoltaic (flat plate)	3000	1500	1400	1080
Bio-Mass (gasification)	1520	1400	1300	1200
Large Hydro	1800	1700	1650	1600
Solar Reflector (power tower)	2300	2550	2500	2500

Table A-3: Cost of Electricity From Coal, Nuclear, Natural Gas, and Renewables

(cents/Kwh)

	Year of Startup			
Type	**2005**	**2010**	**2015**	**2020**
Nuclear	4.8	4.5	4.4	4.3
Coal	3.5	3.3	3.0	2.8
Natural Gas	3.2	3.1	3.0	2.8
Wind	3.0	2.8	2.7	2.6
Photovoltaic (flat plate)	15.0	8.0	7.0	6.0
Bio-Mass (gasification)	6.0	5.5	5.0	4.5
Large Hydro	5.8	5.5	5.3	5.0
Solar Reflector (power tower)	12.5	8.0	7.5	7.0

(Levelized cost of electricity estimates based on the efficiencies, book lives, capacity factors, and capital, operating and maintenance, and fuel costs pertinent to each system; EIA gas cost projections.)