Assessing prospects for smaller reactors

by Reiner Schmidt

The use of nuclear power plants, like that of many other technologies, has been characterized by substantial growth in spread, numbers, equipment – and plant sizes, with economies of scale generally favouring the large plants. Small- and medium-sized nuclear power plants, or SMPRs, are generally understood to be plants below the sizes being exploited commercially in industrialized countries. Such plants could be more readily adapted to smaller electric grids, particularly in developing countries, fulfill requirements of low load growth, or serve remote locations or special purposes.

The SMPR range is currently understood as the 200 to 500 megawatt (MWe) size for the generation of electricity and sometimes smaller for process-steam and/or low-temperature heat supply. For statistical purposes a size limit of 600 MWe has been in use by IAEA for some years. By this criterion some 140 nuclear power plants, or more than one-third of the world total, could be considered SMPRs. However, most of them are rather old vintage.

The rapid economic and technological growth in the 1960s and part of the 1970s – with growth rates in electricity consumption between 5 to 10% in many countries and corresponding strengthening of grids – appeared to be a particular incentive for a rapid increase of plant sizes. Plant sizes typically escalated in steps from 300 MW to 600 MW and finally to 1200 MW and even 1300 MW, for reasons of economies of scale and cost competitiveness with fossil power plants. While the industry focused its attention and most design efforts on large plants, it also offered them to some of the more advanced developing countries.

The potential needs of a large group of countries with much smaller grids and therefore limitations in maximum plant sizes was essentially left unattended. Only Cuba, India, and countries of the Council for Mutual Economic Assistance (CMEA) continued with the installation of SMPR size units. Inexpensive supply of oil until the early 1970s, critiques and doubts on the nuclear power option in general, and difficulties in preparation of infrastructure, manpower, and financing possibly contributed to a reduced interest in SMPRs from both the buyer and supplier sides.

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Indications of revived interest

Recent trends, however, indicate a revived interest in smaller plants. Manufacturers, faced with diminishing or uncertain home markets, have taken a new look at the future export market and reassessed the SMPR range as an important portion of potential markets. Developing countries are giving closer attention to long-term energy planning with infrastructure assessment, competitiveness, and availability of suitable plants playing important roles.

In addition, some industrialized countries are showing interest in using SMPRs, particularly those with smaller utilities and/or experiencing low load growth. The interest follows careful evaluations of the pertinent risks involved in power expansion, investment plans under today's financing conditions, and public acceptance constraints. In this context some SMPRs may become forerunners of simpler and safer plants in general.

Today's SMPR supply situation

Due to the increasing recognition that a new market could develop, suppliers have invested in updating and readying their SMPR designs. Among the objectives, trends, and philosophies of the updated small-reactor designs, the following appear particulary noteworthy:

- *Application of modularization.* An example is the Candu design, which shares many components with the 600 MWe plant; an extreme is the Interatom high-temperature reactor (HTR) design, which is based on a number of identical modules.
- *A high level of prefabrication/shop fabrication.* This already is evident in several design descriptions and is maximized in the Rolls Royce 300 MWe unit that is mounted on a barge.
- *Simplification of process and safety systems.* This includes taking advantage of the inherent characteristics of small reactors, such as natural circulation in some boiling-water reactor (BWR) concepts (which is less practical in the large unit due to pressure-vessel size limitations); taking advantage of the high heat-sink capacity of small high-temperature, gas-cooled modules; or making use of integral shutdown and heat-sink capability, such as proposed in the new Swedish concept "process inherent ultimate safety" (PIUS).

Table 1. Available SMPR plants

Country	Company	Type	Power level (MWe)	Ready to bid (years)	Fuel enrichment (%)	Main plant reference
Canada	AECL	Candu	300	0	Natural	600-Plant
France	Framatome	PWR	300	2	4	Pat./Cas.
Germany,	HRB	HTR	100	0	5–9	AVR
F.R.			300			THTR
			500			THTR
	Interatom	HTR	80*	0	7.8	AVR
	KWU	PHWR	300	0	Natural	Atucha
Japan	Mitsubishi	PWR	340	0	3	Mihama-1
	Toshiba	BWR	300	0	3	Onagawa-1
			500	0		Hamaoka-1
UK	NNC	Magnox	300	0	Natural	Oldbury
	Rolls Royce	PWR	300	1	3.3	Submarines
USA	GE	BWR	300	4	2–3	600-BWR
	B&W	PWR	90	5	2–4	Otto Hahn
	B&W	PWR	400	5	2–4	Otto Hahn
USSR	Atomen. Exp.	PWR	440	0	4	Many plants

* To be offered in 2 to 8 modules.

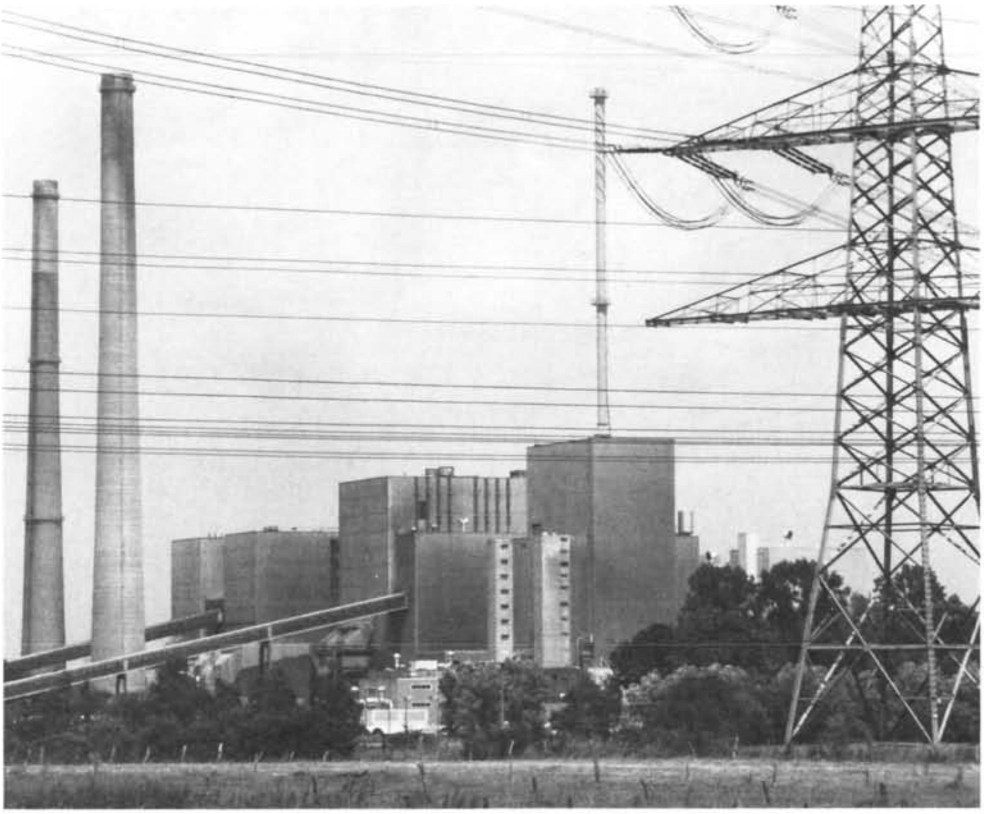
- *The use of standard components.* Examples are using fewer components from a large plant, or derating a large component to a lower output and, therefore, more conservative design. Others count on mass-production benefits.
- *Construction time.* Strong emphasis is placed on shortened and well-controlled construction schedules, supported by engineered constructability and well-defined contract packages, such as the turnkey type.
- *An emphasis on proven demonstration.* This may or may not involve a new prototype but includes using concepts, systems, and components proven by commercial operation in other plants.
- *Enhanced flexibility in site selection.* This is mainly from the point of view of reduced heat-rejection requirements, but also from simpler transportation of major components, e.g. by rail or road instead of barge. SMPRs also should have a psychological advantage with the public, and may be more readily accepted. In addition, most SMPR designs incorporate a relatively high seismic design level, and function satisfactorily with relatively high cooling-water temperatures, further increasing flexibility in site selection.
- *Long-term storage of spent fuel.* To alleviate problems with reprocessing and ultimate waste disposal, most concepts offer options for extended storage facilities, taking spent fuel for up to 30 years.
- *Emphasis on lessons learned.* To achieve good operating performance, lessons from currently operating nuclear power plants are being given significant weight. Designs reflect efforts to increase plant availability, enhance operability and maintainability, and minimize radiation exposure to plant personnel.
- *Operational Services.* Services by suppliers sometimes extend into complete operation and maintenance of the plant for a transition period, before complete turnover to the qualified owning organization.

Presently available designs – those which are ready to be bid within a maximum of five years – are summarized in Table 1. Others are still under development and review by the respective manufacturers. This relatively large number of designs with a good level of development and readiness to bid is only a recent phenomenon.

Evolving Agency programme: New study

To retain the nuclear power option for developing countries, SMPRs have been a programme item in Agency activities for nearly two decades. Efforts have involved many meetings, missions, and reports, even a research contract with a supplier. This was initially to help start and co-ordinate SMPR development and later to explore and update information on important technical and economic aspects.

In the early 1970s, substantial work was invested in an overall market survey in developing countries and in detailed evaluations of a number of candidate Member States. A partial but important objective of this survey was to demonstrate the existence of an SMPR market if the reactors would be available at



Shown at right-center, the 300-MWe high-temperature demonstration reactor, Hamm-Uentrop, in the Federal Republic of Germany is built alongside a coal plant, at left. (Photo courtesy of HRB)

certain costs. Detailed assistance also was provided in the case of two bid evaluations, namely Kuwait in 1975 and Bangladesh in 1978.

An SMPR information meeting held in 1981, in conjunction with the 25th IAEA General Conference, provided a summary of the status and recent thinking, but also pointed out important areas of the complex decision-making process, financing constraints, and infrastructure considerations.

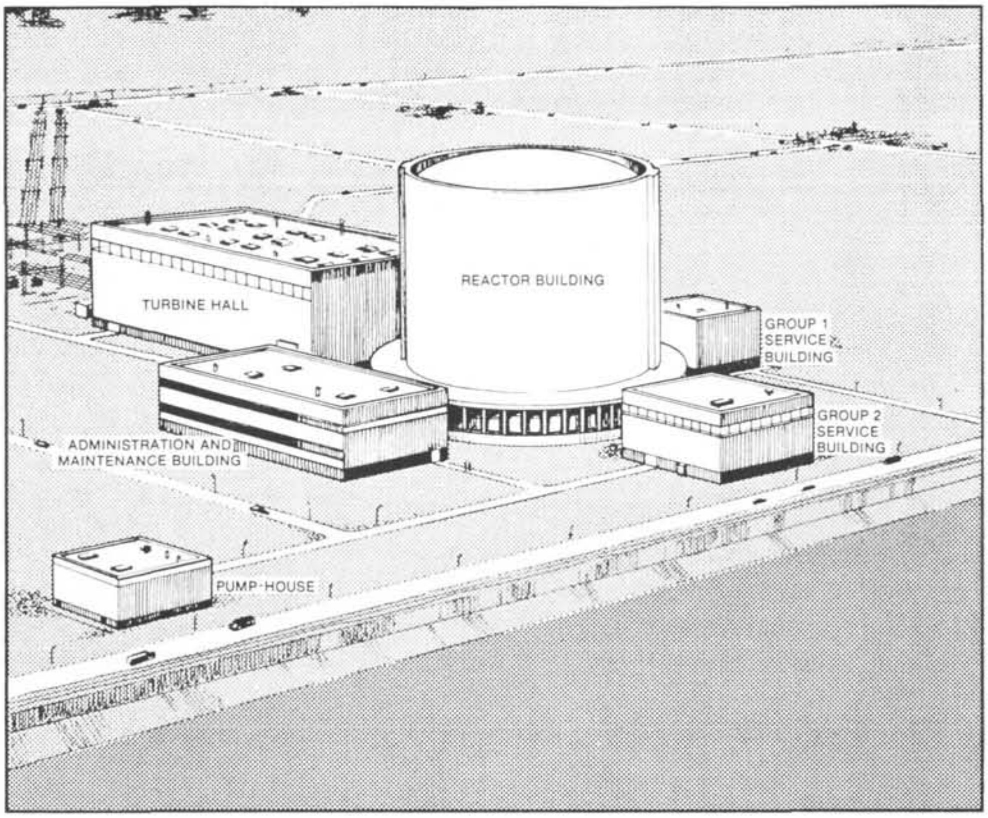
Historical experience and recent trends were largely considered in launching a new study – the IAEA Small- and Medium-Sized Power Reactor Project Initiation Study – conceived as a joint effort between buyers, suppliers, and the financing community. In September 1983, a first Technical Committee meeting was held with participants from the buyer and supplier sides. More recently banks responded favourably to become more involved in this matter. The first meeting generally endorsed the overall concepts of the new study and a phased approach for its implementation was adopted.

According to the main objectives of Phase I of the study, clarification is being sought of major factors in decision-making processes before a concrete nuclear power plant contract negotiation. This includes basic power options, power expansion plans, available plant technology, infrastructure and manpower preparation, as well as financing possibilities. The necessary information is being collected from both the buyer and supplier sides via a rather comprehensive two-part questionnaire and is being supplemented considerably by data in IAEA files. The responses are being compiled and analysed in a Phase I report to provide bases for further planning and decision-making and to build up confidence in the SMPR option. The Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development has shown a keen interest in this study and is providing a survey of the potential SMPR industrialized country market.

Applying study results to specific cases may or may not be favourable for the nuclear power option with an SMPR in a particular country and the particular time-frame studied. Development of other energy options, larger nuclear plants, or a deferred application of SMPR also could be indicated. In any case, the study will offer significant improvements over the present *status quo,* where neither the market nor the status of economically viable designs is well defined.

Market indications

Normally, an SMPR market analysis would be based on a concrete demand in the form of requests for bids for nuclear power plants in the small- and medium-sizes by certain countries and utilities around the world. Actually, such demands have recently not been made known in a concrete form outside Bangladesh, Cuba, India, the Libyan Arab Jamahiriya, and the CMEA countries. On the other hand, many energy experts and many suppliers with knowledge of the developing country market have come to the conclusion that there *ought to be* such a



Recent design of the Candu-300 station. (Courtesy of AECL)

market for the nuclear power option in the future. Therefore, the SMPR programme has been talking about the potential market, recognizing that the preparation for the decisions in Member Countries would take time and would possibly need data, information, and analysis from the SMPR Project Initiation Study.

One assessment of the potential market was developed from a plot of present primary energy consumption per capita against the projected time for which presently-known energy resources in the country would last, as shown in Figure 2. It is interesting to note that most of the 25 countries with operating nuclear power plants fall into a distinct upper left-hand area of the graph, of low resources and high consumption. Twenty countries are included in this area, with Brazil marked as a borderline case for the criteria chosen. Not shown in the shaded area are several countries that could have considered the nuclear option but did not by these simple criteria, for example Austria, Denmark and Greece.

Only five countries with operating nuclear power plants fall outside the shaded area of high consumption and low resources, namely South Africa, the USA, and the USSR in the high-resource area, and India and Pakistan with a still relatively low *per capita* energy consumption rate. It might be noted that India and Pakistan are two relatively large countries with considerable gradients of economic and technological development internally and with the potential of establishing "high-technology islands" for their nuclear power programmes. In this low-consumption area outside the shaded area, the Phillipines would be next, once their plant starts operation.

By method of deduction the next potential candidates for nuclear power, now and for the forthcoming two decades, could be indicated simply by considering the growth direction for countries as shown for Brazil in the graph over a period of 20 years. Accordingly some 25 countries presently without commercial nuclear power plants would be expected to move into the shaded area. Thus, they could become prime candidates for nuclear power, if favourable evaluations are also obtained on other important considerations, such as grid sizes, infrastructure preparation, and financing aspects.

Another approach being explored in Phase I of the study is based on internally-generated gross national product and financial positions of the country. Such considerations will take into account the priority energy investments should enjoy and the relatively secure demand for electricity in developing countries. Again, a list of some 10 to 25 countries is expected from such an investigation and would partially overlap with the former list. Such a number of countries and their projected energy needs constitute a significant increment of energy demand before the turn of the century. If only part of this would be met by nuclear, and half of the nuclear portion would be plants of small size, it could mean a market of over 100 SMPR units. On the other hand, the market could also continue at the near-zero level if present uncertainties are not removed or if encouraging results are ignored.

As an overlay to the above potential market considerations, an exemplary but not exclusive subgroup will be represented by the growing number of countries which respond to the questionnaire of the IAEA SMPR study.

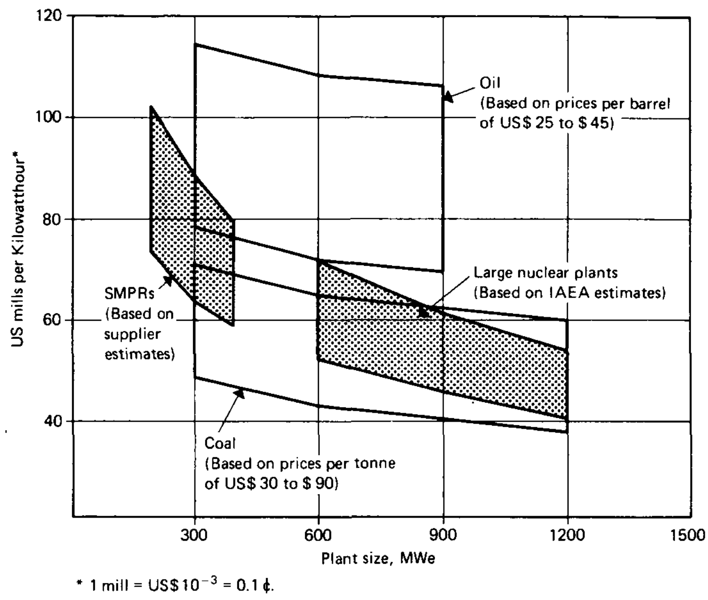


Figure 1. Cost ranges of electricity generated by nuclear, coal, and oil-power plants starting operation in 1990.

So far, Argentina, Chile, Finland, Indonesia, Malaysia, Mexico, Sri Lanka, and Thailand have responded. Although several of these countries now indicate that their plans for the nuclear power option are not yet firm, the active interest in the SMPR study could eventually lead to concrete indications in the market.

Economic competitiveness and financing aspects

Economic competitiveness is a precondition for the feasible introduction of nuclear power plants into a country and for securing project financing. Long-term considerations of alternate energy options, assured energy supplies, the export/import balance and infrastructures enter the picture as well. An estimate for nuclear power's present competitiveness with other major energy sources is presented in Figure 1. The final electricity generation costs were calculated with a set of typical assumptions, such as a plant capacity factor of 70%, an effective discount rate of 10% per year, and a plant economic life of 30 years. For the nuclear plants, net capital costs are the determining factor and were varied within the current spread of supplier indications for the SMPRs and IAEA large plant estimates, respec-

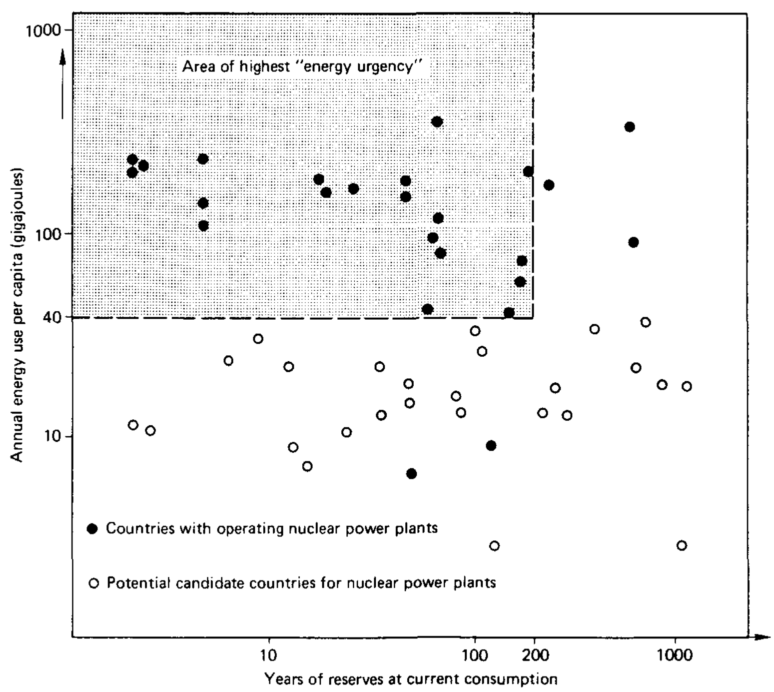


Figure 2. Presentation of countries in terms of energy need.

tively. For the fossil competition, worldwide averages for capital costs were assumed but the more influential fuel costs were varied as shown. Construction schedules were varied from six years for the SMPR to eight years for large nuclear plants and five to six-and-a-half years for corresponding fossil plants. Other size-dependent factors, such as financial risk assessment were not considered, but are discussed below.

Under the above assumptions and the presently large spread in expected capital costs, an expensive SMPR at the 300-MW level would still compete with oil at current prices and would easily compete with possibly increasing prices. SMPRs in the lower-projected cost range, a possibility by the latest cost indications, could be competitive with expensive coal. This could become relevant where local infrastructure and inland transportation costs are added to current world market price levels of coal.

As to competition with hydroelectric plants, the greater flexibility in locating nuclear plants, possibly closer to load centres, is a consideration. While well-located and well-managed hydroelectric plants may be considerably less expensive, recent experience with large hydro plants in countries with poorly developed infrastructures, remote locations, and long transmission lines, for example, suggests that SMPRs may be a viable alternative.

To focus more closely on the competition between large and small nuclear power plants – where this option exists – one has to recognize the domination of capital costs, a particular feature of nuclear power it has partly in common with hydroelectric plants. Large capital layouts are needed at the project's beginning,

Factors of scale

To understand the scaling detriment of the SMPR, it is important to review some fundamental facts of the economics of large equipment. Typically in the power and chemical industries, a simplified consideration would – on the one hand – make *volume* of tanks, pipes, and so on, roughly proportional to the power output or to production volume, while the ***surface area*** more closely determines the material quantities used and the costs incurred. Since surface area develops to the two-thirds power of volume, the relationship of material quantities or costs with output would also follow a two-thirds power (exponent) law. This means that plant costs would move with power output to a scaling exponent of two-thirds (0.67), rather than to 1.0, which would make them proportional to output. Taking into account that engineering licensing and inspection costs may not vary much with size at all, the scaling exponent actually would even be lower, about 0.5. (This corresponds to a well-known square root law that has largely been assumed to be applicable to all types of large industrial equipment, including nuclear power plants.)

The end result is that a plant twice the size of another would only cost 1.4 times as much in total net capital expenditures, and the specific cost per unit of output would favour the larger plant by about 40%. Assuming average cost trends, amounting to about US $2500 per kilowatt for the 300-MWe size, a net capital cost disadvantage of some US $700 per kilowatt installed of the 300-MWe plant versus the 600-MWe size is found.

Besides capital costs, other points were identified and clarified in a specialist meeting held within the scope of the IAEA SMPR study. These are all potential qualitative effects that appear size-dependent and have a bearing on the economical or technical performance of nuclear plants. The factors identified are:

- Local participation
- Local infrastructure
- Construction schedule
- Capacity factor
- Reserve margins
- Transmission system
- Financing availability and terms
- Import dependence, resources
- Low load growth
- Institutional considerations
- Public acceptance
- Diverse risks in planning, implementation, financing, and side-effects

Several of these factors – namely local participation, local infrastructure, and transmission system – could be neutral, positive, or negative, depending on local conditions. The last five items would moderately favour the 300-MWe size plant. Four other items – the construction schedule, capacity factor, reserve margins, and financing availability and terms – would contribute important credits of US $200, $100, $100, and $200 per kilowatt, respectively. This would nearly offset the capital cost detriment.

This somewhat surprising result – not analysed to this extent before – may very well explain why several energy planners and some smaller utilities in industrialized countries are reconsidering smaller nuclear plants. The findings also may convince some developing countries that want to make use of nuclear power in the future, that they should not wait for the larger size if they can accommodate an SMPR sooner. Even if the SMPR solution is only barely competitive, two major feasibility considerations may make it a prime choice:

First of all, some smaller grids in developing countries can meaningfully integrate only the SMPR size in the near future. A counterpart of this factor in industrialized countries would be smaller total load increases that require capacity additions in smaller blocks.

Secondly, in situations of difficult financing – which may apply to developing countries or to indebted utilities in industrialized countries – the huge investment needed for large plants and a tendency for full financing sometimes make such projects unfeasible. Plants that may cost up to half as much, on the other hand, could improve the financing chances.

have to be sustained over extended periods of construction without any revenue from electricity sales, and require stretched-out payback periods because of cash-flow considerations. Based on net capital cost per kilowatt-installed, SMPRs would be more marginally competitive than large plants, although in a limited grid situation competing smaller fossil-fired and hydropower plants also might suffer from scaling effects to some extent. On second glance, however, there are a number of additional size-dependent factors that can change the comparative picture between large and small plants, as explained in the accompanying box.

Considering the experience with scaling factors, the findings of a recent consultants meeting on SMPR financing also can be considered a welcome addition to the understanding of SMPR projects. The participants – who had a wide range of banking experience – identified several items for financial evaluations of risk. After assessment of fundamental macro-economic factors prevailing in the specific country, the bankers cited project considerations that included assurance of project completion, confidence in the budget and schedule, assurance that the project's scope is complete, assurance that financing covers the total project scope, and confidence in project management. Several of these factors may be dependent on plant size and final answers on them may well favour the SMPR option.

In conclusion, then, SMPRs may become a logical option and alternative to large plants in developing and industrialized countries. The renewed interest has advanced SMPR design work to such an extent that concrete negotiations could start on most offers. Further, the implementation of SMPRs is becoming a sound proposal from a technical, safety, and economical point of view. Prefabrication, standardization, shorter construction times, and firm project performance controls are being recognized as important ingredients for their implementation.

SMPRs down to sizes of typically 300 MWe would compete favourably with fossil fuels under many prevailing conditions. SMPRs adapt particularly well to situations of limited grid sizes, limited load growth, difficult financing and/or developing infrastructures, and they could very well rival large nuclear plants in certain situations. Positive recent developments in SMPR make the nuclear power option feasible again to a wider range of countries, possibly adding 20 to 25 potential candidates before the end of the century. The long-term foresight, the national commitment, the proper preparation and the decision-making process, however, will rest with each country and needs its initiative. The supplier readiness can be judged high and IAEA assistance in these processes is reflected in the on-going SMPR Project Initiation Study.