Economic Comparison of Different Size Nuclear Reactors

M. D. Carelli, B. Petrovic, C. W. Mycoff
Westinghouse Electric Company LLC
1344 Beulah Road, Pittsburgh, PA 15235, USA
Tel: (412) 256-1042, Fax: (412) 256-2444, Email: carellmd@westinghouse.com

P. Trucco, M. E. Ricotti, G. Locatelli
Politecnico di Milano, Italy
Via Ponzio, Milano 34/3, Italy 20133

Abstract

Smaller size reactors are going to be an important component of the worldwide nuclear renaissance. However, a misguided interpretation of the economy of scale would label these reactors as not economically competitive with larger plants because of their allegedly higher capital cost ($/kWe). Economy of scale does apply only if the considered designs are similar, which is not the case here.

This paper identifies and briefly discusses the various factors which, beside size (power produced), contribute to determining the capital cost of smaller reactors and provides a preliminary evaluation for a few of these factors. When they are accounted for, in a set of realistic and comparable configurations, the final capital costs of small and large plants are practically equivalent. The IRIS reactor is used as the example of smaller reactors, but the analysis and conclusions are applicable to the whole spectrum of small nuclear plants.

1. INTRODUCTION

To fulfill the growing energy needs of developing countries and emerging markets, smaller size reactors are needed. This has been identified within the US DOE Global Nuclear Energy Partnership (GNEP) initiative as one of the key elements, "Grid-Appropriate Reactors", needed to enable worldwide expansion of the peaceful use of nuclear power. In a speech at a conference in Algiers on January 9, 2007, the International Atomic Energy Agency (IAEA) Secretary General Mohamed El Baradei discussed the interest in "….new small and medium-size reactor designs which allow a more incremental investment than is required for a big reactor, and provide a better match to grid capacity in many developing countries".

Smaller size reactors (IAEA defines as "small" those reactors with power <300 MWe and "medium" with <700 MWe) are the logical choice for smaller countries or those with a limited electrical grid. In fact, smaller reactors are now in different stages of development throughout the world and interest in their deployment has been expressed as well. Small reactors have attractive characteristics of simplicity, enhanced safety and require limited financial resources. However, the other side of the coin is that they are not seen as economic because of the accepted axiom of the economy of scale. The capital cost ($/kWe) of a nuclear reactor decreases with size, because as the size and power increase, the numerator ($) increases less than the denominator (kWe). Thus, in large, developed countries the reactor size has steadily increased from a few hundred MWe 40 years ago to 1500 MWe and more today.

But, the economy of scale applies only if the reactors are of a very similar design, as it has been the case in the past. This is no longer true today, where smaller modular reactors have very different designs and characteristics from the large ones. Thus, assuming that, because of the economy of scale principle, the capital cost of a smaller size reactor is by definition higher than for a large size reactor is simplistic and wrong. The awareness and realization of the economic potential of smaller reactors has grown significantly in the last few years (even though some work is over 15 years old, like the paper [1] by UKAEA, which has been the guide of the present work).

In addition to individual studies, the IAEA has launched in 2006 a collaborative project to address the competitiveness of Small-Medium Reactors (SMRs). As part of the IRIS (International Reactor Innovative and Secure) [2] development, Westinghouse had already initiated investigation of the economic characteristics of IRIS. A more comprehensive outlook at the various components which make up the economics of SMRs was then undertaken by Westinghouse and some of the IRIS team partners, as a contribution to the IAEA study.

The general approach to smaller reactors economics and some preliminary results obtained by Westinghouse and the Politecnico di Milano, Italy (POLIMI) are reported in this paper.

2. SMRs MARKET CONSIDERATIONS

Since nuclear power reactors have historically been deployed for the most part in large, developed countries, a rather immediate question is how SMRs would fare economically against larger size (1000 MWe or more) reactors. The implicit assumption is that both smaller and larger reactors are power plant candidates on any given market.

The reality is that, as briefly mentioned in the introduction, for many countries the larger size reactors are not an option at all, period. Some of the conditions which prevent large plants from being viable candidates, are:

– Electrical grids with limited capacity, as previously mentioned. It is a general rule of thumb that a grid should not be subjected to power variations in excess of 10% of the total grid capacity. So, 1000 MWe plants cannot be deployed in grids of 10 GWe or less.

– Remote areas requiring smaller, localized power centers, to avoid long and expensive transmission lines.

– A geography and demography featuring mid-size urban and power needing areas fairly scattered, rather than concentrated in a few "mega centers".

- Financial capabilities which preclude raising the several billions dollars capital investment required by larger plants, and are instead limited to hundreds of millions of dollars characteristic of smaller plants.

- Need for cogeneration (desalination, district heating, industrial steam). While in principle cogeneration is independent of the nuclear plant size, in practice economic considerations have driven the larger plants to be pure producers of electricity.

Most of these conditions do also characterize many developing countries. The ones which most strongly favor SMRs are the grid size, financial limitations, and the need for potable water.

Thus, the real question for the competitiveness of SMRs is not how they fare versus larger nuclear plants, but rather versus same size conventional plants. We are not going to assess here such competitiveness. Rather, we are going to identify which are the various factors contributing to define the SMR economics, to allow a future quantification and comparison against the cost of conventional sources.

For larger countries, which do not have the restrictions mentioned above, SMRs will compete against both conventional and larger nuclear plants.

3. COST FACTORS AFFECTING SMRs VIS-A-VIS LARGER NUCLEAR PLANTS

When evaluating the competitiveness of SMRs versus large reactors, the various individual factors can be grouped into two classes:

- Factors which are either applicable to SMRs only or are critically affected by the difference in design and approach brought in by the SMRs (SMR specific factors)

- Factors which affect SMRs and large plants in a comparable way (common factors). Even for the common factors, a comparative quantitative evaluation might not be straightforward.

The SMR specific and common factors are listed in Tables I and II and qualitatively discussed in the following Sections 3.1 and 3.2. The list is by no means exhaustive and others might be considered. Presented here are the ones judged to have higher priority for a quantitative evaluation; six factors (identified by (*) in the Tables) have actually been addressed, as discussed in Section 4.

Table I. SMR specific factors

• Design Related Characteristics (*)
• Compactness
• Cogeneration
• Match of Supply to Demand (*)
• Reduction in Planning Margin
• Grid Stability
• Economy of Replication
• Bulk Ordering
• Serial Fabrication of Components

(*) Quantitatively evaluated

Table II. Common factors

• Size (*)
• Modularization
• Factory Fabrication
• Multiple Units at a Single Site (*)
• Learning (*)
• Construction Time (*)
• Required Front End Investment
• Progressive Construction/Operation of Multiple Modules

(*) Quantitatively evaluated

3.1 SMR Specific Factors

The most important SMR specific factor is of course *design related characteristics*. Since it is "design related", this factor will vary from design to design and it will include different subcomponents for each design. Still, there are general characteristics which pretty much envelope the entire SMR spectrum. They are:

– Simplicity, reduced type and number of components.

  SMRs are generally new designs which try to simplify existing solutions. Their safety characteristics tend to be enhanced because passive and intrinsic safety is better enabled by the smaller size; enhanced safety, if properly accounted for, translates into a cheaper design.

– Specific O&M costs

  Because of their vastly enhanced safety, SMRs have the potential to attain licensing without the need for emergency response, which will eliminate personnel training and infrastructure requirements. Some SMRs, like the integral configuration PWRs, have extended, up to four years, maintenance intervals and integral shielding which dramatically decrease the personnel routine exposure and ALARA costs.

– Security

Engineering additions required to enhance security are intrinsically less expensive in SMRs because of their smaller size and simpler design. For example, SMRs offer a much smaller target to terrorists driven aircrafts. Also their enhanced intrinsic safety and passive systems decrease the chances (thus, costs of counteracting measures) of internal sabotage.

– Lifetime

SMRs are designed for longer lifetimes of both the core and the reactor structures, including the pressure vessel.

Next to the unit power cost ($/kWe), another index is also considered in evaluating a reactor plant, i.e., the amount of required commodities (such as steel and concrete). Because of their *compactness*, the "commodities index" (m^3/kW) in SMRs is approximately the same as, and in many cases lower than in large plants. Another effect of their compact design is that a cluster of SMRs, having the same total power as a large plant, generally requires less land.

As mentioned in Section 2, *cogeneration* is the province of SMRs because the utilities much rather prefer that the multi-billion dollars investment in a large nuclear plant produces the highest amount of baseload electricity. Besides this consideration, there is another factor which makes SMRs the best nuclear plants for cogeneration. Cogeneration can be the production of: fresh water by desalination; steam for district heating, industrial or agricultural application; process heat for chemical industry. One common characteristic is that, while electricity can be transported long distance, cogeneration products require close proximity of producer and end user. Since nuclear plants are licensed with population restrictions (exclusion zone, low population zone, etc.) either significant infrastructure/transportation costs are incurred or cogeneration is simply not possible. As previously mentioned, the safety characteristics of some SMRs may allow them to attain licensing without the need for emergency response. One of the IRIS objectives is to obtain licensing with a collapsed population exclusion zone, which will be very close to the plant boundary [3].

SMRs size allows them a much closer *match of supply to demand* than possible with large plants. This of course reduces financing commitments and allows better planning, with *reduction in planning margin*. Also, insertion of smaller units reduces the challenge to *grid stability*. While it was seen in Section 2 that SMRs are the only viable reactors for smaller electric grids, even in larger interconnected grids large power additions/subtractions can cause grid instabilities. These instances have been rather common in the last few years, as demonstrated by blackouts in northern U.S./Canada and Italy in 2003 and Central Europe in 2006.

Finally, SMRs are characterized by what can be called *economy of replication*, based on *bulk ordering* and *serial fabrication of components*. To give an example, the 335 MWe IRIS module employs eight steam generators versus the two steam generators of the about 1200 MWe

AP1000. Thus, production of 6000 MWe by IRIS requires the fabrication of 96 steam generators versus ten for AP1000. The small, simple components of SMRs can be produced on a small scale assembly line rather than one at a time.

3.2 Common Factors

The first and most obvious of the common factors is *size*, which of course generates the economy of scale. If the design is only marginally different, the overnight capital cost of a larger unit is significantly cheaper than for a smaller version.

The smaller size and lower power of SMRs allows them to be more accessible to *modularization*, i.e., construction and deployment of a larger number of standardized units. Modularization reduces the requirements for more expensive and time consuming on-site construction and also allows more *factory fabrication*. Still, modularization is considered a common factor, because it is also employed in the most recent large plants designs and thus has to be comparatively evaluated.

Similar considerations apply to the deployment of *multiple units at a single site*. The obvious advantages are the sharing of infrastructure and better utilization of site material and human resources. Of course, more SMR units are deployed for the same amount of power attained with larger reactors, but both small and large plants can be deployed in multiples at a single site and in fact, several multi-unit sites with thousands of installed MWe do exist. Thus, while in principle the factor favors the SMRs, a case-by-case evaluation must be done.

Another factor which needs parallel evaluation is *learning*. It is well known that a Nth-Of-A-Kind (NOAK) plant costs less than a First-Of-A-Kind (FOAK) because of the lessons learned in the construction and deployment of earlier units. The learning curve generally flattens out after 5-7 units. Comparing a 350 MWe and a 1400 MWe plant, the NOAK is reached after approximately 2100 MWe for the SMR and 8400 MWe for the large plant. Thus, 18 more units of the SMR can take advantage of the learning factor before the large plant is able to “catch up”. Learning is definitely an advantage for the SMRs in the early stages of the market, to be eventually equalized as the market for both designs mature.

In addition to the above learning “worldwide” (it does not matter where the units to reach the Nth are built) there is also learning “on site”, obtained from the construction of successive units.
Specific characteristics of SMRs such as smaller size, simpler design, increased modularization, higher degree of factory fabrication and serial fabrication of components lead to a shorter *construction time*. In fact current projected schedules for SMRs are three years for the FOAK, projected to be reduced to as little as two years for the NOAK.

The unit cost of a SMR is of course a fraction of the cost of a larger plant (several hundreds million, rather than a few billion dollars). This reduced *required front end investment* can be “the” critical factor for a utility or country with limited resources.

Finally, the combination of the reduced front end investment and the shorter construction time makes it possible to minimize the cash flow through *progressive construction/operation of* *multiple modules* deployed in succession. Assuming that construction of a module starts when the preceding one initiates operation, the power producing module will finance construction of the following one. An example is shown in Figure 1 where four modules of 335 MWe each (three year construction) are compared against a 1340 MWe plant (five years construction). Financing at 10% over a ten-year period was assumed for both.

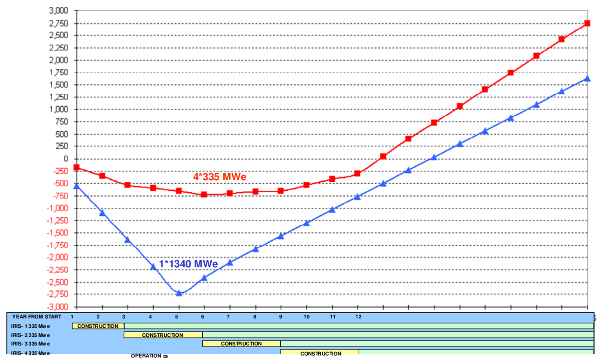

Figure 1. Cash flow profile for construction/operation of 4 smrs versus a single large plant

Table III presents the results of a sensitivity study for the net maximum negative cash flow versus the time interval between first operation of successive units.

Table III. Maximum negative cash flow (comparable large and SMR capacity)

Time between SMR Units (Months)	Percent of Large Value (Percent)
9	82%
12	70%
24	41%
36	35%

4. PRELIMINARY EVALUATION

The SMR specific and common factors discussed in the previous section do not by any means represent a complete list but they are the ones judged to be most representative. An initial quantification of some of these factors has been attempted. The SMR representative was the IRIS reactor, which is offered in single (335 MWe) or in twin (670 MWt) units. The large reactor used as reference was a hypothetical 1340 MWe PWR. The IRIS reactor was used because of the obvious familiarity and interest of the authors, but the evaluation conducted here is fully applicable to SMRs in general.

Six factors were evaluated: *size*; *multiple units at a single site*; *learning*; *construction time*; *match of supply to demand*; and, *design related characteristics*. The results are reported in Figure 2 and Table IV.

The first factor represents the economy of scale, assuming that the two plants are comparable in design and characteristics. The usual correlation

$$OCC_{SMR} = OCC_{LARGE} \times \left(\frac{size_{SMR}}{size_{LARGE}} \right)^{n-1} \qquad (1)$$

was adopted with n = 0.62. All other things being equal, the overnight capital cost (OCC; \$/kWe) of the SMR would be 70% higher than the large pant. But all other things are not equal and other factors will tend to reduce the SMR disadvantage.

The site multiple units factor was evaluated considering that there are fixed, un-repeatable costs only incurred for the first unit and there are costs which are shared by the multiple units. The experience reported in the literature for Korean and French units on the same site was factored in our evaluation. For the four versus one plant comparison, it was evaluated that a 14% savings exists for the multiple SMRs.

The learning factor considered here is the "on site" type factor and it was evaluated from the various models reported in the literature (e.g., Gen IV) [4]. It was found that for the four units case the cost reduction is between 8 and 10%. The 8% value was conservatively chosen.

The next two effects, construction schedule and matching of supply to demand (or "timing"), were evaluated together, assuming a construction schedule for the large plant and SMRs of five and three years respectively and calculating the cumulative expenditures for the two cases. A 6% savings was estimated for the shorter construction time coupled with the SMRs capability of better following the demand curve.

The principal design related characteristics for IRIS are: elimination of the pressurizer, steam generators pressure vessels, canned pump housings, all large primary piping, vessel head and bottom penetrations and seals; elimination of several safety systems such as the high pressure injection emergency core cooling system due to the safety-by-design approach which eliminates several postulated accidents; compact containment; lower amount of commodities. A conservative evaluation of these effects indicated a 17% cost savings.

When the various factors are combined, a pack of four 335 MWe SMRs has a capital cost only 5% higher than the monolithic 1340 MWe reactor.

Some sensitivity studies were also conducted, for example, to allow also the large plant to take advantage of multiple units on site and "worldwide" type learning. The reference case reported here and yielding a cumulative 1.05 factor considered four IRIS and one large plant on site, with no prior experience for either. A case of eight IRIS and two large plants on site, still with no prior experience yielded a total factor of 1.16, reflecting the proportionally higher effect of two large units on site. On the other hand, a case of four IRIS and one large plant on site, but with a prior worldwide experience of 2680 MWe for both (which means two large plants and eight IRIS) yielded a total factor of 1.0, reflecting the much larger learning deriving from the higher number of units.

All the other sensitivity cases fell within the 1.0-1.16 range.

Obviously this evaluation is necessarily approximate and only six factors were considered, but it can be concluded that the capital cost of the SMR is quite similar to that of the large plant.

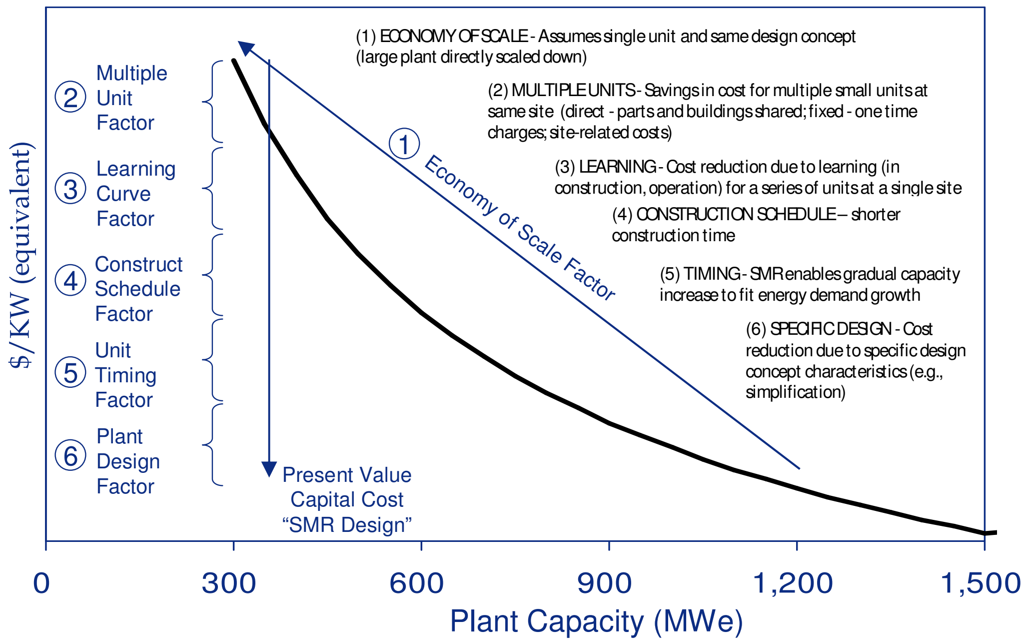

Figure 2. Potential for small reactors economic competitiveness

Table IV. Quantification of factors evaluated in SMRs/large plant comparison (Figure 2)

Factor	Individual SMR/Large	Cumulative SMR/Large
(1) Economy of scale	1.7	1.7
(2) Multiple units	0.86	1.46
(3) Learning	0.92	1.34
(4) (5) Construction schedule and timing	0.94	1.26
(6) Design specific	0.83	1.05

SMR: One 335 MWe plant, as part of four units
Large: One single 1340 MWe plant

5. CONCLUSIONS

Smaller and larger reactors address different markets and there are many market related factors favoring one versus the other, independently from their capital cost.

When, however, they are competing on the same market the capital cost is not a discriminator and the two types of nuclear plants can be practically equivalent under this respect. The so-called economy of scale is not applicable "as is" and it is just one of many factors.

This paper presents only the beginning of the evaluation of the competitiveness of SMRs and expanded, more detailed investigations will follow.

REFERENCES

1. M. R. Hayns and J. Shepherd, "SIR-Reducing Size Can Reduce Cost," Nucl. Energy, 1991, 30, No. 2, pp. 85-93.

2. M. D. Carelli and B. Petrovic, "Here's Looking at IRIS," Nuclear Engineering International, March 2006, pp. 12-17.

3. M. D. Carelli, B. Petrovic and P. Ferroni, "IRIS Safety-by-Design™ and Its Implication to Lessen Emergency Planning Requirements," 13th International Conference in Nuclear Engineering, Beijing, China, May 16-20, 2005, ICONE 13-50712.

4. "Cost Estimating Guidelines for Generation IV Nuclear Energy Systems," Rev. 3, November 30, 2006, GIF/EMWG/2006/003, available at www.gen-4.org .