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COMPETITIVENESS OF SMALL-MEDIUM, NEW GENERATION REACTORS: A COMPARATIVE STUDY ON CAPITAL AND O&M COSTS

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ABSTRACT

Smaller size reactors are going to be an important component of the worldwide nuclear renaissance. An inappropriate application of the economy of scale would label the small-medium size reactors as not economically competitive with larger plants because of capital costs ($/kWe) and O&M costs ($/kWh) that would appear to be significantly higher. However, the economy of scale applies only if the considered designs are similar, which is not the case here, since the small size allows original design solutions not accessible to large size reactors. In the paper the historical trend of capital costs vs. plant size is estimated from literature, and a reference exponent factor for the economy of scale for the light water reactor is derived. Then the paper identifies and briefly discusses the various factors which, beside size, contribute in differentiating the capital cost of smaller reactors with respect to large reactors. In this reference frame the evaluation for of the following factors is provided: · design characteristics · modular build · multiple units · accelerated learning in construction · operation, and shorter construction time. The IRIS reactor is used as the example of small modular reactor (SMR), but the analysis and conclusions are applicable to the whole spectrum of small nuclear plants. The results show that when all these factors are accounted for in a set of realistic and comparable configurations, and with the same power installed in the site, the capital costs of small and large plants installations are practically equivalent.

Considering the O&M cost the paper shows how the plant size is not the only and fundamental cost driver. In fact there is a range of other factors (e.g. location, regulatory issues, capacity factor, plant obsolescence and number of reactors on a site) able to influence the annual O&M cost for a specific plant. The paper provides a preliminary evaluation of these factors by historical analysis of reactors built in the United States, concluding, also in this case, that when all the factors are considered the difference between the average cost ($/KWh) of Large Size vs. SMR is about 20% less than would be expected.

1. INTRODUCTION

To fulfill the growing energy needs, the nuclear power can provide a large amount of reliable, cheaper and greenhouse gases free electrical energy. In this context, especially focusing on emerging markets, Small and Medium Reactors (SMR) 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. Therefore, smaller size reactors (IAEA defines “small” those reactors with power less than 300

MWe and "medium" smaller than 700 MWe) are the logical choice for small countries or those with a limited electrical grid and available capital. SMRs have attractive characteristics of simplicity, enhanced safety and require limited financial resources. However, on the other side they are not seen as economic because of the accepted axiom of the economy of scale: for this reason in the last 50 years in developed countries the reactor size has steadily increased from a few hundred MWe to 1600 MWe (Figure 1-1).

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 by definition that, because of the economy of scale principle, the capital and O&M costs of a smaller size reactor is higher than for a large size reactor is simplistic and wrong.

In this perspective the IAEA has launched in 2006 a collaborative research activity to address the competitiveness of Small-Medium Reactors. As part of the IRIS (International Reactors Innovative and Secure) development [1], Westinghouse had already initiated the 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 its IRIS team partners, as a contribution to the IAEA study.

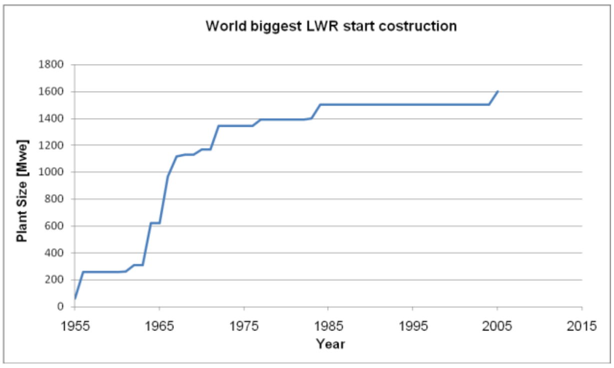

Figure 1-1 World Largest LWR size built over the years

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

1.1 Cost Factors affecting SMRs vis-à-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 only to SMRs 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 the common factors are listed in Table 1-1. The list is not exhaustive and other factors might be considered. Presented here are the ones judged to have higher priority for a quantitative evaluation; six factors (identified by (*) in Table 1-1) have actually been addressed in the model, as discussed in Section 2.

SMR Specific Factors	*Common Factors*
Design Related Characteristics (*)	Size (*)
Compactness	Modularization
Cogeneration	Factory Fabrication
Match of Supply to Demand (*)	Multiple Units at a Single Site (*)
Reduction in Planning Margin	Learning (*)
Grid Stability	Construction Time (*)
Economy of Replication	Required Front End Investment
Bulk Ordering	Progressive Construction/Operation of Multiple Modules
Serial Fabrication of Components	

Table 1-1 List of SMR Specific and Common factors for a differential evaluation

1.2 The life cycle cost breakdown

This paper aims to investigate some cost factors affecting the Capital (Section 2) and O&M (Section 3) costs of nuclear power plants, which globally account for around the 70% - 80% of the LUEC (Levelized Unit Electricity Cost), as shown in Table 1-2.

The approach to evaluate each single account is shown in the Figure 2-1: starting from the economy of scale law, which is surely a disadvantage for SMRs, the computation of other factors may reduce the gap between SMRs and LR, giving the opportunity of "breaking the Economy of Scale",

as said in a CRP started by IAEA (march 2006). A similar approach has been used to compare Operation and Maintenance Costs.

	Williams et Miller, 2006 [2]	Gallanti et Parozzi, 2006 [3]	U.S. Congress/ EIA 1993 [4]	DOE/EIA forecast, 2005 [5]	NERA study 2004 [6]
Capital Costs	48.7 %	68 %	62 %	71.9 %	60-75 %
O&M Costs	23.25 %	13 %	12 %	11.19 %	5-10 %
Fuel Costs	27.22 %	15 %	26 %	16.91 %	8-15 %
Decommissioning Costs	0.84 %	4 %	0 %	0 %	1-5 %

Table 1-2 Cost Breakdown Structure (CBS) of Nuclear Power Plants

2. CAPITAL COST

The SMR specific and common factors discussed in the previous section do not 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 MWe) units. The large reactor used as reference was a hypothetical 1340 MWe Generation III+ 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 construction schedule to demand; and design related characteristics. The main idea is reported in Figure 2-1 and the quantification in Table 2-2.

Figure 2-1 shows how the economy of scale is a big disadvantage for the SMR, i.e. increases the specific capital cost, while the other factors are theoretically able to reduce the specific capital cost [$/kWe].

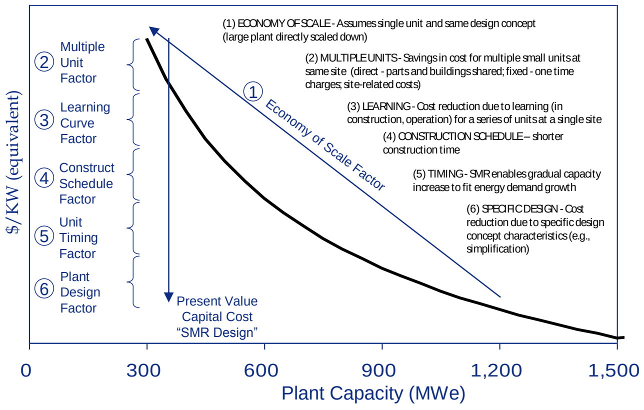

Figure 2-1 Potential for small reactors economic competitiveness

The first factor represents the economy of scale, assuming that the two plants are comparable in design and characteristics. The traditional equation (1) has been used, where AC^c is the average capital cost [€/kWe], S is the Nuclear Power Plant (NPP) size [MWe], α_{ES} is the economy of scale exponent.

$$AC^C_{SMR} = AC^C_{LR} \times \left(\frac{S_{SMR}}{S_{LR}} \right)^{\alpha_{ES}} \qquad (1)$$

In order to quantify α_{ES}, an historical analysis has been made from different literature sources to find consistent model and values, identifying minimum ("High economies of scale"), expected ("Standard economies of scale") and maximum ("Low economies of scale") exponents. Almost all the references (for example, Bowers et al. 1983 [7] and DOE 1988 [8]) indicate an overall scale exponent between 0.5 and 0.7, with an average value around 0.6.

It is possible to compute the same exponent (α_{ES}) in a more accurate way considering the CBS of the NPPs. By dividing the overall cost in its main accounts and considering for each *i-th* account its economy of scale exponent (n_i) it is possible to better estimate the overall exponent. Practically the following algorithm has been implemented:

1. Assume the breakdown cost for the Large Size reactor;
2. Compute the economies of scale for each account using equation (2) and the specific n exponent (the main reference for the n_i exponents were Phung, 1987 [9] and Rasin et. al, 2005 [10])
3. Sum the accounts' value to compute the total capital cost for the SMR [€]. The SMR is now characterized by a size S_{SMR} and an average Cost C_{SMR} (total capital cost/ Size)
4. Compute the general exponent used in the equation with the following formula

$$\alpha_{ES} = \frac{\ln \dfrac{AC^C_{SMR}}{AC^C_{LR}}}{\ln \dfrac{S_{SMR}}{S_{LR}}} \qquad (2)$$

The result from this "account by account" analysis, led to an equivalent exponent value of $\alpha_{ES} = 0.619$, that means a site with one 335 MWe SMR has a average cost [€/kWe] around 70% greater than a site with one 1340 MWe LR (Table 2-1).

	High	*Normal*	*Calculated*	*Low*
EOS exp (α_{ES}).	0.50	0.60	*0.62*	0.70
Average cost ratio AC^{C}_{SMR}	2.00	1.74	*1.70*	1.52
Difference (%)	+100%	+74%	*+70%*	+52%

Table 2-1 Estimation of economy of scale exponents, on an historical (High, Normal, Low) and on a cost breakdown (Calc.) basis

At this point, there are several factors that can reduce the gap resulting from the economies of scale factor (1.70). Among the different *ad*-hoc and *common* factors described in Section 2, five specific factors have been taken into account and estimated.

2.1 Multiple Units at a single site Factor

The 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. It is well-acquainted in literature (Kadak, 2002 [11]; Shepherd and Hayns, 1991 [12]) how the multiple installations of power plant reap a great saving. This recognition derives not only from theoretical considerations, but also by Korean, French and USA experience. For the four versus one plants comparison, it was evaluated that a 14% saving exists for the multiple SMRs.

2.2 Learning Factor

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., Rasin et. al, 2005 [10]). It was found that for the four units case the cost reduction is between 8 and 10%. The 8% value was conservatively assumed.

2.3 Construction Schedule Factor

The next two effects, construction time and matching of construction schedule 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 trend.

2.4 Design Related Characteristics Factor

The principal design related characteristics for IRIS (compared to a GEN III+ reactor) 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. This is consistent with the ORNL evaluation (Reid, 2003 [13]).

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 (Table 2-2).

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

Note: SMR is one 335 MWe plant, as part of four units. Large is one single 1340 MWe plant.

Table 2-2 Quantification of factors evaluated in SMRs/large plant comparison (Figure 2-1)

Some sensitivity studies were also conducted to allow also the large plant to take advantage of multiple units on site and "worldwide" type learning. The reference case reported Table 2-2 yields a cumulative 1.05 factor considering 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 an SMR pack is quite similar to a single large plant.

3. OPERATING AND MAINTENANCE COSTS

The second major component of LUEC are the O&M costs: they are the costs for the decisions and actions regarding the control and upkeep of property and equipment. They are inclusive, but not limited to, the following: 1) actions focused on scheduling, procedures, and work/systems control and optimization; and 2) performance of routine, preventive, predictive, scheduled and unscheduled actions aimed at preventing equipment failure or decline with the goal of increasing efficiency, reliability, and safety [14]. Nuclear operating costs have been analyzed using multiple regression analysis. This statistical tool allows a deep examination of the variations in the dependent variable associated with changes in explanatory variables, so that the resulting regression coefficients are direct measures of the relationship between the dependent and independent variables. The statistical analysis has been done following an index cost approach, i.e. normalizing at 100 the minimum O&M annual cost for a plant in one year and calculating the ratio for all other O&M costs in the same year. By this way the data are scaled with all common historical situation (learning, regulation, world technical knowledge) and not only with the GDP deflator. In Table 3-1 the factors that have been investigated with multiple regression analysis are shown.

Factor	*Plant Size*	*Number of units in the site*	*Plant Location*	*NRC Activity*	*Reactor Type (BWR-PWR)*	*Plant Age*	*Fuel Cycle Length*
Statistical significance	Yes	Yes	Yes	Yes	Yes (before 1997)	No	No
Differential Investment Factor	Yes	Yes	No	Further analysis required	No	No	Yes

Table 3-1 Factors investigated with regression analysis and preliminary findings

3.1 Historical Trends

This section aims at estimating some key factors that influence the O&M costs of nuclear power plants in the North America. To do this, three database have been poured together in order to get to one more complete database:

1. O&M nuclear power plants costs (from 1981 to 2005);
2. Refueling outages length and occurrence database divided by plant unit (from 1993 to 2005)
3. NRC database considering all NRC regulatory activity (NOV, NOVCP, ORDERS, etc…) divided by plant unit (from 1996 to 2005).

There were from 53 to 72 plants in the database, covering the 1981-2005 period, not constant because in certain years some plants have not transmitted their data to the FERC[1] or they have been deregulated.

The O&M cost estimate cannot be made straightforward, many factors are involved and many of them are interrelated, but some historical trends could be identified from a rough data snooping:

a) Cost escalation

The cost escalation could be easily related to some factors, like plant age and NRC regulatory activity; although each of these factors will be discussed in detail below, one general comment about the data could be made: the preceding figure (in 2005 USD) clearly shows a positive cost trend (+11% annual) from 1981 to 1987, an almost constant behaviour (just +1%) from 1987 to 1993 and a negative cost trend (-5% annual) from 1993 up to 2005.

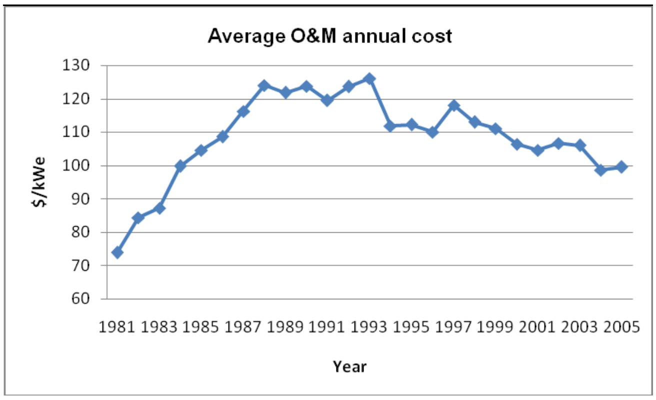

Figure 3-1 Annual O&M cost (average 2005USD) from 1981 to 2005

b) Capacity Factor

In Figure 3-2 and Figure 3-3, the effect of learning can be easily identified; the industry learning played a role on two different sides: first of all, the average plant availability shifted from 52% in 1981 to 62%, 75% and 90% respectively in 1990, 2000 and 2005; secondly, it reduced CF standard deviation from 18% in 1981 to less than 12% in 2005.

[1] FERC: The data on nuclear power operating costs were obtained from Schedule 402 of the Federal Energy Regulatory Commission Form 1, "Annual Report of Major Utilities, Licensees and Others"

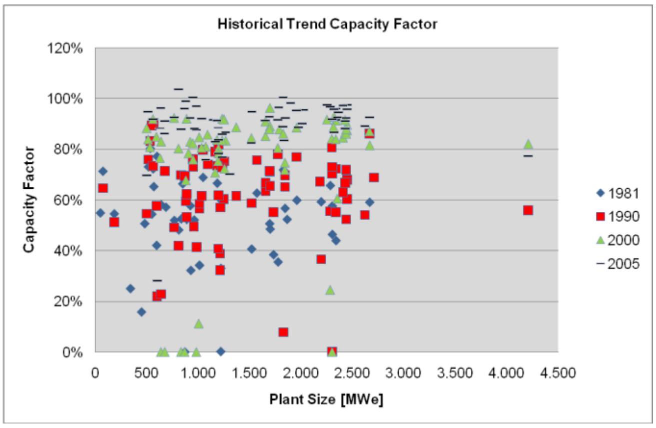

Figure 3-2 Historical Trend Capacity Factor: sample years (1981, 1990, 2000, 2005)

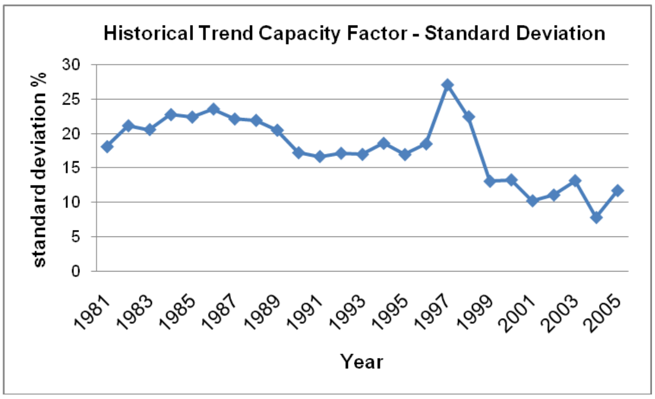

Figure 3-3 Historical Trend Capacity Factor - Standard Deviation

3.2 Economy of scale

According to the common knowledge of power plants, economy of scale is the almost unique cost driver for new buildings. The analyses performed with nuclear O&M costs proves that economy of scale is the main factor –but not the only one – and its influence on O&M cost is less than expected. The calculated EOS coefficient is higher (n=0,71) than the values given in the literature (Bowers et al. 1987 n=0,6 [15]), so that the gap due to the reduced size of SMRs is mitigated (Table 3-2).

Type of economy / Exponent δ_{EOS}		
Name	*Bowers*	*Calculated*
Economy of scale value	0.6	0.71
Normalized value ($\alpha+\Delta=\delta_{EOS}$)	1.74	1.5
Difference	74%	50%

Note: SMR is one 335 MWe plant, as part of four units. Large is one single 1340 MWe plant.

Table 3-2 Economy of Scale coefficients: comparison of values from literature and regression analyses

3.3 Multiple Units at a single site

The presence of one (or more) additional unit, through sharing staff and activities, surely reduces the O&M annual plant costs. Nevertheless, this important key-factor for SMRs has reduced its impact over time. In the decade from 1981 to 1990 the results are almost consistent (n=0,6-0,65) with the previous literature (Bowers, n=0,5 [15]), which means that the saving due to an additional unit is close to 20-22%; in the last decade (from 1993 to 2005), the coefficient is equal to 0,88, showing a reduction of the saving that has been estimated at 7,5%. It should be remembered that Bowers's model does not consider as much variables as our regression model and does not consider O&M total annual costs. The difference between the two models can explain part of the existing gap. Furthermore, the major loss of savings is probably due to the enforcement of Nuclear Regulatory Commission activities, that has been developed after the Chernobyl accident (1986).

3.4 Other Factors

Nuclear plants do their maintenance work during plant outage for fuel change, in order to minimize the plant availability: turbine maintenance, transformer maintenance, motor and pump refurbishment, etc. Those operations require both money and time, so the outage can be observed on two sides: an additional cost and a time extension. None of the analyses performed in this study observed a statistical relevance for the additional O&M costs due to outages (probably because the outage cost is a small portion of the annual O&M costs). Anyway, other studies (Dominion 2004 [16]) showed an additional annual cost of 8-10%. Combining this result with the fuel cycle extension – changed from 18-24 months for the existing plants up to 36-40 months for the new SMRs – a 2-5% saving can be obtained. On the other side, fuel outages reduce the plant capacity factor: the fuel cycle extension limits plant outages with a reduction of 3% on the specific O&M annual cost in $/MWh.

Considering other factors explored in the statistical analyses performed in this study - but not differential for an investor - the first important one is the plant location. The main O&M cost account is surely on-site and off-site staff, which covers about 70% of O&M annual plant cost: a different wage policy (according to the existing laws in one region) can make plants with same characteristics have different cost performances, related to workers' productivity. The nuclear plants have been divided into two regions: Southeast (SERC, SPP and ERCOT) and Non-Southeast plants (other North-America regions), according to the regions existing in 2000. The regression analysis showed a saving between 20 and 25% for plants located in the Southeast regions. It is important to underline that just a rough regions classification has been used and more detailed work should be done.

A further analysis carried out in this study is related to plant age, which is a controversial issue. Some of the operators argue that plant O&M costs dramatically grow after a "break-in" point located at the very end of the plant planned life. Some critics think that the aging process begins early in a plant's life and can be observed over most of its life (Hewlett [17] & EIA [18]). A "plant age" variable has been developed in order to catch this issue, but none of the analyses performed showed a significant relevance for this factor. Actually, even an old plant, with the substitution of its vital components (e.g. steam generators), can mask its age and perform like plants at the early stage of their life. Anyway, this is not a differential factor for cost analyses on new plants with same design life.

Also the NRC activity has been analyzed, showing that plants with a NRC Notice of Violation in one year will perform an additional cost of 7-12% in the next year: this is due to the plant changes required by the NRC regulations, in order to keep the plant operation license and avoid the loss of revenues related to the plant shutting down. Anyway, in order to identify potential technical savings related to a reduced exposure to NRC activity, which will drive the O&M costs down, more investigations are required.

Considering all the differential factors, the gap between a large size reactor of 1340 MWe and a pack of 4 SMR of 335 MWe is just 19%, as it can been seen in Table 3-3.

Factor	*Individual SMR/Large*	*Cumulative SMR/Large*
(1) Economy of scale	1.51	1.51
(2) Multiple units	0.85	1.28
(3) Outage Additional Cost	0.97	1.24
(4) Outage Duration (CF improvement)	0.96	1.19

Note: SMR is one 335 MWe plant, as part of four units. Large is one single 1340 MWe plant.

Table 3-3 Quantification of factors evaluated in SMRs/large plant O&M costs comparison

4. FURTHER DEVELOPMENTS AND OPEN ISSUES

Many variables influence the O&M cost performance of a nuclear plant, and just some of them have been analyzed here in detail. More analyses need to be done:

- More detailed analysis of salary policy: a new method needs to be developed in order to co-relate the workers productivity – and their salaries - to the nuclear plant O&M costs.
- Other variables, as the industry learning: some plants are owned by the same society, so the internal learning could play an important role for the explanation of the variability of costs.
- A new model for NRC activity: more investigations need to be done in order to get this possible saving related to the technical characteristics of plants (the simpler and safer the plant, the lower the exposure to NRC activity and related costs).

From a more general point of view, the main open issue to still consider is the modularization factor, which affects both the Capital and O&M costs. A possible way to quantify this key driver which seems to be one of the most important lever of the SMR competitiveness is the analytic cost analysis of each account conducted with the support of equipment suppliers.

By developing the Fuel and Decommissioning Cost models will be possible to complete the differential estimation of the LUEC, thus these are other sectors still under investigation.

Other aspects that broad the competitiveness of SMR vs. Large Reactora are the financing profile (the SMRs, with the shorter construction length and the progressive deployment reduce financial exposure of the investors) and other non-monetary factors, i.e. enhanced safety, easier grid matching, non-proliferation policies, opportunities of co-generation, etc..

5. CONCLUSIONS

The objective of this study was to determine the differential factors for the comparison of SMRs and Large Reactors on both the Capital and Operation and Maintenance costs. Some findings came out: if the economy of scale is the unique driver for cost estimation Small Modular Reactors are not competitive, but there are evidences of other key factors able to reduce the gap between the two classes of reactors. Considering these factors (site sharing, learning, construction timing, fuel cycle length extension, different technology solutions) the specific Capital cost [$/MWh] of an SMR is only 5% greater than a Large Reactor, while the Operation and Maintenance costs [$/MWh] are 19% greater. If more than 1 Large Reactor is considered the gap increases since also the Large Reactor investment reaps advantages from key factors like site sharing. Therefore the target market for SMRs is relative to investment in power plants of about 1 – 1, 5 GWe or less.

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