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Current Status, Technical Feasibility and Economics of Small Nuclear Reactors

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Foreword

Larger nuclear reactors typically have lower specific costs due to the economy of scale, resulting in nuclear power plants with reactors of 1 000-1 600 MWe being most commonly commercialised today.

However, there is currently a growing trend in the development and commercialisation of small and medium-sized reactors (SMRs), i.e. reactors with effective electric power less than 700 MWe. The main arguments in favour of SMRs are that they could be suitable for areas with small electrical grids and for remote locations, and that due to the smaller upfront capital investment for a single SMR unit the financial risks associated with their deployment would be significantly smaller than for a large reactor. This offers flexibility for incremental capacity increases which could potentially increase the attractiveness of nuclear power to investors.

This report is a summary of the development status and deployment potential of SMRs. It brings together the information provided in a variety of recent publications in this field, and presents the characterisation of SMRs currently available for deployment and those that are expected to become available in the next 10-15 years. Additionally, it highlights the safety features and licensing issues regarding such reactors.

Particular attention is given to the economics of SMRs, and the various factors affecting their competitiveness are analysed and discussed. Vendors' data on the economics of different designs are compared with independent quantitative estimates of the electricity generating costs, and the deployment potential of such reactors in a number of markets and geographic locations is assessed.

Acknowledgements

This report was prepared by Vladimir Kuznetsov, Consultant, and Alexey Lokhov of the NEA Nuclear Development Division.

Detailed review and comments were provided by Ron Cameron and Marco Cometto of the NEA Nuclear Development Division, with other reviews and input from members of the NEA Nuclear Development Committee.

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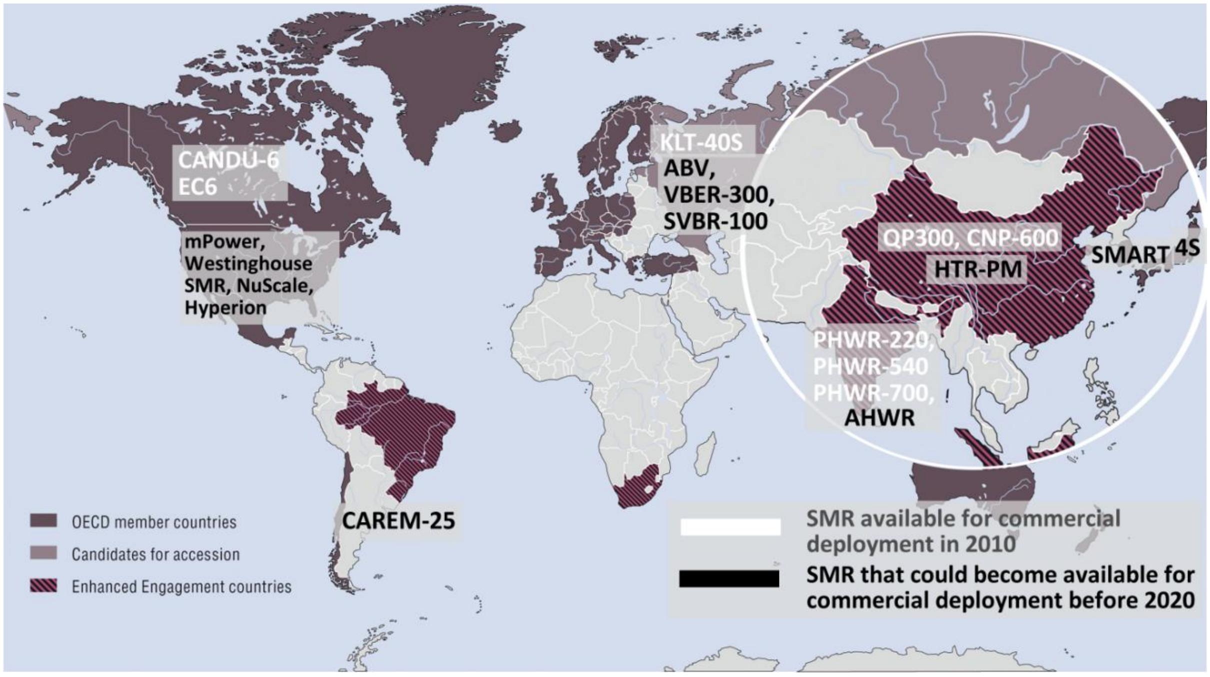
Executive Summary

Currently, there are two definitions of such reactors widely used in the literature: small and medium-sized reactors (SMRs) and small modular reactors. Small modular reactors have attracted much attention since 2008 when several very small reactors (less than 125 MWe) were being designed in the United States. In this study, the general class of reactors with effective electric power of less than 700 MWe will be considered, but the principal focus is on reactors of less than 300 MWe.

First, the report summarises the information provided in a variety of recent publications in this field, and presents the characterisation of SMRs already available for deployment and those that are expected to become available in the next 10-15 years, see Figure E.1.

In the second part of the report, the study provides an independent estimate of electricity generation costs for the near term SMRs, and an analysis of their deployment potential. It also highlights the safety features and licensing issues of such reactors.

Figure E.1. Currently available and advanced SMRs



The SMR concept has been considered since the early days of nuclear power. Historically, all early reactors were smaller in size compared to those deployed today. However, the general trend has always been toward larger unit sizes (with lower specific costs due to the economy of scale), resulting in nuclear power plants with reactors of 1 000-1 600 MWe, being most commonly commercialised today.

However, starting from the mid-1980s, a new set of requirements has motivated, in some countries, the **development of intentionally smaller reactors aimed at niche markets that cannot**

accommodate large nuclear power plants (NPPs). Slow progress over the past two decades has resulted in about a dozen new SMR concepts reaching advanced design stages (see Table E.1), with one plant (a barge-mounted co-generation plant with two ice-breaker type KLT-40S reactors) currently under construction in the Russian Federation, three more are in a formal licensing process in Argentina, China, and the Republic of Korea, and several others being under pre-licensing negotiations in the United States and India.

At a fundamental level, **plants with SMRs are not different from those with large reactors.** However there is a need to consider SMRs separately because of the:

- Higher degree of innovation implemented in their designs; and
- Specific conditions and requirements of target markets.

Today, SMRs target two general classes of applications:

- Niche **applications in remote or isolated areas** where large generating capacities are not needed, electrical grids are poorly developed or absent, and where non-electrical products (such as heat or desalinated water) are as important as the electricity.
- Traditional deployment in **direct competition with large NPPs**. As we shall see, the upfront capital investment for one unit of a SMR is significantly smaller than for a large reactor. Thus there is more flexibility in incremental capacity increases, resulting in smaller financial risks, making such reactors potentially attractive to investors and for countries initiating a nuclear programme.

Overview of SMR designs considered

Currently available SMRs

At the time of this report (2011), there are eight proven SMR designs available for commercial deployment. Among these SMRs, the Canadian CANDU-6 and EC6 and the three Indian PHWR-220, 540 and 700 are pressure-tube type heavy water reactors, while the Russian KLT-40S and the Chinese QP-300 and CNP-600 are pressurised water reactors. The CANDU-6 and the QP-300 have already been deployed internationally, and there are agreements to build more of these reactors in Romania and Pakistan, respectively. Other designs among the currently available SMRs also target international markets.

All the plants except the Russian KLT-40S are traditional land-based nuclear power stations. The first-of-a-kind (FOAK) Russian barge-mounted plant with two KLT-40S reactors is still in the construction phase, targeted for deployment in 2013. This plant will provide 2×35 MWe of electricity and 25 Gcal/h of heat for district heating.

Advanced SMRs currently being developed

About twelve advanced SMRs currently being developed have reached advanced design stages and could in principle be implemented as FOAK or prototype plants before 2020. In some cases, the pre-licensing negotiations or a formal licensing process have been initiated.

As can be seen from Table E.1, the majority of these near-term advanced SMRs are pressurised water reactors (PWRs), but there is one indirect cycle high temperature gas cooled reactor (HTGR, using superheated steam in the power circuit) and one advanced heavy water reactor (AHWR). Three liquid metal cooled SMRs, (two lead-bismuth cooled and one sodium cooled), are also currently being developed. However, only prototype plants are expected by 2020 due to the high degree of innovation required in relation to the long refuelling intervals.

Table E.1. Design status and potential timeframes for deployment of advanced SMRs

SMR	Technology family	Electric output, MWe	Plant configuration	Design status	Licensing status/Completion (Application) date	Targeted deployment date
KLT-40S, Russia	PWR	2×35	Twin-unit barge-mounted plant	Detailed design completed	Licensed/Under construction	2013
VBER-300, Kazakhstan, Russia	PWR	302	Single module or twin-unit, land-based or barge-mounted plant	Detailed design nearly completed.	n/a	> 2020
ABV, Russia	PWR	2×7.9	Twin-unit barge-mounted or land-based plant	**Barge-mounted plant:** detailed design completed **Land-based plant:** detailed design for plant modification in progress	Part of design licensed	2014-2015
CAREM-25, Argentina	PWR	27	Single module land-based plant	Detailed design being finalised	Licensing in progress/2011	Prototype: 2015
SMART, Republic of Korea	PWR	90	Single module land-based plant	Detailed design in progress	Licensing in progress/2011	~2015
NuScale, USA	PWR	12×45	Twelve-module land-based plant	Detailed design being finalised	Licensing pre-application/ (Application: 2011)	FOAK in 2018
mPower, USA	PWR	×125	Multi-module land-based plant	Detailed design in progress	Licensing pre-application/ (Application: 2011)	~2018
IRIS*, USA	PWR	335	Single module or twin-unit land-based plant	Basic design completed and is under review by the vendor		
Westinghouse SMR	PWR	>225				
HTR-PM, China	HTGR	2×105	Two-module land-based plant	Detailed design completed	Licensing in progress/ 2010 or 2011	FOAK in 2013
AHWR, India	Advanced heavy water reactor	300	Single module land-based plant	Detailed design being finalised	Licensing pre-application/ (Application: 2011)	~2018
SVBR-100, Russia	Pb-Bi cooled fast reactor	×101.5	Single module or multi-module land-based or barge-mounted plant	Detailed design in progress.	n/a /Prototypes have operated in Russian submarines	Prototype: 2017
New Hyperion power Module, USA	Pb-Bi cooled fast reactor	×25	Single module or multi-module land-based plant	n/a	Licensing pre-application/(Application: not known)	FOAK by 2018
4S, Japan	Na cooled fast reactor	10	Single module land-based plant	Detailed design in progress.	Licensing pre-application/ (Application: 2012)	FOAK after 2014

* Late in 2010 the Westinghouse Electric Company stopped the development of the IRIS project and announced it would go with an alternative integral design PWR of a 200 MWe class. Very few technical details of this new SMR were available as of June 2011.

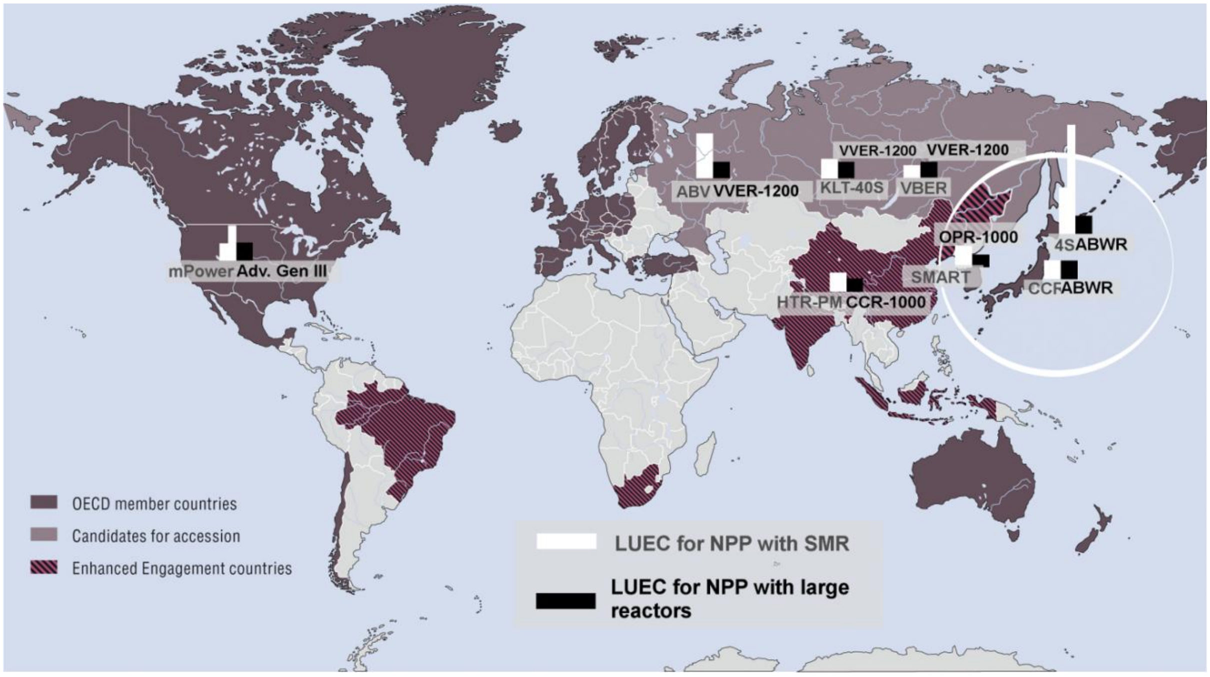
The electrical output of these advanced SMRs varies from 8.5 to 335 MWe (per reactor module). The majority of advanced SMRs provide for twin-unit or multi-module plant configurations with the correspondingly increased overall capacity of a nuclear power station. All Russian SMR design concepts provide for, or do not exclude, a barge-mounted plant configuration. In other countries the SMR projects are traditional land-based. Endeavours

Some SMRs, especially those targeting applications in remote or isolated areas, propose to implement co-generation with non-electrical energy products. District heating is included in all Russian PWR SMR designs, with the production of desalinated water specified as an option. Water desalination is proposed by the Indian AHWR and Korean SMART concepts.

The analysis of factors influencing the competitiveness of SMRs

SMR vendors' projections on the levelised unit cost of electricity[1] (LUEC) suggest that in many cases the designers may intend to compete with large nuclear power plants (see Figure E.2). Other SMR concepts target niche applications in remote or isolated areas where the corresponding costs of generating electricity are significantly higher than in more populated areas.

Figure E.2. Comparison of the designers' data on SMR LUEC to the projected costs of generating electricity by NPPs with large reactors in the corresponding countries



The key parameters

In order to analyse the economics of different SMR projects and their deployment potential, the factors affecting the competitiveness are estimated and analysed in this report.

It is expected that the deployment of SMRs foreseen in the next decade would mainly take place in regulated electricity markets with loan guarantees. For such markets, the LUEC appears to be an appropriate figure of merit. The LUEC, measured in USD per MWh, corresponds to the cost assuming certainty of production costs and stable electricity prices. In view of this, LUEC

[1] Levelised unit cost of electricity (LUEC) is calculated using the discounted cash flow method over the whole lifetime of the plant, and includes the initial investment, operations and maintenance, cost of fuel, financing and decommissioning costs. LUEC is measured in the units of currency per units of energy (*e.g.* in USD per MWh).

was selected as the figure of merit for all estimates, evaluations and comparative assessments carried out within this study.

The assumption of a regulated market is not correct for liberalised electricity markets where prices are not regulated. In such markets the fixed costs, the total costs and the capital-at-risk matter more than LUEC. No quantitative examinations using these factors have been performed in this study.

Factors affecting the competitiveness of SMRs

At a very general level, SMRs could be divided into two major categories: traditional land-based nuclear power plants and transportable (e.g. barge-mounted) plants. Land-based SMRs could be assembled on-site (like large reactors) or fabricated and assembled in full at a factory. These options have very different effects on the competitiveness of each particular project.

Factors influencing capital investment costs

One of the main factors negatively affecting the investment component of LUEC for all SMRs is the **economy of scale**. Depending on the power level of the plant, the specific (per kWe) capital costs of SMRs are expected to be tens to hundreds of percents higher than for large reactors. While the lack of economy of scale increases the specific capital costs and, therefore, the total investment, other SMR features are put forward by the designers to improve their economic outlook:

- **Construction duration**. According to the vendors' estimates the construction duration of SMRs could be significantly shorter compared to large reactors, especially in the case of factory-assembled reactors. This results in an important economy in the costs of financing, which is particularly important if the discount rate is high (the specific capital costs could be reduced by up to 20%).

- **First-of-a-kind factors and economy of subsequent units on the site/multi-module plants**. According to reported experience, the FOAK plants are 15-55% more expensive than the subsequent serial units. Building several reactors on the same site is usually cheaper than building a NPP with a single reactor. These factors apply both to large reactors and SMRs. However, if the overall capacity requirement for the site is limited to, say, 1-2 GWe, the effects of learning in construction and sharing of the infrastructure on the site will be stronger if building several plants. The reduction in effective (per unit) capital cost of SMRs could be 10-25%.

- **Economy of subsequent factory fabricated units**. In contrast to large reactors, some SMRs could be fully factory manufactured and assembled, and then transported (in the assembled form) to the deployment site. Factory fabrication is also subject to learning which could contribute positively to a reduction in capital costs of SMRs and in the investment component of the LUEC. The magnitude of the effects of learning in factory fabrication of SMRs is considered to be comparable to that of the effects for on-site built plants (up to 30-40% in capital cost reduction, on the total).

- **Design simplification**. In some advanced SMRs, significant design simplifications could be achieved through broader incorporation of size-specific inherent safety features that would not be possible for large reactors. If such simplifications are achieved, this would make a positive contribution to the competitiveness of SMRs. The vendors estimate that design simplification could reduce capital costs for near-term pressurised water SMRs by at least 15%.

- **Full factory fabrication of a barge-mounted plant**. According to the vendors' data, a full factory fabricated barge-mounted NPP could be 20% less expensive compared to a land-based NPP with a SMR of the same type. The corresponding improvement of the LUEC would, however, be limited to 10% because of increased operation and maintenance costs for a barge-mounted plant.

The possible impact of the factors above and their combined action were assessed though a number of case studies presented in this report. **However, even if all of the above mentioned factors are taken into account, the investment component of the LUEC for a SMR would be at least 10-40% higher than in the case of a NPP with a large reactor** in the same country.

Another notable feature of SMRs is that the total overnight costs are significantly lower (in absolute value) than the costs of large NPPs. This could make them attractive for investors in liberalised energy markets and to countries willing to develop their nuclear programme but having limited financial power.

Also, SMRs allow for incremental building which reduces considerably the capital-at-risk, compared to conventional large nuclear power plants.

Factors influencing O&M, fuel and decommissioning cost.

Regarding the sum of the **operation and maintenance (O&M)** and **fuel cycle** components of the LUEC for advanced SMRs, it is likely to be close to the corresponding sum for a large reactor (of similar technology). This observation results from the combined action of the following two factors:

- The SMR vendors often indicate the **O&M contribution to the LUEC could be lower** than in present day large reactors due to a stronger reliance of SMRs on the inherent and passive safety features, resulting in simpler design and operation.

- Regarding the fuel costs, SMRs generally offer lower level of fuel utilisation compared to state-of-the-art large reactors, mainly because of the poorer neutron economy of a smaller reactor core. Lower levels of fuel utilisation results in a **higher fuel cost** (per MWh), which is most sharply manifested for SMRs with long refuelling intervals.

Thus, in this study, the sums of the O&M and fuel costs for land-based SMRs were taken to be equal to the corresponding sums for reference large reactors. For barge-mounted plants, the corresponding sums were multiplied by a factor of 1.5 reflecting the assumption of a higher O&M costs from the need for periodical factory repairs of a barge.

Because of the discounting in the LUEC calculation, the impact of the **decommissioning costs** (which are the expenditures to be made in 40-60 years after the start-up of commercial operation of a plant) on LUEC is very small for both SMRs and large reactors.

Co-generation of energy products

NPP operation in a **co-generation mode** with co-production of heat or desalinated water can potentially lead to significant additional revenue or credit[2] expressed in a currency unit per MWh. For

[2] In order to arrive at a heat credit per MWh of electricity, one needs to establish the total value of the heat produced over the lifetime of the plant by multiplying total heat output by its per unit value. The total value of the heat output is then divided by the lifetime electricity production to obtain the per MWh heat credit. For plants operated in a co-generation mode, a heat credit is then subtracted from total unit costs to establish an equivalent of the levelised costs of producing only electricity.

some SMR designs operating in a co-generation mode, the values of LUEC could be in this way improved by about 20-30%.

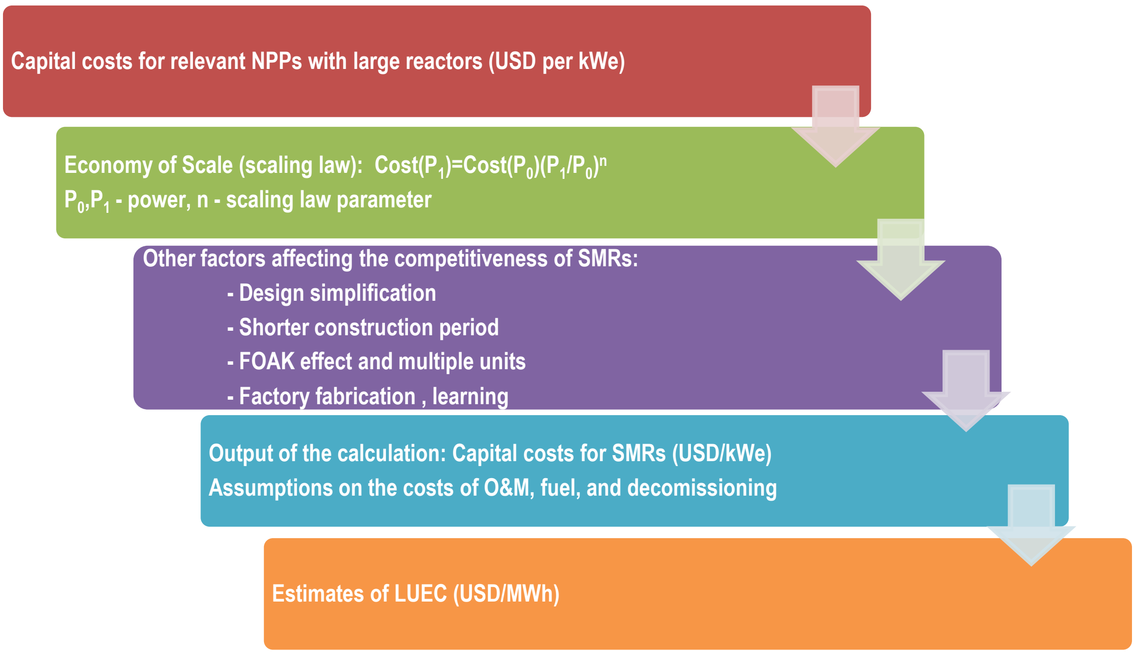
However, co-generation is not an attribute of SMRs only. From a technical point of view it could be realised with NPPs with reactors of any capacity. However, the SMR power range seems to better fit the requirements of the currently existing heat distribution infrastructure. Also, in isolated and remote areas the co-generation of heat or desalinated water is a high priority and must be implemented in the power plant (nuclear or not).

Estimates of levelised unit electricity cost

Methodology

In this report, independent estimates of the cost of generating electricity (LUEC) on NPPs with SMRs (PWR type) were performed using the scaling-law methodology and the numerical estimates of the various factors affecting the competitiveness of SMRs. This approach is schematically summarised in Figure E.3.

Figure E.3. Methodology for independent LUEC estimates



Because of the approximate nature of the methodology[3] and sparse input data, the estimates were performed for some "model" designs (denoted as PWR-X, where X stands for the electric output), rather than for the actual advanced SMR design concepts. For the purpose of this study these "model" **PWR-X are assumed to belong to the same or similar technology families and the only variable parameters are the electric output X and the deployment strategy**.

[3] The parameter n of the scaling law is not known precisely. Based on reported values and analysis, an interval of n=0.4-0.6 has been considered in the calculations. For example, if the size of the unit is decreased by a factor of 2, the capital cost would decrease only by 25-35%. That would result in an increase of the specific capital cost by a factor 1.3-1.5.

The electric output values and the deployment strategies for the PWR-X (see Table E.2) were inspired by the advanced SMR designs listed in Table E.1. For each PWR-X a relevant large nuclear reactor was selected. The cost data for this large reactor was used as an input data for the calculation of the investment cost of the PWR-X using the scaling law approximation (see Figure E.3). Next, the estimates of the O&M and fuel costs are added, and finally an estimate of LUEC for the PWR-X is obtained.

Table E.2. Advanced SMRs (PWRs) for which the LUEC estimates were performed

Plant configuration and layout	Electric output of the power plant, MWe	PWR-X is inspired from:	Capital cost of PWR-X is obtained (scaled) from:
PWR-8TB PWR-8 twin-unit barge-mounted	15.8	ABV Russia	VVER-1150 Russia
PWR-35TB PWR-35 twin-unit barge-mounted	70	KLT-40S Russia	VVER-1150 Russia
PWR-90SL PWR-90(1) single module plant	90	SMART Korea	APR-1400 Korea
PWR-90SL PWR-90(2) single module plant	90	SMART Korea	OPR-1000 Korea
PWR-125ML PWR-125 five module plant	625	mPower USA	Advanced Gen. III+ USA
PWR-302TB PWR-302 twin-unit barge-mounted	604	VBER-300 Russia	VVER-1150 Russia
PWR-302TL PWR-302 twin-unit land-based	604	VBER-300 Russia	VVER-1150 Russia
PWR-335TTL PWR-335 two twin-units	1 340	IRIS USA	Advanced Gen. III+ USA

Results for LUEC estimates

The resulting LUEC estimates were compared to the designers' cost data (see Figure E.4). Such a comparison was found useful in understanding the various factors influencing the economics of SMRs, and also to highlight the points that may need further clarification. The major findings of the comparison are the following:

- The LUEC estimates are quite sensitive to the selection of the parameter for the scaling law, and the inclusion of the heat credit. It is not clear if the designers have included the heat credit in their announced LUEC values. Thus, two cases have been considered:

  – If the heat credit is not taken into account the majority of the independent LUEC estimates are significantly higher when compared to the designers' data on LUEC.

  – If heat credit is taken into account (where it applies), most of the independent LUEC estimates for land-based SMRs envelope the designers' data on the LUEC.

  – However, the independent LUEC estimates for some barge-mounted SMRs are significantly higher than the designers' data. No explanation has been found for this.

Figure E.4. Difference (in %) between estimated LUEC and the designers' values for LUEC (dark blue). light blue - heat credit

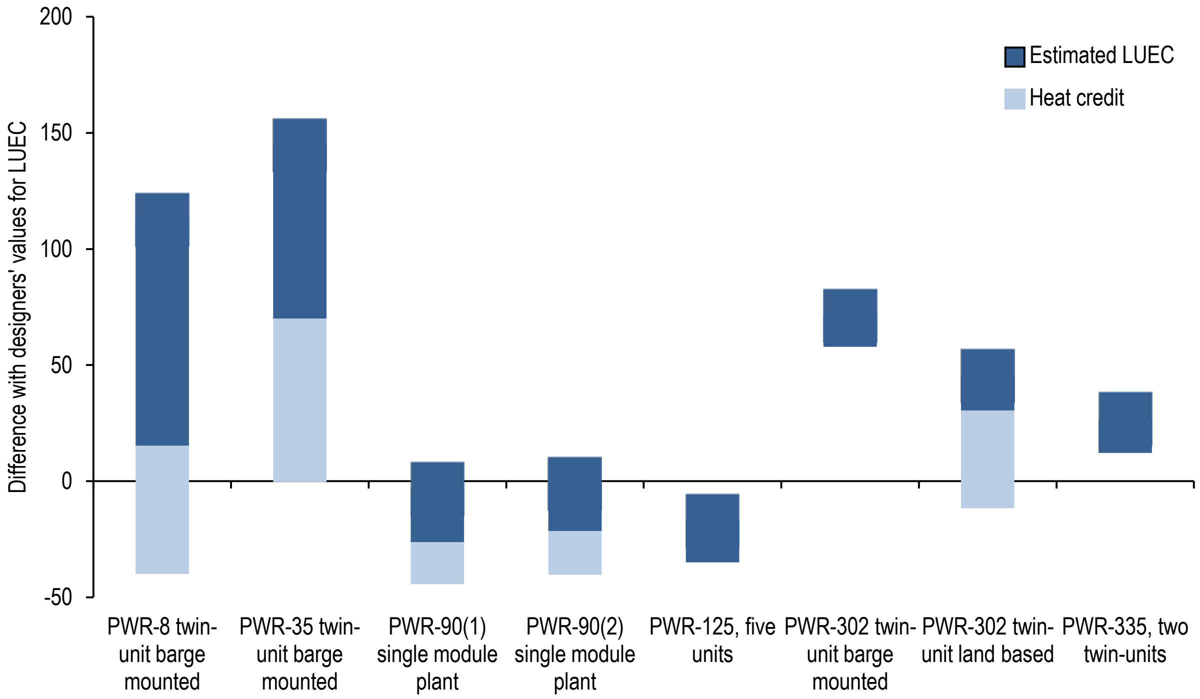


Figure E.5 plots the overnight cost for SMR based plant configurations of Table E.2 versus the total net electric outputs of the plants. It can be seen that, even though the specific investment costs (per kWe) for SMRs are in some cases rather high, the total investments are relatively small for a small reactor. **For single module SMR plants with the electric output below 125 MWe the total investments are below USD 1 billion.**

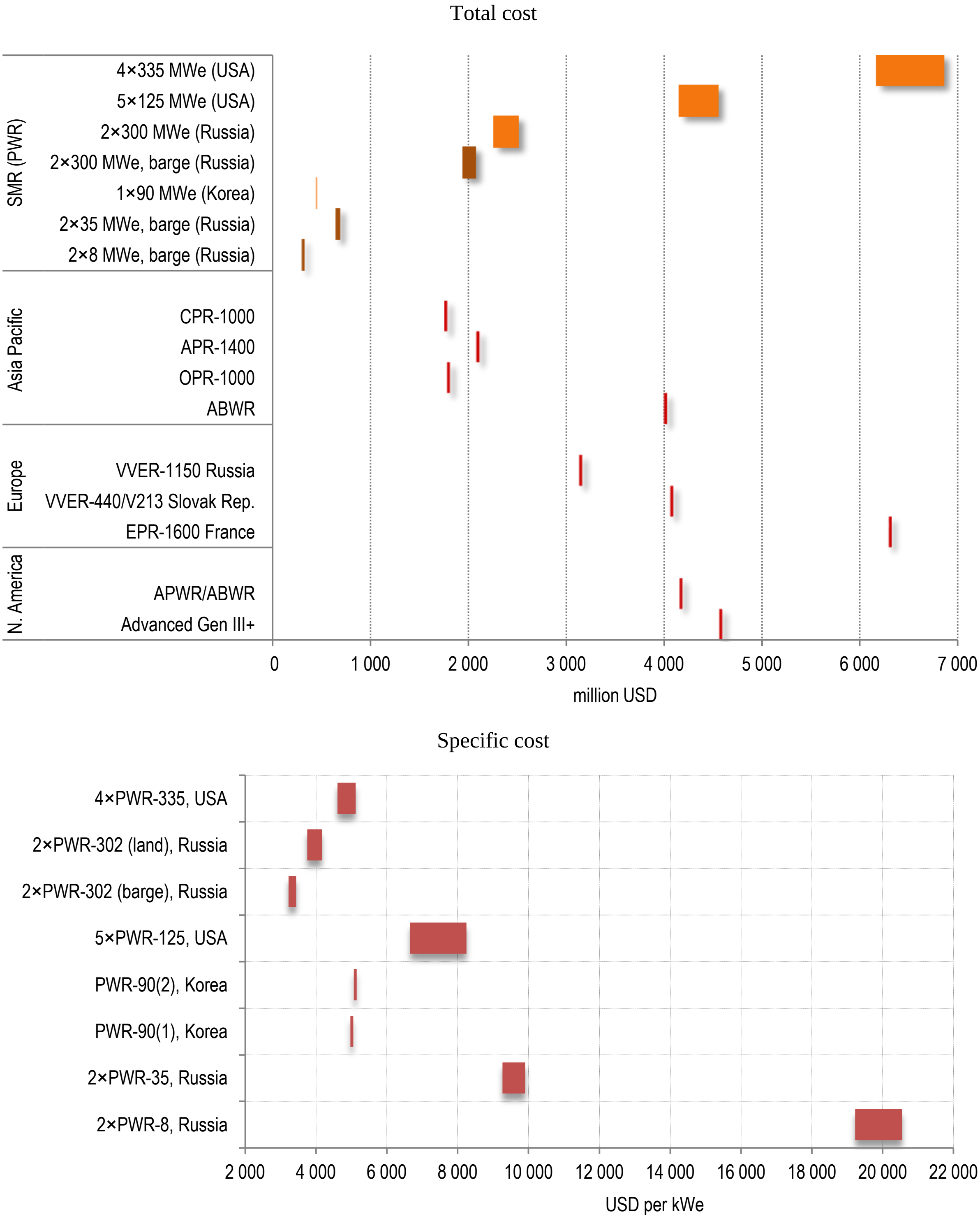
Another interesting feature of SMRs is that they could be incrementally deployed in relatively short time frames, owing to a shorter construction period. Together with low per-unit costs, this could lead to a significant reduction of the front-end investment and the capital-at-risk, when compared to using large reactors to increase capacity.

In view of the above mentioned issues, there is an increasing interest of private investors in SMRs. Recently the so-called "mini" or small and modular reactors have attracted a lot of attention. Since 2008, several small private companies have been created in the United States to support the design development, patenting, licensing and commercialisation of several new SMR concepts.

The attributes of small and modular reactors, such as small upfront capital investments, short on-site construction time (with the accordingly reduced cost of financing), and flexibility in plant configuration and applications are attractive for private investors.

In the United States, the formation of public-private partnership supporting the certification and licensing of small and modular reactors is being supported by the new Small and Modular Reactor programme of the Office of Advanced Reactor Concepts belonging to the Office of Nuclear Energy of the Department of Energy (DOE) which started in May 2011. In the Russian Federation, a public-private joint venture company named "AKME Engineering" was recently created to drive forward the project of the SVBR-100 reactor expected to be constructed by 2017 (see Table E.1).

Figure E.5. Overnight cost for various SMRs and large reactor deployment projects



The competitiveness of SMRs deployed in regular and remote or isolated areas

The independent LUEC estimates performed in the report were used to analyse the competitiveness of SMRs in the electricity and combined electricity/heat markets of some countries. In this analysis the LUEC estimates for the various SMR plant configurations were compared to the projected costs of generating electricity or the electricity tariffs. The analysis has been performed separately for the generation of electricity and co-generation of electricity and heat in areas with large interconnected electricity grids ("on-grid" locations), and also for the isolated or remote locations with small, local electricity grids or with no grids at all ("off-grid" locations).

For the "on-grid" locations the countries addressed included Brazil, China, Japan, the Republic of Korea, the Russian Federation, and the United States for electricity, and China, the Russian Federation, and the United States for combined electricity and heat generation. The basis for comparison was provided by the recent OECD-IEA/NEA publication, *Projected Costs for Generating Electricity, 2010 Edition*, which contains reference projections on LUEC for NPPs with large reactors, coal-fired plants, gas-fired plants, and the renewable plants (including hydroelectric plants, wind plants, etc).

Regarding the "off-grid" locations, the countries addressed included Canada, the Russian Federation and the United States. In the evaluations, LUEC estimates for the NPPs with SMRs derived in the report were compared to the electricity tariffs in selected locations.

Traditional deployment in large interconnected electricity grid

In Figure E.5, the total investment costs for the various plant configurations with SMRs are compared to those of the currently available NPPs with large reactors. It could be seen that the projects with several SMR units, yielding significant amounts of electric power, seem to require investments comparable to those of some NPP projects with large reactors in Europe and North America. In Asia, the construction of NPPs with large reactors requires less capital than in Europe and North America, and all of the plant configurations with SMRs, except for the very small ones, appear to be significantly more expensive to build.

Figures E.6 and E.7 present the regional ranges of LUEC for large nuclear, coal and gas plants and the estimated values of SMR LUEC at 5% and 10% discount rates, for the "on-grid" locations.

The general findings from the study on the competitiveness of SMRs in the "on-grid" locations are similar to the general conclusions on nuclear power made in the recent OECD-IEA/NEA study, *Projected Costs for Generating Electricity, 2010 Edition*. In addition to this, there are some important SMR-specific conclusions:

- Within the assumptions of the evaluation performed, the nuclear option (NPPs with a large reactor or with SMRs) is competitive with many other technologies (coal-fired plants, gas-fired plants, renewable plants of the various types) in Brazil[4], Japan, the Republic of Korea, the Russian Federation and the United States, but not in China.

- **SMRs, including twin-unit and multi-module plants, generally have higher values of LUEC than NPPs with large reactors.**

- Similarly to large NPPs, **some SMRs are expected to be competitive with several projects of coal-fired, gas-fired and renewable plants of various types, including those of small to medium-sized capacity (below 700 MWe).**

For example, a plant with SMRs could be a competitive replacement for the decommissioned small and medium-sized plants using fossil fuel in the cases when certain siting restrictions exist, such

[4] In Brazil, more that 70% of electricity is generated from the hydroelectric power plants offering very low cost electricity. Other sources of electricity, including nuclear power plants (with large reactors or SMRs), have higher electricity generation costs.

as limited spinning reserve or limited availability of water for cooling towers of a power plant. Like the nuclear option in general, SMRs would be more competitive if carbon taxes were in place.

Figure E.6. Regional ranges for LUEC and the estimated values of SMR LUEC (at 5% discount rate)

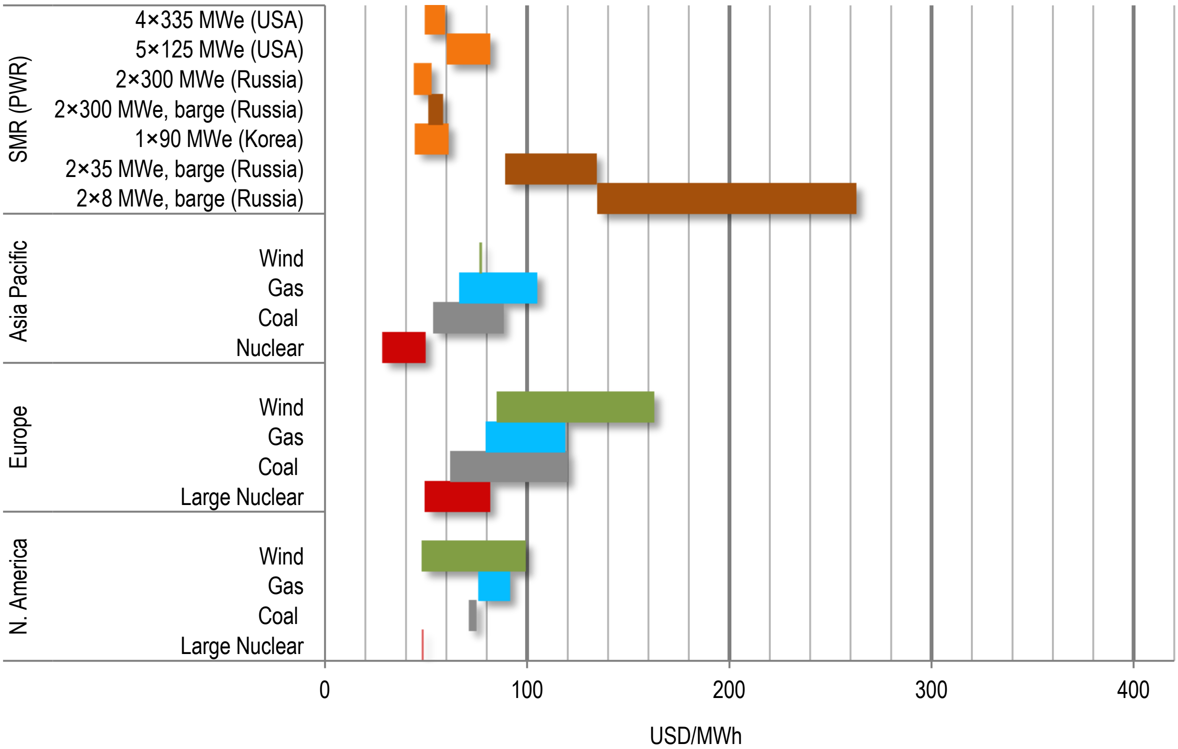
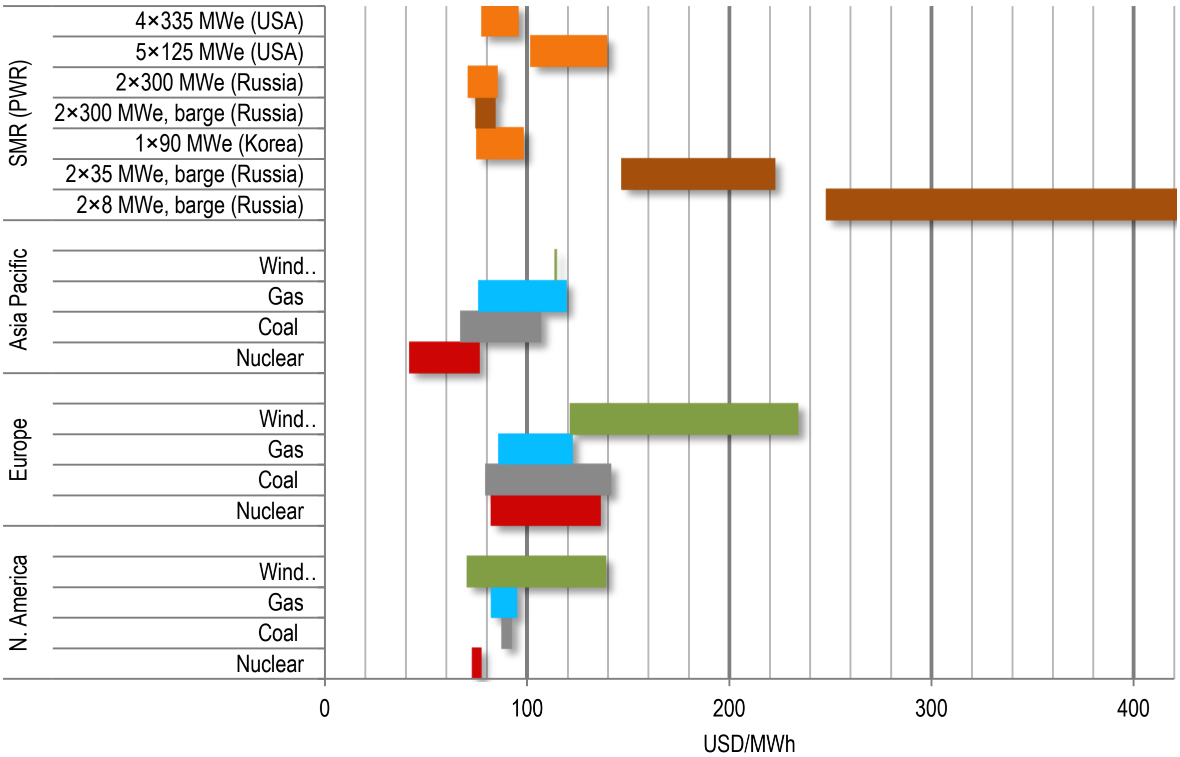


Figure E.7. Regional ranges for LUEC and the estimated values of SMR LUEC (at 10% discount rate)



In summary, **SMRs could be competitive with many non-nuclear technologies for generating electricity in the cases when NPPs with large reactors are, for whatever reason, unable to compete.**

Regarding the competitiveness of SMRs in the combined electricity and heat markets in "on-grid" locations, at least some SMRs could be competitive with other combined heat and power plant (CHP) technologies in China and in the Russian Federation at both 5% and 10% discount rates.

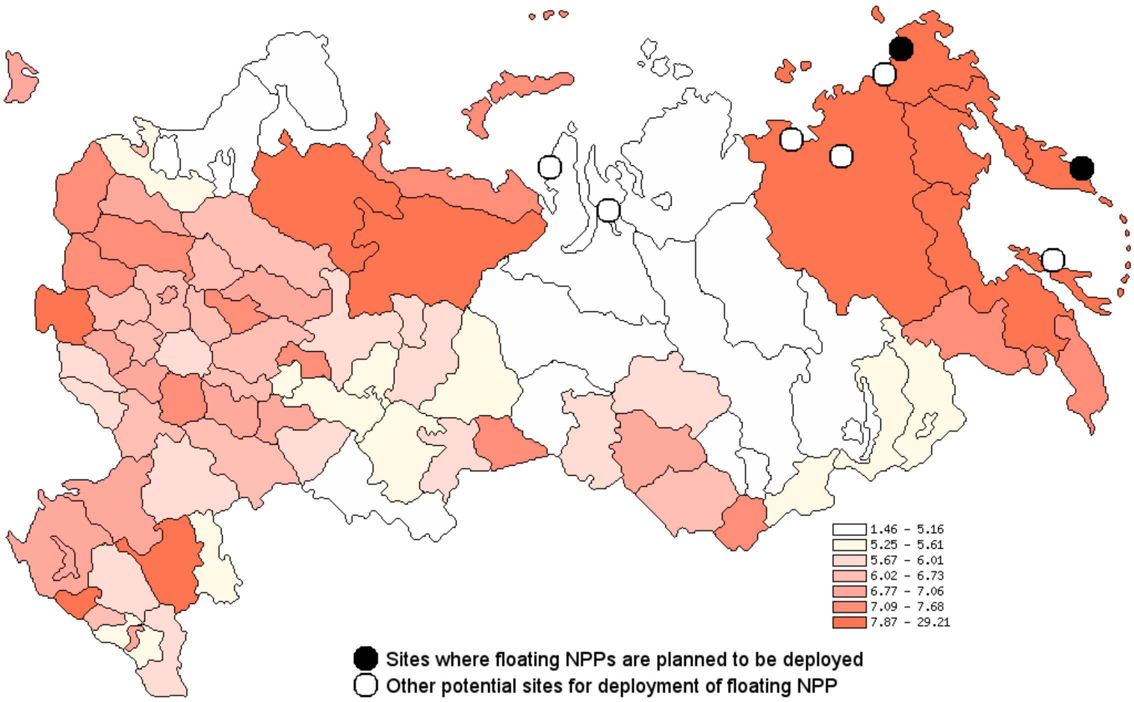
In the evaluations performed for the "on-grid" locations, no cases were found when small barge-mounted NPPs with the PWR-8 and the PWR-35 twin-unit plants (based on the Russian ABV and KLT-40S designs) would be competitive.

Deployment in remote and isolated areas

Large NPPs do not fit in any of these specific markets; therefore, SMRs would compete only with the local non-nuclear energy options.

To analyse the deployment potential of SMRs in remote or isolated areas, the LUEC estimates were compared with the electricity tariffs for that area (because the generating costs of other technologies would be extremely difficult to calculate). The analysis of **SMR competitiveness in "off-grid" locations has identified a significant potential for their applications in remote areas with severe climatic conditions hosting mining or refinement enterprises, or military bases, and the affiliated small settlements** (see Figure E.8).

Figure E.8. Map of electricity tariffs (in USD cents per kWh) in the Russian Federation in 2010



On a purely economic basis, isolated islands and small off-grid settlements in populated developing countries (e.g. Indonesia, India) could also become potential market.

It has been found that a variety of land-based and barge-mounted **SMR plants with LUEC substantially higher compared to large reactors could still be competitive in these niche markets**

if they meet certain technical and infrastructure requirements, defined by the specific climate, siting and transportation conditions. In particular, co-generation with the production of heat or desalinated water appears to be a common requirement in many of the niche markets analyzed.

In the analysis performed for the "off-grid" locations, many cases were found when small barge-mounted NPPs with the PWR-8 and the PWR-35 twin-unit plants (based on the Russian ABV and KLT-40S designs) would be competitive.

Safety features and licensing of SMRs

Safety features of SMRs

The safety aspects of SMRs have been intensively discussed in several recent publications, mostly originating from the International Atomic Energy Agency (IAEA), which are summarised below. However, one should keep in mind that the safety features of SMRs will be re-analysed following the Fukushima Dai-ichi accident in order to take into account the lessons learnt from it.

The major findings regarding SMR safety are the following:

- The designers of advanced SMRs aim to implement safety design options with maximum use of inherent and passive safety features (also referred to as "by design" safety features).

- On their own, the "by design" safety features used in SMRs are in most cases not size-dependent and could be applied in the reactors of larger capacity. However, SMRs offer broader possibilities to incorporate such features with higher efficacy.

- In the case of some technologies (such as high-temperature gas reactors), the incorporation of passive safety features limits the reactor capacity.

- All of the SMR designs considered here aim to meet international safety norms, such as those formulated in the IAEA Safety Standard NS-R-1 Safety of the Nuclear Power Plants: Design Requirements, regarding implementation of the defence-in-depth strategy and provision of redundant and diverse, active and passive safety systems.

- The available information on safety features of advanced SMRs for plant protection against the impacts of natural and human-induced external events is generally sparser compared to that on internal events.

- The core damage frequencies (CDFs) indicated by the designers of advanced SMRs are comparable to, or even lower than the ones indicated for the state-of-the-art, large water-cooled reactors.

Licensing of SMRs

The licensing of SMRs will be affected by the Fukushima accident in the same way as for large reactors. Regarding licensing status and regulatory issues relevant to SMRs, the analysis of recent publications leads to the following observations:

- According to the vendors and designers, all the advanced SMRs listed in Table 1 have been designed or are being designed in compliance with their current national regulations.

- The SMRs available for deployment, which are the CANDU-6, the PHWR, the QP-300, the CNNP-600, and the KLT-40S, have already completed the licensing procedures in the countries of origin. The CANDU-6 and the QP-300 have also been licensed and deployed in countries other than the country of origin.

- For advanced SMR designs, three of them are in a formal licensing process in Argentina, China and the Republic of Korea, and several others are in pre-licensing negotiations in the United States and India, see Table E.1.

Regulatory issues and delays regarding SMR licensing may occur due to the following main reasons:

- Some advanced, water-cooled SMR design concepts incorporate novel technical features and components targeting reduced design, operation and maintenance complexity which will need to be justified by the designers and accepted by the regulators. There is currently no regulator which has approved such designs for construction.

- Non-water-cooled SMRs may face licensing challenges in those countries where national regulations are not technology neutral, e.g. they may be based on established water-cooled reactor practice. A lack of regulatory staff familiar with non-water-cooled reactor technologies may also pose a problem in some countries.

- Some of the advanced SMR design concepts provide for a long-life reactor core operation in a "no on-site refuelling mode". The regulatory norms providing for justification of safety in such operation modes may be not readily available in national regulations.

Government support for licensing of selected, advanced SMRs could help overcome the corresponding delays.

Another important set of regulatory requirements concern the ability of SMRs to resist nuclear proliferation. All advanced light water PWR SMRs use conventional LEU fuel and most of the PWR SMR designs use the *same* fuel as large PWRs. However, particular attention should be paid to the non-proliferation potential of some heavy-water or liquid-metal cooled designs, especially if they are intended to be deployed in politically unstable areas. The IAEA has an on-going activity on the options of incorporation of intrinsic proliferation resistance features in NPPs with innovative SMRs, and the report is expected to be published soon.

Conclusions

A principal conclusion of this study is that SMRs have a significant potential to expand the peaceful applications of nuclear power by catering to the energy needs of those market segments that cannot be served by conventional NPPs with large reactors. Such segments could be:

- Niche applications in remote or isolated areas where large generating capacities are not needed, the electrical grids are poorly developed or absent, and where the non-electrical products (such as heat or desalinated water) are as important as the electricity;

- Replacement for the decommissioned small and medium-sized fossil fuel plants, as well as an alternative to newly planned such plants, in the cases when certain siting restrictions exist, such as limited free capacity of the grid, limited spinning reserve, and/or limited supply of water for cooling towers of a power plant;

- Replacement for those decommissioned fossil-fuelled combined heat and power plants, where the SMR power range seems to better fit the requirements of the currently existing heat distribution infrastructure;

- Power plants in liberalised energy markets or those owned by private investors or utilities for whom small upfront capital investments, short on-site construction time (with the accordingly reduced cost of financing), and flexibility in plant configuration and applications matter more than the levelised unit electricity cost.

It should be noted, however, that none of the smaller reactors has yet been licensed for these applications and there remain both development challenges to overcome and regulatory approvals to obtain before deployment, especially in light of the recent accident at Fukushima.

The present study has found no situations where NPPs with SMRs could compete with the NPPs with state-of-the-art large reactors, on LUEC basis. However, it also found that **SMRs could be competitive with many non-nuclear technologies in the cases when NPPs with large reactors are, for whatever reason, unable to compete**.

1. Introduction and Context

The present NEA study is a synthesis report on the development status and deployment potential of SMRs. It brings together the information provided in a variety of recent publications in this field, and presents the characterisation of SMRs already available for deployment and those that are expected to become available in the next 10-15 years. It also highlights the safety features and licensing issues regarding such reactors.

Particular attention is paid to the economics of SMRs, and various factors affecting their competitiveness are analysed and discussed. Vendors' data on the economics of different designs are compared with independent quantitative estimates of costs of generating electricity, and the deployment potential of such reactors in a number of markets and geographic locations is analyzed.

Currently, there are two definitions of such reactors widely used in the literature: Small and Medium-sized Reactors and Small and Modular Reactors. The same abbreviation is used - SMRs. Small and modular reactors have attracted much attention since 2008 when several very small reactors (less than 125 MWe) were announced in the United States. Since these reactors are a sub-class of the wider definition - Small and Medium-sized Reactors - in this paper we consider the general case of reactors with the effective electric power less than 700 MWe. However, the main focus in this report is on small reactors i.e. reactors with less than 300 MWe.

SMRs have been on the agenda since the early days of nuclear power. Historically, all reactors at that time were of smaller size compared to those deployed today[1], but the general trend has always been toward larger unit sizes (with lower specific costs due to the economy of scale), resulting in nuclear power plants with reactors of 1 000-1 600 MWe being most commonly commercialised today.

However, starting from the mid-1980s, a new set of requirements have motivated the development of intentionally smaller reactors in some countries aimed at the niche markets that cannot accommodate NPPs with large reactors. The main arguments advanced in favour of SMRs are:

- Because of their size, the upfront capital investment for one unit is significantly smaller than for a large reactor, and there is flexibility for increasing capacity. This reduces financial risks and could potentially increase the attractiveness of nuclear power to private investors and utilities.

- Smaller nuclear reactors could represent an opportunity to develop new markets for nuclear power plants. In particular SMRs could be suitable for areas with small electrical grids and for remote locations or, alternatively, in countries with insufficiently developed electrical infrastructure.

[1] SMRs constitute an important share of the actual nuclear fleet: 136 of the 441 reactors in operation, mostly those of older design, have a power falling in the SMR range [1.1]. In 2010, nine nuclear power plants under construction were SMRs [1.1].

- SMRs often offer a variety of non-electrical energy products (heat, desalinated water, process steam, or advanced energy carriers) via operation in a co-generation mode[2].

Because of these arguments, there are currently about a dozen new SMR designs reaching advanced development stages, with one plant (a barge-mounted co-generation plant with two ice-breaker type KLT-40S reactors) currently under construction in the Russian Federation, three more in a formal licensing process in Argentina, China, and the Republic of Korea, and several others being under pre-licensing negotiations in the United States and India.

On the other hand, there are some issues regarding the viability of advanced SMRs, namely:

- A question on the economic competitiveness of SMRs, especially the higher specific construction cost of SMRs with respect to larger reactors.

- Potential concerns about the possibility of SMRs being sited in close proximity to end-users, based on the current regulatory norms and practices established to support the deployment of NPPs with large reactors.

- Legal and institutional issues regarding the possibility of international transport of NPPs with factory fabricated and fuelled reactors (a distinct group of advanced SMR designs) from one country for deployment in another.

The present study discusses these issues with a focus on the economic aspects and the competitiveness of a NPP with SMRs, in comparison to large reactors and non-nuclear technologies.

1.1 Outline of the report

In line with its synthetic nature, the present report starts with introducing the definitions (Chapter 2), providing a brief characterisation of SMRs available for deployment (Chapter 3), and introducing in more detail the design concepts of advanced SMRs belonging to the different technology lines (Chapter 4):

- pressurised water reactors (PWRs);

- boiling water reactors (BWRs);

- advanced heavy water reactors (HWRs);

- high temperature gas cooled reactors (HTGRs) and

- sodium cooled fast reactors; and

- lead-bismuth cooled fast reactors.

Reflecting the public interest in the emerging US small and modular reactor designs, a dedicated Chapter 5 lists and analyses the design attributes of small modular reactors developed in the United States and elsewhere in the world

[2] It is important to underline that co-generation is not unique to SMRs. However, as will be discussed later, the SMR power range corresponds well to the infrastructure requirements for non-electrical products (*e.g.* district heating).

Chapter 6 brings into focus the various factors affecting the economic characteristics of SMRs. Numerical examples of how each of these factors, as well as their combinations, could act on the levelised unit electricity cost (LUEC) of a SMR-based plant, are provided, and the results are compared to large reactors. In addition to this, Section 6.5 touches upon the impact of co-generation and non-electrical applications on plant costs.

Section 7.1 presents the results of independent LUEC estimates performed for the selected NPP configurations with SMRs. Of the total, estimates were performed for 12 plant configurations with 8 "model" SMR designs (within the unit power range from 7.9 to 335 MWe) based on certain advanced SMR projects with significant deployment potential in the period 2010-2020.

The estimates started from published cost data for NPPs with large reactors, mostly in the construction phase or already built, and used the cost scaling law methodology together with the various correction factors described in detail in Chapter 6, to arrive at an independent LUEC value for a certain plant configuration with SMRs. The impact of the heat credit and the uncertainty ranges of the LUEC estimates were defined, and the results were then compared to the designers' cost data (discounted to the year 2009).

In Section 7.2, the independent LUEC estimates obtained in Section 7.1 were used to evaluate the competitiveness of SMRs in the electricity and combined electricity and heat markets of several countries. The countries addressed included Brazil, China, Japan, the Republic of Korea, the Russian Federation, and the United States for electricity, and China, the Russian Federation, and the United States for combined electricity and heat generation. For the evaluations, the LUEC estimates for the various plant configurations with SMRs were compared to the projected costs of generating electricity in 2010 (reference [1.2]) using large NPPs, coal-fired plants, gas-fired plants, and renewable energy plants, including hydroelectric plants, wind plants, etc.

In Section 7.2.6, the potential of SMRs to compete in the niche markets (not suitable for NPPs with large reactors) of the Russian Federation, Canada, and the United States was evaluated using the data on electricity tariffs in the remote off-grid or local grid locations in these countries. In the evaluations, LUEC estimates for the NPP configurations with SMRs from Section 7.1 were compared to the electricity tariffs in selected locations.

Chapter 8 provides the description and summary of SMR safety designs. First, in Sections 8.1-8.7, safety designs are presented and summarised for each of the SMRs, each of the distinct SMR design groups, and each of the technology lines. Section 8.8 provides a general summary and conclusions on the SMR safety designs for internal events and external events. It also touches upon the important topics of use of passive versus active safety systems and outlines how the safety design is related to plant economics.

Chapter 9 examines licensing process for the advanced SMR projects, touching upon compliance with the current national regulations and international standards, possible delays and regulatory issues, reduced off-site emergency planning requirements, and new regulatory approaches. This section also includes a summary table of the SMR licensing status late in 2010.

Chapter 10 presents the major findings and conclusions of the present report and includes recommendations on further research in the areas that require further clarification.

The report includes three Appendices with reference data. Appendix 1 provides structured tables with design specifications for each of the SMRs addressed. In Appendix 2, structured summaries of safety design features for SMRs are given. In Appendix 3, additional data on the economics of SMRs is presented.

This report and its economic study was prepared to enable discussion and further analysis among a broad range of stakeholders, including decision-makers, public and private investors, energy economists, regulators and reactor vendors.

References

[1.1] IAEA, Power reactor information system (PRIS): www.iaea.org/programmes/a2/

[1.2] IEA/NEA (2010), *Projected Costs for Generating Electricity*: *2010 Edition*, OECD, Paris, Tables 3.7(a-e), pp. 59-63.

2. Definitions

Over the years, the IAEA has published a number of comprehensive reports on design status of the advanced reactors belonging to different technology lines, including SMRs. These reports contain some useful definitions which are also adopted in the present report.

According to the IAEA [2.1, 2.2]:

- **Small reactors** are reactors with the equivalent[1] electric power less than 300 MW.

- **Medium-sized reactors** are reactors with the equivalent electric power between 300 and 700 MW.

The IAEA-TECDOC-936 "Terms for describing new, advanced nuclear power plants" [2.3] defines an:

- **Advanced design** as a "design of current interest for which improvement over its predecessors and/or existing designs is expected".

A continued advanced reactor development project passes sequentially through the design stages of conceptual design, basic (or preliminary) design and, finally, detailed design. The attributes of these design stages are detailed in the IAEA-TECDOC-881 [2.4]. In short:

- the **conceptual design stage** results in the development of "initial concept and plant layout";

- the **basic (or preliminary) design stage** ends up with the "essential R&D completed (except non-critical items)"; and

- the **detailed design stage** yields the "complete design of the plant, except very minor items. It can be unified (for example, for an envelope of site conditions) or site-specific".

According to the definition given in IAEA-TECDOC-1536 [2.5]:

- **Small reactors without on-site refuelling** are reactors designed for infrequent replacement of well-contained fuel cassette(s) in a manner that prohibits clandestine diversion of nuclear fuel material."

The above definition addresses both *factory fabricated and fuelled reactors* and the *reactors for which infrequent reloading of the whole core is performed on the site*. For the purposes of the present report, the IAEA definition [2.5] was not followed and the reactors with the above mentioned features were categorised separately.

- **Distributed deployment** refers to a situation when a NPP with a single reactor module or a twin-unit NPP is deployed on each of the many sites.

[1] Taking into account non-electrical applications.

- **Concentrated deployment** assumes clustering of multiple NPPs, or construction of a multi-module plant, on a site.

All safety related terms used in Sections 6 and 7 of this report follow the definitions suggested in the IAEA Safety Glossary [2.6].

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[2.1] IAEA (1997), "Introduction to Small and Medium Reactors in Developing Countries", Proceedings of two Advisory Group meetings held in Rabat, Morocco and Tunis, Tunisia, IAEA-TECDOC-999, Vienna, Austria.

[2.2] IAEA (2005), "Innovative Small and Medium Sized Reactors: Design Features, Safety Approaches and R&D Trends", Final report of a technical meeting held in Vienna, 7-11 June 2004, IAEA-TECDOC-1451, Vienna, Austria.

[2.3] IAEA (1997), *Terms for Describing New, Advanced Nuclear Power Plants*, IAEA-TECDOC-936, Vienna, Austria.

[2.4] IAEA (1995), *Design and Development Status of Small and Medium Reactor Systems 1995*, IAEA-TECDOC-881, Vienna, Austria.

[2.5] IAEA (2007), *Status of Small Reactor Designs without On-site Refuelling*, IAEA-TECDOC-1536, Vienna, Austria.

[2.6] IAEA (2007), *IAEA Safety Glossary: 2007 Edition*, Vienna, Austria.

3. Brief Characterisation of SMRs Available for Commercial Deployment

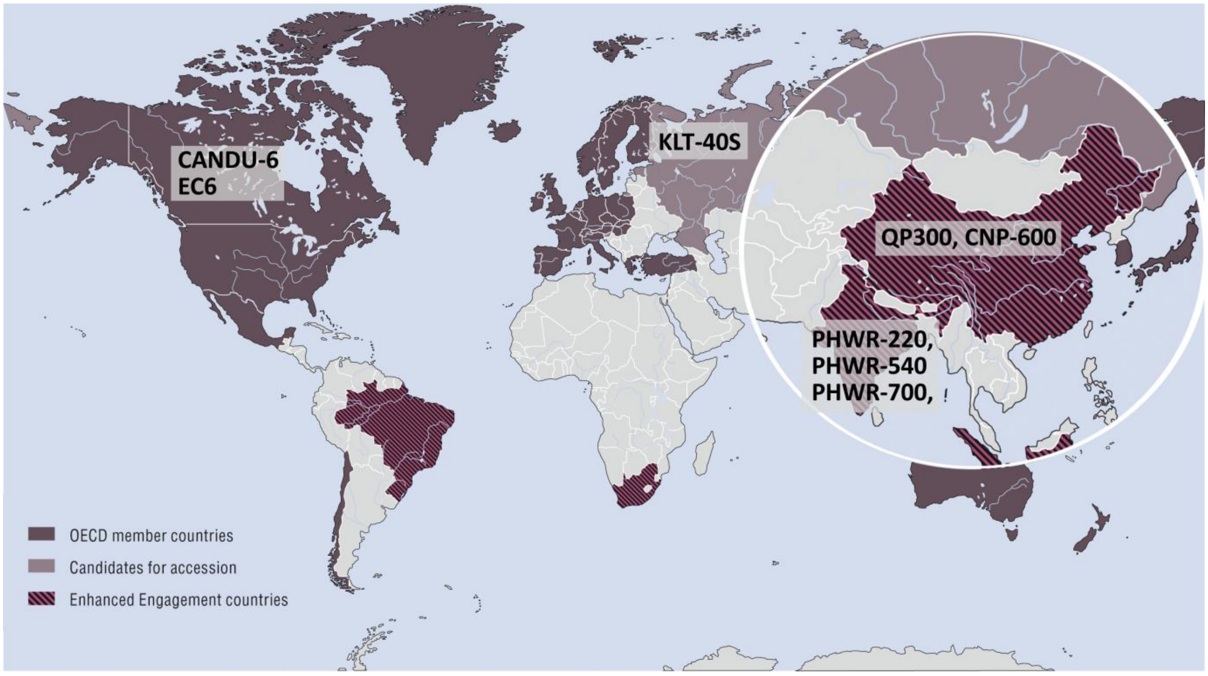
At the time of this report (2011) there were eight proven SMR designs with a prospect of international deployment, see Figure 3.1. Some of those designs have already been completed or are already in operation; basic characteristics of these designs are summarised[1] in Table 3.1.

Of these designs, the CANDU-6, the EC6 and the PHWR-220 are pressure-tube type heavy water reactors. The QP-300, CNP-600 and KLT-40S are pressurised water reactors. Most of the plants provide for both distributed and concentrated (several plants on a site) deployment. For a floating plant with two KLT-40S reactors, location of more than one barge on a site has not been considered yet. The EC6 provides for a twin-unit option, the KLT-40S is a twin-unit.

The construction period ranges from four to seven years, with the shortest one for the Russian KLT-40S and the longest one for the Chinese QP-300 and CNP-600.

All of the SMRs in Table 3.1 have containments, and the PHWR-220 and the KLT-40S offer a double containment.

Figure 3.1. SMRs available for commercial deployment in 2010



3.1 Land-based heavy water reactors (HWRs)

Except for EC6, all heavy water reactors from Table 3.1 have already been deployed in the country of origin and in some cases abroad. The CANDU-6 and the QP-300 have been deployed

[1] The detailed design specifications for SMRs shown in Table 3.1 are given in Table A1.1 of Appendix 1.

internationally, and there are agreements to build more of these reactors in Romania and Pakistan, respectively. All deployments of the CANDU-6 since 1996, as well as all deployments of the PHWR-220 since 2000 are reported to have been accomplished on schedule (or even ahead of it) and without exceeding the budget [3.1, 3.2].

The CANDU-6 reactors are the newest in the CANDU series that have been deployed. The EC-6 is an evolutionary modification of the CANDU-6, based on the experience of the latest deployed CANDU-6 reactors.

The PHWR-220 is an Indian development from the previous low-power CANDU reactors. The safety features of the initial design have been improved resulting in increased level of safety of 15 reactors of this type currently operating in India [3.3].

The operational lifetime of currently available heavy water SMRs is typically 40 years, with the exception of the EC6 for which it is 60 years. The availability factors are quite competitive ranging between 79% and 90% for all SMRs in Table 3.1.

The CANDU-6, the EC6 and the PHWR are refuelled online. This is typical of all pressure tube type heavy water reactors.

A nuclear desalination option is being considered (but still not realised) for the Indian PHWR-220. More details about energy products of the SMR available for deployment can be found in Section 4.4.

3.2 Land-based pressurised water reactors (PWRs)

The QP300 is a low power conventional loop-type PWR with a maximal fuel burn-up of 30 MWday/kg and a one-year refuelling interval. In the CNP-600, fuel burn-up is increased to above 45 MWday/kg, and the refuelling interval is 1.5 years.

The QP300 and the CNP-600 use conventional refuelling in batches with a refuelling interval of 14 and 18 months, respectively.

The operational lifetime of QP300 is 40 years, and for the CNP-600 it is 60 years.

The QP300 incorporates a passive safety system of core flooding with borated water. The CNP-600 incorporates two passive safety systems, one for passive heat removal from the secondary side of the steam generator, and another for passive containment cooling.

3.3 Barge-mounted PWRs

The first-of-a-kind (FOAK) KLT-40S (see Figure 3.2) is the only barge-mounted SMRs in Table 3.1. It is currently under construction and expected to start operation in 2013. This plant offers a maximum of 80 MWe with the co-generation option disabled.

The projected plant operational lifetime is 40 years, and the targeted energy availability factor is 85%.

In the KLT-40S, the whole core is refuelled after the end of its fuel cycle. However, the fuel bundles are shuffled in the core with an interval of slightly above two years. Such refuelling scheme, in which fuel loading and unloading are performed on the barge, is adopted for the cermet fuel of slightly less than 20% enrichment in ^{235}U used in KLT-40S.

Table 3.1. Basic characteristics of SMRs available for deployment

SMR design and vendor	Reactor type and deployment (land or barge)	Thermal/ Electric output, MW (gross)	Availability/ Plant lifetime	Construction period	Mode of refuelling/ Refuelling interval	Mode of deployment/ Plant configuration*	Deployment status
CANDU-6 AECL, Canada [3.6]	PHWR	2 064/715	88.8%/40 years	60 months	On line	Distributed or concentrated	11 units deployed and operated in China, Canada, Republic of Korea and Romania
EC6 AECL, Canada [3.1]	PHWR	2 250/ 730-745	90%/60 years	57 months	On line	Distributed or concentrated/ Twin-unit option	Ready for deployment (evolution of a proven CANDU-6)
PHWR-220** NPCIL, India [3.7]	PHWR	862/220	89.3%/40 years	60 months	On line	Distributed or concentrated	15 units in operation in India
QP300 CNNC, China [3.7]	PWR	1 000/ 310-325	79%/40 years	84 months	In batches/14 months	Distributed or concentrated	One unit deployed in China and 1 in Pakistan, one unit under construction in Pakistan
CNP-600 CNNC, China [3.8]	PWR	1 936/644	87%/60 years	83 months	In batches/18 months	Distributed or concentrated	2 units in operation and 2 units under construction in China
KLT-40S JSC "Rosatom", Russia [3.4,3.8]	PWR	2x150/2x35 2x40 MWe with non-electrical applications disabled	85%/40 years	48 months	Whole core/Shuffling of fuel assemblies in 27.6 months	Distributed/Twin-unit	Under construction in Russia, deployment scheduled for 2013

* Here and after, the default is a single unit plant.

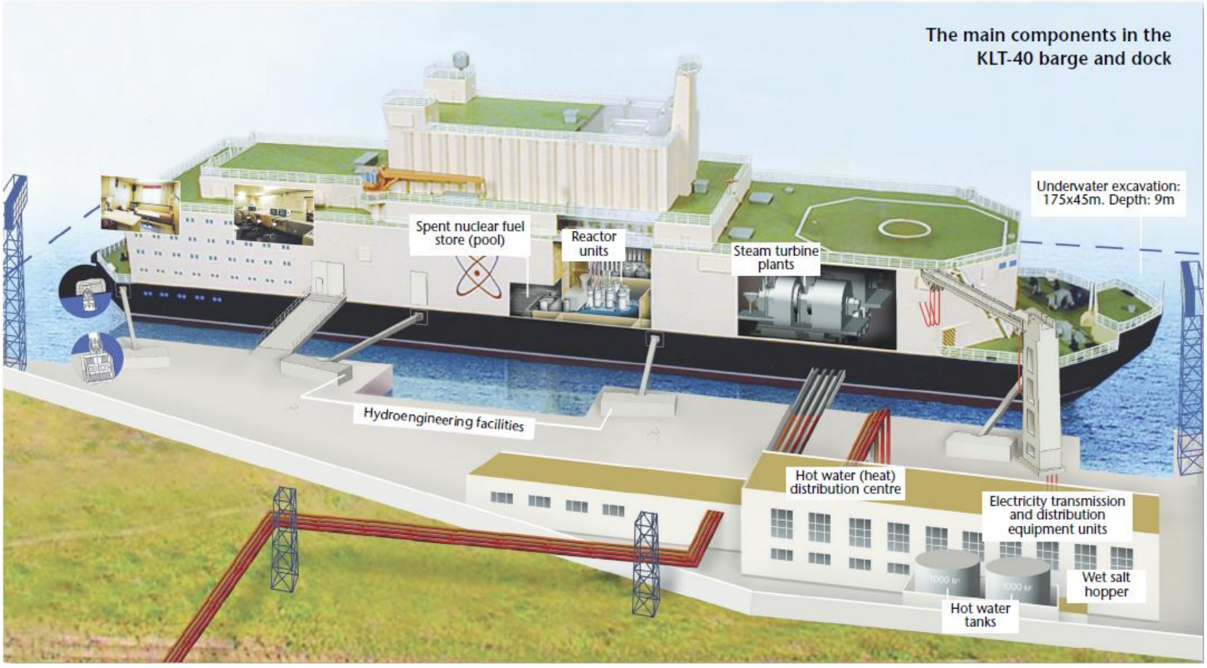
** During the 54th session of the IAEA General Conference in September 2010, India announced its intentions to also export NPPs with the indigenous PHWR-540 and PHWR-700 reactors (similar to PHWR-220 but having higher outputs of 540 and 700 MWe [gross]).

Of the SMR designs available for deployment, only the barge-mounted plant with the two KLT-40S reactors provides for operation in co-generation mode with co-production of heat for district heating.

The KLT-40S is based on the experience of about 6 500 reactor-years in operation of the Russian marine propulsion reactors [3.4]. The KLT-40S design is different from conventional PWRs. This difference is discussed in more detail below.

The KLT-40S offers a compact primary containment of less than 12 m in size. The plant surface area indicated for the KLT-40S is 8 000 m^2 on the coast and 15 000 m^2 in the bay.

Figure 3.2. General view of a floating NPP with two KLT-40 reactors [3.5]



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[3.1] Enhanced CANDU-6 Technical Summary, AECL, Canada: www.aecl.ca/Assets/Publications/EC6-TS_Eng.pdf

[3.2] India completes two CANDU reactors under budget, ahead of schedule: www.democraticunderground.com/discuss/duboard.php?az=view_all&address=115x66278

[3.3] Deolalikar, R. (2008) "Safety in Nuclear Power Plants in India", *Indian Journal of Occupational and Environmental Medicine*, 200, Volume 12, Issue 3: www.ncbi.nlm.nih.gov/pmc/articles/PMC2796747/

[3.4] IAEA (2009), *Design Features to Achieve Defence in Depth in Small and Medium Sized Reactors*, IAEA Nuclear Energy Series Report NP-T-2.2, Vienna, Austria.

[3.5] Nuclear Engineering International, January 2010: www.neimagazine.com/journals/Power/NEI/January_2010/attachments/KLT-40S%20Data%20&%20Diagram.pdf

[3.6] AECL, CANDU-6 Technical Summary, Canada: www.aecl.ca/Assets/Publications/C6-Technical-Summary.pdf?method=1

[3.7] IAEA (1995), *Design and Development Status of Small and Medium Reactor Systems 1995*, IAEA-TECDOC-881, Vienna, Austria.

[3.8] IAEA (2004), *Status of Advanced Light Water Reactor Designs 2004*, IAEA-TECDOC-1391, Vienna, Austria.

4. Characterisation of Advanced SMR Designs

4.1 Introduction

Several recent publications address many advanced SMR design concepts (in most cases still not available for deployment) that are currently being developed in the world [4.1, 4.2]. This report analyses only those reactors that are in advanced stage of development and are designed mainly for electrical production. The followings are therefore not considered in this report:

- purely academic efforts that have not progressed to more advanced design stages;
- design concepts at early design stages announced recently, for which no technical information is currently available;
- design concepts for which development programmes have been stopped, as of 2010;
- design concepts of SMRs intended for the incineration and transmutation of radioactive waste.

Section 4.2 provides the categorisation of advanced SMRs considered in the present report according to the various technologies used and also presents basic characteristics for each of the designs. The technologies are

- pressurised water reactors (PWRs),
- boiling water reactors (BWRs),
- advanced heavy water reactors (AHWRs),
- high temperature gas cooled reactors (HTGRs),
- sodium cooled fast reactors and
- lead-bismuth cooled fast reactors.

Section 4.3 categorises advanced SMRs according to their design status and possible dates of deployment. Section 4.4 provides a categorisation of all SMRs addressed in this report according to the types of energy products.

One of the topical issues is the so-called “mini-reactors” which are, in fact, small modular reactors belonging to various technology lines described in Section 4.2. These “mini-reactors” are analysed in Chapter 5.

> ***Note:*** *Late in 2010 the Westinghouse Electric Company stopped the development of the IRIS project and announced it would go with an alternative integral design PWR of smaller power. The future of the IRIS project is thus uncertain. However, we consider this project in this report for illustrative purposes.*

4.2 Basic characteristics and technology lines

4.2.1 Pressurised water reactors

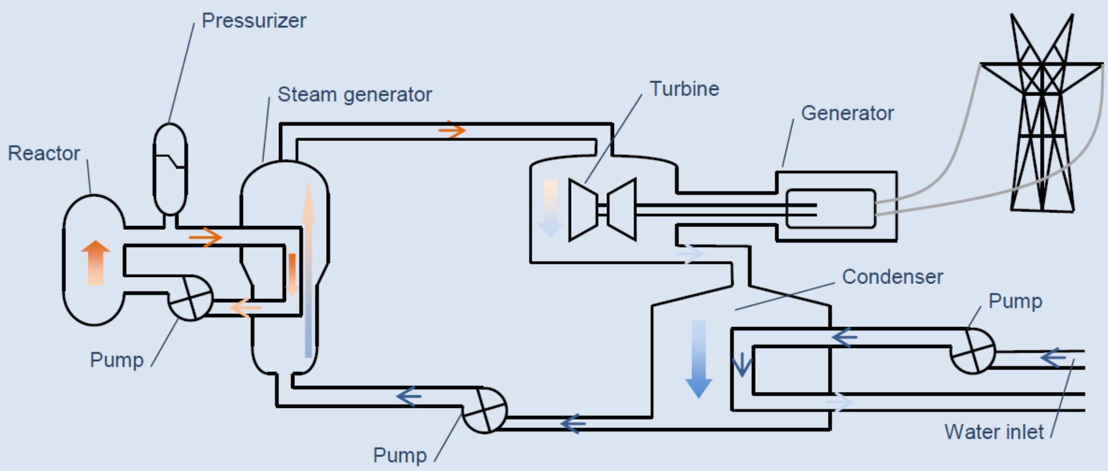
Pressurised water reactors (PWRs, see a brief description in Box 4.1) constitute the majority of nuclear power reactors currently in operation, accounting for 61% of the total reactor fleet in the world [4.3]. PWRs also constitute the majority among the power reactors being currently constructed. In 2010, out of 60 new nuclear power units under construction, 54 were with PWRs [4.4].

Box 4.1. Pressurised water reactors

PWRs are two-circuit, indirect energy conversion cycle plants. The primary coolant is pressurised light water. Nuclear heat generated in the reactor core is transferred to the secondary (power) circuit through steam generators. Boiling of water in the primary circuit is typically not allowed. The power circuit uses the Rankine cycle with saturated or slightly superheated steam for energy conversion.

A conventional PWR includes the reactor pressure vessel hosting the reactor core and the reactor internals, top-mounted external control rod drives. The pressurisers, main circulation pumps, and steam generators are external to the vessel and connected with pipelines (see Figure below). Depending on design, several steam generators can be used (this determines the number of loops). Stages of the turbine may provide for steam take-offs for non-electrical applications, such as production of desalinated water or heat for district heating.

Schematic view of a conventional PWR



Basic characteristics of advanced SMR designs addressed in the present section[1] are summarised in Table 4.1. In contrast to the PWR SMR currently available for deployment (and discussed above), some of the advanced SMRs do not always follow the conventional PWR layout. Generally speaking, the PWR designs shown in Table 4.1 could be divided in two major categories: Self-pressurised PWRs with in-vessel steam generators and compact modular PWRs[2].

[1] The detailed design specifications for SMRs in Table 4.1 are given in Tables A1.2 (a) and (b) of Appendix 1.

[2] Safety implications of the features of the above mentioned design groups are discussed in Section 8.2.

Table 4.1. Basic characteristics of advanced SMR designs - pressurized water reactors

SMR Design Principal designer, Country [Source]	Thermal/Electric output, MW (gross)	Availability/ Plant lifetime	Construction period/ Land-based or floating?	Mode of refuelling/ Refuelling interval	Mode of deployment/ Plant configuration
CAREM-300 CNEA, Argentina [4.1]	900/300 375/125 as an option	90%/60 years	48 months	In batches/11 months	Distributed or concentrated
CAREM-25 CNEA, Argentina [4.1, 4.5]	116/27	90%/40 years	60 months	In batches/11 months	Distributed or concentrated
SMART KAERI, Republic of Korea [4.6]	330/100	95%/60 years	< 36 months	In batches/36 months	Distributed
IRIS[3], USA [4.1]	1 000/335	>96%/>60 years	36 months (96 months as an option)	In batches/48 96 months as an option	Distributed or concentrated/ twin-unit option
Westinghouse SMR	800/225			In batches/24 months	
IMR Mitsubishi Heavy Industries, Japan [4.1]	1 000/350	95-97%/60 years	24 months	In batches/26 months	Distributed and concentrated/ twin-unit option
ABV OKBM Afrikantov, Russia [4.2]	2x38/2x8.5	80%/50 years	48 months	Factory fabricated and fuelled/12 years	Distributed
VBER-300 JSC "Nuclear Plants" Kazakhstan, Russia [4.1]	917/325	92%/60 years	48 months	In batches/24 months	Distributed/single or twin-units
mPower Babcock & Wilcox, Bechtel, USA [4.7]	400/125 per module	>90%/60 years	36 months	Whole core/54-60 months	Distributed or concentrated/ Multi-module plants
NuScale, NuScale Power Inc., USA [4.2, 4.8]	160/48 per module	>90%/60 years	36 months	In batches/24 months	Distributed or concentrated/ Multi-module plants
NHR-200 INET, Tsinghua University, China [4.9]	200/ n/a	95% /40 years	40 months	In batches/36 months	Distributed

- **Self-pressurised PWRs with in-vessel steam generators.** The self-pressurised PWR with in-vessel steam generators, also known as the integral design PWR, are represented by the CAREM-25 and CAREM-300, SMART, IRIS, IMR[4], mPower, NuScale, and NHR-200 (see example at Figure 4.1). These designs differ from conventional PWRs in that they have no external pressurisers and steam generators, with steam space under the reactor vessel dome acting as a pressuriser and steam generators being located inside the reactor vessel. Some of these designs, namely, the CAREM, the IRIS, the IMR, the mPower, and the NuScale also

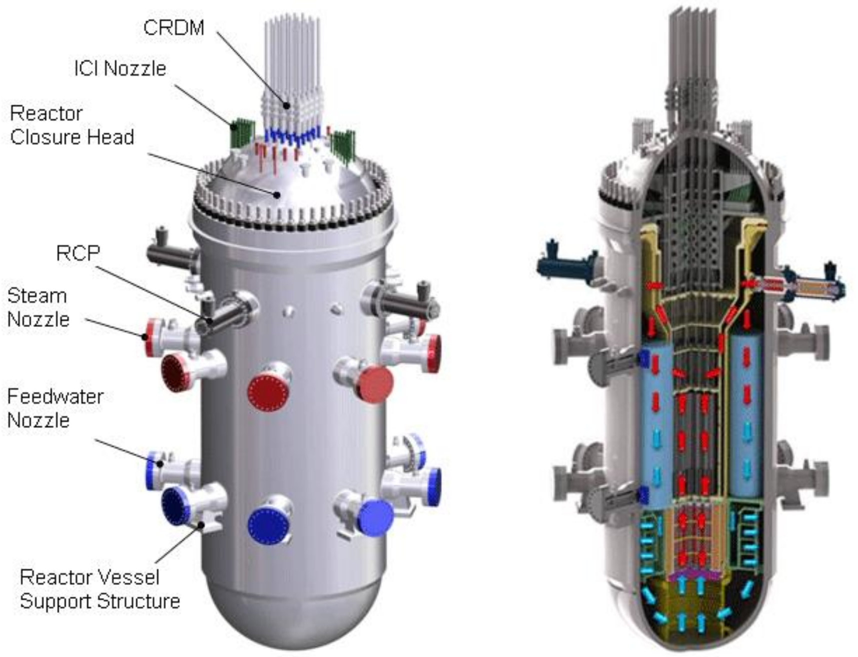
[3] Late in 2010 the Westinghouse Electric Company stopped the development of the IRIS project and announced it would go with an alternative integral design PWR of a 200 MWe class. Very few technical details of this new SMR were available as of June 2011.

[4] IMR is the only PWR design in which coolant boiling is allowed in upper part of the core [4.1]. Boiling boosts natural convection and makes it possible to use natural circulation of the primary coolant in normal operation, at a relatively high power level of 1 000 MWth (350 MWe).

use the in-vessel (internal) control rod drives. CAREM-25, IMR, NuScale, and NHR-200 use natural circulation of the primary coolant in normal operation mode and have no main circulation pumps. Other designs use in-vessel canned pumps.

- **Compact modular PWRs.** The compact modular SMRs, referred to as the "marine derivative" Russian designs in [4.2], appear to be similar to a conventional PWRs. However, the modules hosting the reactor core and internals, the steam generators, the pressuriser, and the coolant pumps are compactly arranged, and linked by short pipes with leak restriction devices. The pipes are mostly connected to the hot branch, and all primary coolant systems are located within the primary pressure boundary, so that the primary coolant system is sometimes referred to as "leak-tight". The designs belonging to this group are VBER-300, KLT-40S (described in Section 3), and ABV. The ABV holds an intermediate position between the two groups as it has internal steam generators and uses natural convection of the primary coolant but employs an external gas pressuriser.

Figure 4.1. Example of an integral design PWR: Korean's SMART reactor [4.6]



The general characteristics of advanced PWR SMRs could be summarised as follows:

- All of the PWR-based SMRs in Table 4.1 are land-based, with the exception of the ABV. This reactor was developed as barge-mounted but could also be based on land. The VBER-300 is land-based but could also be configured to operate on a barge.

- The electric output varies between 15 and 350 MWe. The NHR-200 is a dedicated reactor for heat production. The targeted availability factors are typically around 90% or even higher.

- The plant operational lifetime is in line with that of a modern conventional PWR: generally 60 years, with 50 years for the ABV and 40 years for the NHR-200.

- The projected construction period for advanced SMRs (typically two to five years for PWR SMRs) is typically shorter than the time needed to build SMRs available today.

- The refuelling intervals are longer, the burn-up levels are higher and the plant lifetime is longer, compared to the currently available SMRs. Some of the advanced PWR SMRs offer greater flexibility in capacity deployment (e.g. multi-module plant configurations).

- Of the designs presented, the ABV is a factory fabricated and fuelled reactor designed for 12 years of continuous operation, and the core of the mPower is refuelled after 4.5-5 years of continuous reactor operation. Other designs rely on partial core refuelling in batches. The refuelling intervals are mostly between two and four years. IRIS is being designed for a 4-year refuelling interval (with an 8-year refuelling interval being considered as an option), while CAREM provides for annual refuelling.

- The SMART, the ABV, and the NHR-200 target distributed deployment, while for all other designs both concentrated and distributed deployment are targeted. Twin-unit option is provided for the IRIS, IMR, and VBER-300. The ABV is a twin-unit barge-mounted reactor. The mPower and the NuScale are being designed for multi-module plants of flexible capacity.

- The primary pressure is set to 15-16 MPa in most cases (as in a conventional large PWR). However it is ~12 MPa for the CAREM, ~13 MPa for the mPower, ~11 MPa for the NuScale, and only 2.5 MPa for the NHR-200.

- The fuel is typically UO2 with less than 5% enrichment in 235U (as in large light water reactors). The exception is the ABV which, similar to the KLT-40S, uses cermet fuel with uranium enriched in 235U to slightly less than 20%.

- The average projected fuel burn-up is between 30 and 70 MWday/kg, but typically around 40 MWday/kg or slightly above.

- Several of the designs offer compact containments with maximum dimensions less than 15-25 m. These are the IRIS, the IMR, the ABV, the NuScale, and the NHR-200. For the ABV, all primary containment dimensions are within 7.5 m.

- The plant surface areas, where indicated, vary and depend on plant configuration[5]. The minimum areas are indicated for the ABV (6 000 m^2 on the coast and 10 000 m^2 in the bay) and NHR-200 (8 900 m^2). In other cases the areas are between ~100 000 and 300 000 m^2, with a substantial reduction in the relative size of the area needed for twin or multi-module units.

4.2.2 Boiling water reactors

Boiling water reactors (BWRs) are second to PWRs in global deployment, accounting for nearly 21% of all currently operated reactors. However, in 2010, out of 60 new nuclear power units under construction, only 2 were BWRs [4.4].

BWRs are single circuit, direct cycle plants. The coolant is boiling light water. Saturated steam condensation cycle (Rankine cycle) is used for energy conversion.

A conventional state-of-the-art BWR (e.g. the ABWR [4.5]) is self-pressurised and includes the reactor pressure vessel hosting the reactor core and the steam separators and dryers, the bottom

[5] See the last row in Tables A1.2(a) and (b) of Appendix 1.

mounted external control rod drives, and the bottom mounted external canned recirculation pumps. There are no BWRs in the small and medium-size range currently available for deployment.

Table 4.2. Basic characteristics of advanced SMR designs - boiling water reactors

SMR Design, Principal designer, Country	Thermal/Electric output, MW (gross)	Availability/ Plant lifetime	Construction period/ Land-based or floating	Mode of refuelling/ Refuelling interval	Mode of deployment/ Plant configuration
VK-300 NIKIET, Russia [4.1]	750/ 250	91%/ 60 years	60 months	In batches/ 18 months	Distributed or concentrated
CCR Toshiba Corporation, Japan [4.1, 4.10]	1 268/423	> 95%/ 60 years	25 months	In batches/ 24 months	Distributed or concentrated/ Single or twin-units, Multi-module plant option

The two advanced BWR SMR designs presented in this report[6] are different from ABWRs in that they use top-mounted external control rod drives (such as in PWRs) and rely on natural circulation of the coolant in all operating modes (i.e., they have no recirculation pumps), see Table 4.2. Proposals to use natural circulation of the coolant are not unique to small or medium-sized BWRs. For example, no recirculation pumps are used in the design of the ESBWR of 1 550-1 600 MWe [4.5].

The designs discussed here are quite different from conventional BWRs[7], and have the following features:

- The CCR of 400 MWe uses compact high pressure containment with its maximum dimension (height) limited by 24 meters, and with the reactor building structures providing the secondary containment.

  By using compact high pressure containment, the CCR aims to reduce the volume and mass of the reactor building and nuclear island components proportionally to the power reduction from a conventional large sized ABWR, an approach to overcome the disadvantage of the economy of scale [4.1].

- The VK-300 of 250 MWe is placed within a conventional large PWR type containment (about 45×60 m) within which a primary protective hull (the primary containment) and a gravity driven water pool are located.

- Both designs are land-based reactors; however, location of the VK-300 on a barge is not excluded.

- The projected plant lifetime is 60 years and the targeted availability factors are above 90% for both designs.

- For the VK-300 the construction duration is five years, while for the CCR it is claimed to be only two years, a minimum among all advanced SMR designs addressed in this study. It is expected that such a short construction period is based on the experience of building the

[6] The detailed design specifications for BWR SMRs are given in Table A1.3 of Appendix 1.

[7] Safety implications of BWR SMRs are further discussed in section 8.3.

ABWR[8] and taking benefit of the design compactness to maximise factory fabrication of large reactor modules [4.1].

- Both designs use low enrichment UO2 fuel with partial core refuelling in batches. Twin-unit and multi-module plant options are being considered for the CCR.

- For both designs the main specifications are similar to those of the state-of-the-art BWRs. Notably, a very small plant surface area of 5 000 m^2 is indicated for a single module CCR.

4.2.3 Advanced heavy water reactors

Heavy water reactors (HWRs) account for about 10.5% of all currently operating power reactors. However, in 2010, out of 60 new nuclear power units under construction, only 2 were with HWRs[9] [4.4].

There are only two vendors for this type of reactor, the AECL in Canada and the NPCIL in India. There are several HWR designs within the SMR range that are already available for deployment (see Chapter 3).

Conventional HWRs use an indirect energy conversion cycle. The primary coolant is heavy water and the primary moderator (separated from the coolant) is also heavy water. The secondary coolant is light water, and the Rankine cycle is used for energy conversion.

Table 4.3. Basic characteristics of SMR designs - advanced heavy water reactors

SMR Design Principal designer, Country	Thermal/Electric output, MW (gross)	Availability/ Plant lifetime	Construction period/ Land-based or floating	Mode of refuelling/ Refuelling interval	Mode of deployment/ Plant configuration
AHWR BARC, India [4.1]	920/300	90%/ 100 years	FOAK plant: 72 months	On line	Distributed or concentrated

A conventional HWR has no pressure vessel and appears as a horizontally laid cylinder (the calandria) with low-pressure heavy water moderator penetrated by the horizontal pressure tubes - fuel channels containing fuel element bundles. Pressurised heavy water flows in each of the channels removing heat produced by the reactor. Heavy water coolant is distributed among the channels, and then collected, by a system of pipelines starting from the inlet headers and up to the outlet headers. The pressuriser is connected to the outlet header, while the pumps are connected to the inlet header. From the outlet headers the coolant is directed to steam generators where it passes the heat to the light water coolant of the secondary circuit. The fuel is UO_2 with natural uranium. The reactivity control (in operation) is performed using several mechanisms, including absorber elements of different design and neutron poison addition to the moderator.

There is only one advanced SMR design in the HWR category - the Indian AHWR[10]. The basic characteristics of this AHWR are provided in Table 4.3.

This AHWR is different from the currently operated CANDU and PHWR reactors:

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[8] Recent deployments of the ABWR in Japan were accomplished with a three-year construction period [4.4].

[9] Including one atypical, dated-design pressure vessel type HWR in Argentina.

[10] The design specifications for the AHWR are given in Table A1.4 of Appendix 1.

- it has boiling light water primary coolant and direct steam condensing cycle for energy conversion;
- it uses natural circulation of the coolant in all operating modes and, to boost it, it uses a vertical calandria and vertical pressure tube channels;
- it uses only mechanical control rods for reactivity control in operation;
- it uses fuel bundles of heterogeneous structure with Pu-Th or U-Th fuel.

Safety implications of the above mentioned design features are discussed in Section 8.4.

The use of mixed oxide thorium containing fuel is intended to involve thorium in power generation through ^{233}U production and burning in-situ, without involving a complex chain with fast reactors and thorium fuel reprocessing. More details about the AHWR fuel design could be found in [4.1].

The AHWR employs only passive systems for heat removal, which results in the large size of the containment (about 55×75 m), for a reactor of 300[11] MWe.

The AHWR makes purposeful use of a part of the reject heat to run a seawater desalination plant. It also targets a 100-year lifetime for the plant, assuming all replaceable plant components are replaced periodically within this very long lifetime.

The indicated plant surface area is very small - 9 000 m^2.

4.2.4 High temperature gas cooled reactors

High temperature gas cooled reactors (HTGRs, see a brief description in the box 4.2) were operated in the past in the United Kingdom, the United States and Germany, and there are currently two small operating experimental reactors of this type in China (HTR-10) and in Japan (HTTR). The previous operating experience, cumulatively stretching from 1965 to 1989 [4.1], is probably too dated to be judged according to the current regulatory norms or safety standards. In 2010 there were no operating commercial reactors of this type anywhere in the world.

Basic characteristics of the HTGR designs considered in this report are given in Table 4.4[12]. All HTGRs are helium cooled reactors. The PBMR appeared to be a promising concept in an advanced development stage, with targeted deployment date in South Africa set for 2013. However in 2010 the vendor company - PBMR Pty - suffered from financial difficulties with the government no longer supporting the project. By that stage they had started to develop an indirect cycle HTGR similar to the Chinese HTR-PM.

As will be discussed in more detail in Section 8.5, all HTGR safety design concepts provide for passive decay heat removal to the outside of the reactor vessel. In view of this, with the currently known reactor vessel materials it appears that ~600 MWth is an upper limit of the unit size for HTGRs, which means that all HTGRs would fall into the SMR category.

Plant configuration with direct Brayton cycle is employed in all of the designs of Table 4.3, except the Chinese HTR-PM which is an indirect cycle HTGR employing the steam generators and a

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[11] An option to increase AHWR unit power up to 500 MWe is being discussed.

[12] The design specifications for these reactors are provided in Table A1.5 of Appendix 1.

Rankine cycle with reheating for power conversion. The indirect cycle efficiency of the HTR-PM is also remarkably high, 42%, due to steam reheating.

Table 4.4. Basic characteristics of advanced SMR designs - high temperature gas cooled reactors

SMR Design Principal designer, Country	Development status (2010)	Thermal/Electric output, MW (gross)	Availability/ Plant lifetime	Construction period/ Land-based or floating	Mode of refuelling/ Refuelling interval	Mode of deployment/ Plant configuration
HTR-PM, INET, Tsinghua University, China [4.1]	In licensing, in construction	250/105 per module	85%/ 40 years	48 months	On line pebble transport	Concentrated/ Two-module plants, Multi-module plants as an option
PBMR (previous design) PBMR Pty, South Africa [4.1]	Stalled	400/182 per module	≥ 95%/35 years	FOAK plant: 30-34 months; Commercial plant: 24 months	On line pebble transport	Concentrated/ Four- and 8-module plants
GT-MHR GA, USA, OKBM Afrikantov, Russia [4.1, 4.11]	Design development in progress (at a slow pace)	600/287.5	> 85%/ 60 years	First module: 36 months	In batches/15 months	Distributed or concentrated/ Single or multi-module plants
GTHTR300 JAEA, Japan [4.10]	Design development in progress	600/274	90%/ 60 years	Not specified	In batches/24 months	Distributed or concentrated/ Single or multi-module plants

Because the high-power Brayton cycle gas turbines are currently not available from the industry, the indirect cycle HTR-PM appears today as a leader among all HTGRs, with the construction related actions and licensing started in China, see Section 4.4.

When high temperature non-electric applications are targeted, the HTGR design includes an intermediate heat exchanger to deliver heat to process heat application systems. Because of high temperatures (up to 850-900^{o}C), HTGRs appear to be the only SMR technology line for which complex co-generation is considered, such as, for example, electricity generation with co-production of hydrogen and use of reject heat for seawater desalination.

The main technical characteristics of HTGR SMRs considered are the following:

- All HTGR designs target availability factors of more than 85%. The plant lifetime is typically 60 years for HTGRs with pin-in-block (non-moveable) fuel design and 35-40 years for those with pebble bed (moveable) fuel design.
- On-line refuelling is used in the pebble bed designs (HTR-PM and PBMR [previous design]), while the pin-in-block designs use partial refuelling in batches.
- All HTGRs provide for concentrated deployment with multi-module plants, although distributed deployment is not excluded for the 'pin-in-block' GTHTR300 and GT-MHR.
- The operating helium pressure is between 7 and 9 MPa, with 7 MPa being the preference.
- The average fuel burn-up is between 80 and 120 MWday/kg, being the maximum for the 'pin-in-block' designs.

- The diameter and height of the reactor vessels for all HTGRs are typically within the ranges 6.5-8 m and 23-31 m, correspondingly. In all designs the containment is provided by a single or double walled citadel of the reactor building. The containment secures a path for helium release as a safety action in overpressure accidents, see Section 8.5.

- The plant surface area, specified only for the PBMR (previous design), is remarkably small - 11 639 m^2 for an 8-module plant of 1 320 MWe.

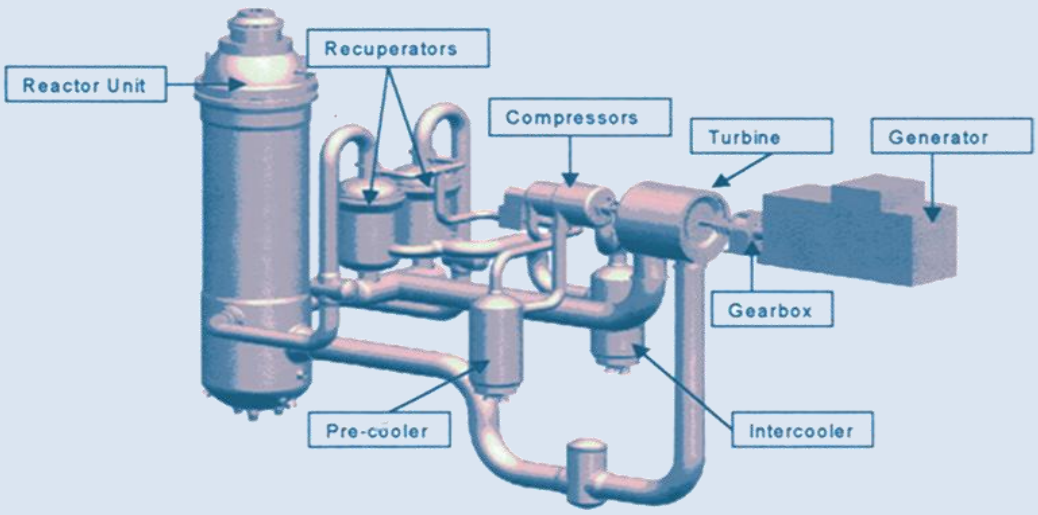
Box 4.2. High temperature gas cooled reactors

Historically, HTGRs have been considered primarily for high temperature non-electrical applications, such as hydrogen production or coal gasification, etc. For this purpose, all HTGR designs employ tri-isotropic (TRISO) fuel: Tiny (typically, less than 1 mm in diameter) ceramic fuel kernels with multiple ceramic coatings (typically, several pyrocarbon layers and a silicon carbide layer). TRISO fuel has a proven capability to confine fission products at high temperatures (up to 1 600^{o}C in the long-term) and operate reliably at very high fuel burn-ups up to 120 MWday/kg [4.1].

There are two basic modes of TRISO fuel used in HTGRs. In one case coated particles are embedded in graphite matrix to form spherical fuel elements continuously moving through the core (pebble bed fuel used in the HTR-PM and the PBMR [previous design]), in another - similar coated particles are embedded in graphite matrix to form fuel pins to be fixed in dedicated holes located in the graphite moderator (“pin-in-block” fuel used in the GTHTR300 and the GT-MHR). In both cases the core has an annular shape with central and radial graphite reflectors. This configuration improves the power distribution allowing for a higher thermal output and a higher average fuel burn-up.

The use of TRISO fuel in HTGRs of any fuel design contributes to a low volumetric power density in the reactor core, 6-7 MW/m^3 [4.1], which is a factor negatively affecting the economy of the plant. To face this, a direct Brayton cycle is being traditionally considered for HTGRs, employing a compressor and horizontal or a vertical shaft gas turbine (see Figure below). Energy conversion with Brayton cycle may offer cycle efficiencies of up to 45-48% (against 32-34% in PWRs) at 750-950^{o}C core outlet helium temperature, contributing to an improved plant economy.

Conceptual layout of the PBMR (previous design) primary system [4.10]



4.2.5 Sodium cooled fast reactors

In the second half of 2010, there were only two operating sodium cooled fast reactors worldwide, the BN-600 in the Russian Federation and the restarted MONJU in Japan. In the past, there were more sodium cooled fast reactors (the last of the two units in France was shut down early in 2010), and several such reactors are expected to start operation in the coming years (in China, India and the Russian Federation) [4.4].

There are two advanced SMR designs in the sodium cooled fast reactor category - the Japanese 4S of 10 MWe and the US PRISM reactor of 311 MWe (840 MWth). The 4S is a pool-type reactor with an intermediate heat transport system and metallic U-Zr fuel. The basic characteristics of the 4S and PRISM are given[13] in Table 4.5. The PRISM reactor is intended to be fuelled with metallic UPuZr fuel using plutonium and depleted uranium from used light water reactor fuel.

The 4S is different from typical past and present sodium cooled fast reactors in that it is being designed for:

- 30 years of continuous operation on a site without reloading or shuffling of fuel;
- whole core refuelling on the site after the end of a 30-year operation cycle.

Box 4.3. Sodium fast reactors

Sodium has high heat capacity, allowing linear heat generation rates in the reactor core as high as 485 W/cm, but reacts exothermically with air and water. For this reason all sodium cooled fast reactors incorporate an intermediate heat transport system with secondary sodium as a working fluid. Primary sodium delivers heat generated in the reactor core to an intermediate heat exchanger located within the reactor vessel (pool type reactor) or outside (loop type reactor). Secondary sodium delivers core heat to the steam generators located reasonably far from the reactor in a dedicated premise to localise the impacts of still possible steam-sodium reaction. Indirect Rankine cycle on superheated steam is used for power conversion.

Using three circuits is not favourable to the plant's economics, but operation at relatively high temperatures (~530^{o}C at core outlet) gives higher thermodynamic cycle efficiency in sodium cooled fast reactors, ~42% compared to 32-36% in PWRs. Primary and intermediate sodium circuits operate at a very low pressure of ~0.3 MPa. The space over the sodium pool surface in the reactor pressure vessel is typically filled with a low pressure inert gas, such as argon.

Conventional sodium cooled fast reactors use forced circulation of the primary and secondary sodium in normal operation. The systems of decay heat removal are typically active.

To be competitive economically, sodium cooled reactors target high fuel burn-ups of up to 130 MWday/kg. In most cases they are being designed in view of operation with the future closed nuclear fuel cycles. Positive experience of operation of fast sodium cooled reactors with oxide and metallic (U-Zr, U-TRU-Zr) fuel exists [4.12].

Although it has a very long core lifetime, the 4S offers a very small linear heat rate of 39 W/cm in the core and yields an average fuel burn-up of only 34 MWday/kg at the end of a long operation cycle. Correspondingly, the Rankine cycle efficiency is only 33% compared to 42% reached in other sodium cooled fast reactors.

[13] The detailed design specifications of the 4S are provided in Table A1.6 of Appendix 1.

The 4S uses non-conventional mechanisms of reactivity control in operation and reactor shut down, and utilises decay heat removal systems that are all passive and operate continuously. These mechanisms and safety design features of the 4S are described in Section 8.6.

The reactor vessel is thin and tall (3.55×24 m) and the containment, provided by the guard vessel and the concrete silo with a top dome in which the reactor is located, is compact.

Table 4.5. Basic characteristics of advanced SMR designs - sodium cooled fast reactors

SMR Design Principal designer, Country	Thermal/Electric output, MW (gross)	Availability/ Plant lifetime	Construction period/ Land-based or floating	Mode of refuelling/ Refuelling interval	Mode of deployment/ Plant configuration
4S Toshiba Corporation, Japan [4.2]	30/10 50 MWe option	95%/ 30 years	12 months on the site	Whole core/30 years	Distributed or concentrated
PRISM, General Electric, USA [4.44]	840/311 WMe			In batches/12-24 months	

The 4S is designed for both distributed or concentrated deployment. Different from other known sodium cooled fast reactors, the 4S provides for an option of hydrogen (and oxygen) co-production with high temperature electrolysis.

4.2.6 Lead-bismuth cooled fast reactors

There is no operational experience with commercial lead-bismuth-cooled fast reactors in any country of the world. The Russian Federation is the only country that had used the technology of lead-bismuth eutectics coolant and produced and operated small marine propulsion reactors[14] with such coolant, gaining a cumulated 80 reactor-years experience of their operation in nuclear submarines. However, the lead-bismuth-cooled reactors in these Russian submarines were not fast reactors. A moderator (BeO) was used to soften the neutron spectrum.

A principal technical issue with the lead-bismuth eutectics is the corrosion of the fuel element claddings and structural materials in the coolant flow. Corrosion is temperature-dependent and, according to multiple studies performed worldwide [4.12], is easier to cope with at lower temperatures. In the Russian Federation the technology for reliable operation of stainless steel based structural materials in lead-bismuth eutectics was developed, allowing a reactor core continuous operation during seven to eight years within a moderate temperature range below ~500^{o}C[15]. The technology includes chemical control of the coolant.

Another issue with the lead-bismuth eutectics is related to its relatively high melting point of 125^{o}C, which requires continuous heating of the lead-bismuth coolant to prevent possible damage of the reactor internals due to coolant expansion in phase transition. In the Russian Federation they have developed and tested a safe freezing/unfreezing procedure for lead-bismuth cooled reactor cores based on the observance of a particular temperature-time curve.

One more issue with the lead-bismuth cooled reactors is related to the accumulation of volatile ^{210}Po - a strong toxic alpha emitter. Polonium-210 is generated from ^{209}Bi under irradiation and has a

[14] Seven Alfa class submarines (powered with 155 MWth lead-bismuth cooled reactors BM-40A) were in service from 1972 till 1990.

[15] The technology was developed for non-fast spectrum lead-bismuth cooled reactor cores. Applicability of this technology to fast spectrum cores may need additional validations.

half-life of about 138 days. In the Russian Federation, techniques to trap and remove ^{210}Po have been developed. However, the presence of ^{210}Po is by itself an incentive to consider complete factory fabrication and fuelling for a lead-bismuth cooled reactor.

Otherwise, lead-bismuth eutectics is chemically inert in air and water, has a very high boiling point of 1 670^{o}C, a very high density and a large specific heat capacity which enable an effective heat removal. Also, owing to a freezing point of 125^{o}C, lead-bismuth eutectics solidifies in ambient air contributing to the effective self-curing of cracks if they ever appear in the primary lead-bismuth coolant boundary.

For reasons mentioned above, a typical lead-bismuth cooled fast reactor design concept would be a two-circuit indirect cycle plant. Different from sodium, lead-bismuth cooled fast reactors do not use intermediate heat transport system.

The basic characteristics of the three lead-bismuth cooled SMR design concepts considered in this report are presented in Table 4.6[16]. Of the three SMRs, only the SVBR-100 has reached a degree of maturity with the detailed design development currently being in progress.

Table 4.6. Basic characteristics of advanced SMR designs - lead-bismuth cooled fast reactors

SMR Design Principal designer, Country [Source]	Thermal/Electric output, MW (gross)	Availability/ Plant lifetime	Construction period/ Land-based or floating	Mode of refuelling/ Refuelling interval	Mode of deployment/ Plant configuration
SVBR-100 AKME Engineering (Joint venture of Rusal and Rosatom) [4.2, 4 .13]	280/101.5	95%/ 50 years	42 months	Factory fabricated and fuelled/ 7-8 years	Distributed or concentrated/Single or multi-module plant
PASCAR NUTRECK SNU, Republic of Korea [4.14]	100/37	>95%/ 60 years	Not defined	Factory fabricated and fuelled/ 20 years	Distributed
New Hyperion Power Module Hyperion Power Generation, USA [4.15]	70/ 25 per module	Not specified	21 months on the site	Factory fabricated and fuelled/ 10 (5-15) years	Distributed or concentrated/Single or multi-module plants

All SMR designs are within 25-100 MWe range, with the New Hyperion Power Module being the minimum and SVBR-100 being the maximum. All designs are pool type reactors employing an indirect Rankine steam cycle for generating electricity. All designs are factory fabricated and fuelled reactors that are operated at very low, gravity defined primary pressures and are intended for 7-20 years of continuous operation without refuelling on site. Of the three, the Russian SVBR-100 has the shortest burn-up cycle duration of seven to eight years and does not rely on natural convection of the primary coolant in normal operation.

All lead-bismuth cooled fast SMRs are land-based reactors, although a barge-mounted option has been considered for the SVBR-100. Multi-module plant configurations are indicated for the SVBR-100 and the New Hyperion Power Module. For the SVBR-100, two concepts of such plants of a 400 MWe and a 1 600 MWe overall capacity have been elaborated at a design level [4.5].

The projected plants lifetimes are 50-60 years, and the targeted capacity factor is 95% or higher.

[16] The corresponding detailed design specifications are provided in Table A1.7 of Appendix 1.

Owing to full factory fabrication and fuelling of the reactor modules, the targeted construction period is very short, 3.5 years for the SVBR-100 and 1.75 years for the New Hyperion Power Module.

When described, the reactor pressure vessels are compact, with the maximum dimension not exceeding 10 m, and in the case of the SVBR-100 - 7 m. External cooling of the reactor vessel by air is provided in the PASCAR, while the SVBR-100 and the New Hyperion Power Module are immersed in water pools. Safety implications of these and other safety design features of the lead-bismuth cooled SMRs are explained in Section 8.7.

The SVBR-100 and the New Hyperion Power module provide for a start-up fuel load based on the uranium of slightly less than 20% enrichment. PASCAR is being considered to operate with U-TRU fuel loads in a closed nuclear fuel cycle. The fuel burn-ups are reasonably high, 60-70 MWday/kg.

4.3 Design status and possible timeframes for deployment

Table 4.7 provides an evaluation of the deployment timeframes for some of the SMRs addressed in this report.

The SMRs included in Table 4.7 are those:

- for which the construction is in progress (KLT-40S);
- which are in the process of licensing (HTR-PM, CAREM-25, SMART);
- for which licensing pre-applications have been made and the dates of a formal licensing application have been defined (NuScale, mPower, Westinghouse SMR, AHWR, 4S, New Hyperion Power Module[17]);
- for which previous design versions have been licensed, or the prototypes are (or were) operated, and which are strongly supported by national programmes with deployment timeframes clearly defined at a national level (ABV, VBER-300, SVBR-100).

Table 4.7 does not include SMRs:

- that are still at a conceptual design stage (IMR, PASCAR);
- for which the basic design stage is still not completed (CAREM-300, CCR);
- for which the detailed design has been completed more than a decade ago, but no construction project was initiated (NHR-200, VK-300);
- which are targeted for deployment in the middle of 2020s, at the earliest (GTHTR300, GT-MHR);
- which were targeted for near term deployment, but then suffered a major disruption of the original plans (PBMR [previous design)), see Section 4.2.4).

[17] For the New Hyperion Power module the date of a formal licensing application is still not defined, while licensing pre-application is already in progress.

The SMR designs currently being developed, and that could become available before 2020 are presented in Figure 4.2.

Table 4.7. Design status and potential timeframes for deployment of advanced SMRs

SMR	Technology line	Design status	Licensing status/ Completion (Application) date	Targeted deployment date
KLT-40S Russia [4.16]	PWR	Detailed design completed	Licensed Under construction	2013
VBER-300 Kazakhstan, Russia [4.24]	PWR	Detailed design nearly completed.	No	After 2020
ABV Russia [4.18]	PWR	Barge-mounted NPP: detailed design completed; Reactor plant: detailed design for plant modification in progress	Part of design licensed	2014-2015
CAREM-25 Argentina [4.19]	PWR	Detailed design being finalised	Licensing in progress/2011N	Prototype: 2015
SMART Republic of Korea [4.20]	PWR	Detailed design in progress	Licensing in progress/2011	~2015
NuScale USA [4.21]	PWR	Detailed design being finalised	Licensing pre-application/ (Application: 2011)	FOAK plant in 2018.
mPower USA [4.21]	PWR	Detailed design in progress	Licensing pre-application/ (Application: 2011)	~2018.
IRIS* USA [4.22]	PWR	Basic design completed and is under review by the vendor		
HTR-PM China [4.17]	HTGR	Detailed design completed	Licensing in progress/2010 or 2011	FOAK: 2013
AHWR, India [4.23]	AHWR	Detailed design being finalised	Licensing pre-application/ (Application: 2011)	~2018
SVBR-100 Russia [4.13]	Pb-Bi cooled fast reactor	Detailed design in progress.	No Prototypes have operated in Russian submarines	Prototype: 2017
New Hyperion power Module USA [4.15, 4.21]	Pb-Bi cooled fast reactor	Design status not known	Licensing pre-application/(Application: not known)	FOAK by 2018
4S Japan [4.21]	Na cooled fast reactor	Detailed design in progress.	Licensing pre-application/ (Application: 2012)	FOAK: after 2014

* Late in 2010 the Westinghouse Electric Company stopped the development of the IRIS project and announced it would go with an alternative integral design PWR of a 200 MWe class. Very few technical details of this new SMR were available as of June 2011.

The data given in Table 4.7 indicate that:

- By the middle of the 2010s, several PWR SMRs could be constructed (KLT-40S, ABV, CAREM-25, SMART), as well as an indirect cycle HTGR for electricity production (HTR-PM).

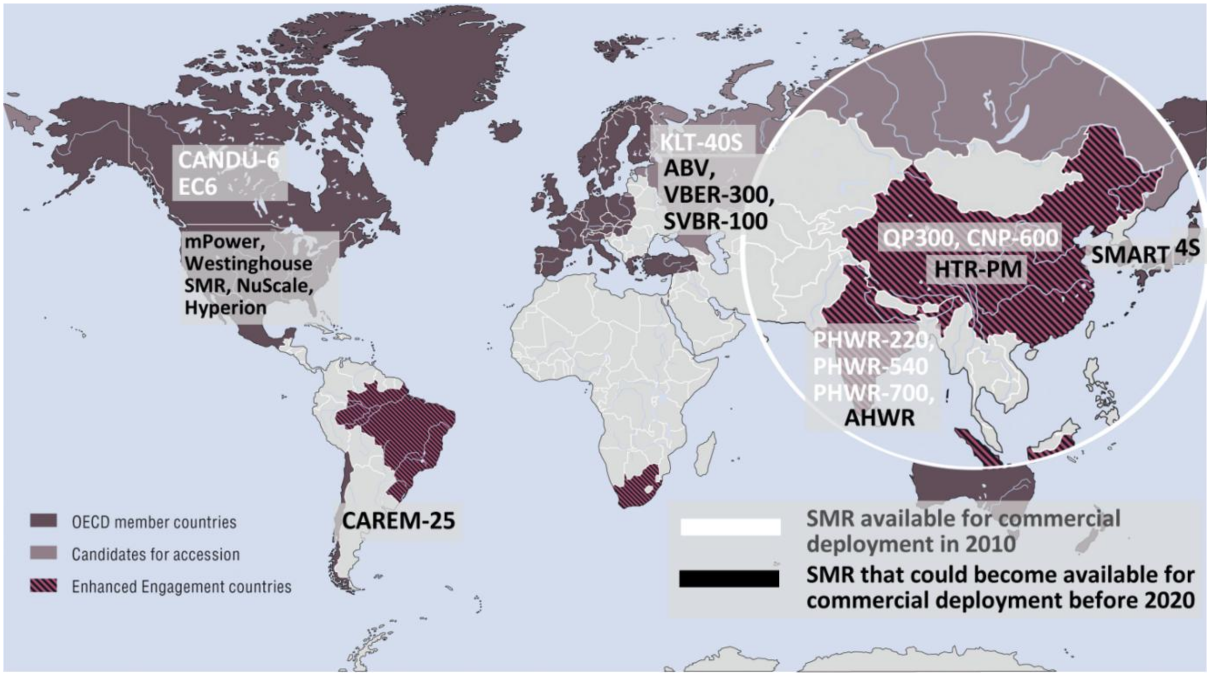
- In the period 2010-2020, more SMRs with pressurised water reactors could become available as FOAK plants (NuScale, mPower, Westinghouse SMR, VBER-300). In addition to this a FOAK of an AHWR could also become available. Should the experience in deployment and operation of FOAK SMRs be successful, commercial deployments of many units of these reactors may follow, starting from the first half of 2020.

- The prospects for nearer term fast spectrum SMRs (SVBR-100, 4S, New Hyperion Power Module) are less certain because of many novel features incorporated in their designs. Even if deployed by 2020, they would be prototype or demonstration plants that would need to be operated for a number of years (especially in view of the targeted long refuelling intervals) before a decision on commercialisation could be taken. It is unlikely that these SMRs could be commercialised before 2025.

- FOAK HTGRs for high temperature non-electrical applications might be deployed around 2025. Their deployment is likely to be conditioned by the progress in hydrogen (or an alternative advanced energy carrier) economy and will also be conditioned by the operation experience of the HTR-PM.

- The countries in which FOAK SMRs could be deployed within the next 10-15 years are Argentina, China, India, Kazakhstan, Republic of Korea, the Russian Federation, and the United States.

Figure 4.2. SMR designs that could be commercially deployed before mid-2020s



4.4 Energy products

NPP operation in a co-generation mode (for example, with co-production of heat or desalinated water) is not a prerogative of SMRs. On a technical level it could, in principle, be realised in NPPs with large reactors as well. Plans exist to use the reject heat of large reactors operated (or being built) in Finland and the Russian Federation for local district heating systems; however, the prospects of their realisation are not clear at the moment[18,19]. With regard to desalinated water production, one of

[18] http://www.powergenworldwide.com/index/display/articledisplay/3386201290/articles/cogeneration-and-on-site-power-production/volume-11/issue-3/features/carbon-free-nuclear.html

[19] http://www.vnipiep.ru/dalnee_teplosnabzhenie.html

the considered processes - reverse osmosis - requires only electricity to pump water through a cascade of membranes, which is by default independent of the reactor capacity.

On the other hand, examples exist where NPPs with SMRs have been used or are being used for co-production of non-electrical energy products. For example, the Bilibino NPP (four 12 MWe LWGR reactors) in the Extreme North of Russia co-produces heat for district heating along with the electricity[20]. The Beznau NPP in Switzerland (two 365 MWe PWR reactors) co-produces heat for district heating for a community of about 20 000 inhabitants. A NPP in Japan produces desalinated water for the plant's own needs [4.30].

The reasons why non-electrical applications are more often considered for SMRs are as follows:

- Some small reactors target the niche markets in remote or isolated areas where non-electrical energy products are as much a value as the electricity is.

- Many SMRs are considered as possible replacement for the currently operated combined heat and power plants (CHPs). In many countries the distribution networks serviced by CHPs are tailored to the equivalent plant capacity of 250-700 MWe [4.31]. Therefore, the use of a NPP with SMRs as a replacement would allow making full use of these networks (that cannot accommodate a large plant).

- Transport of heat or desalinated water over long distances increases costs and may incur losses. The expectation is that SMRs could be located closer to the users (see the discussion in section 9.3), which would help minimise the associated losses and costs.

The production of hydrogen or other advanced energy carriers requires high temperature heat, which makes the HTGR particularly suited for that application.

The data on energy products of SMRs is summarised in Table 4.8 for water cooled SMRs, and in Table 4.9 for non water cooled SMRs. With the exception of HTGRs, no multiple co-generation options are included, which means that, if two non-electrical products are specified, they cannot be used simultaneously.

Regarding the co-generation with SMRs:

- Among the 27 SMRs considered, seven are intended for electricity production only, and for another six the co-generation options, although not discarded, have so far not been considered at the design level.

- There is only one design - the Chinese NHR-200 - which has no electricity generation equipment within its standard configuration. It is a dedicated district heating reactor, but, as an option, it could supply heat for seawater desalination or centralised air-conditioning [4.25].

- Nuclear desalination is included in standard design configurations of the near-term SMART and AHWR (where part of the reject heat is used for that purpose). In all other cases it is still considered as a design option, even though some numerical evaluations have been performed and some data is included in the tables.

- Production of heat for district heating is included in standard design configurations of the Chinese NHR-200 and the following Russian designs:

[20] http://bilnpp.rosenergoatom.ru/eng/about/info/

– near-term marine derivative reactors, the KLT-40S (which is in the construction stage), the ABV, and the VBER-300;

– small and medium-sized BWR, the VK-300; and

– a standard four module plant configuration with the lead-bismuth cooled SVBR-100.

- Hydrogen production is traditionally targeted by HTGRs; however, the Chinese HTR-PM, for which the construction related actions have been initiated with a plan to build 19 modules in the near future, will produce only electricity.

- Atypically for sodium cooled fast reactors, the designers of the 4S have considered an option of hydrogen (and oxygen) production by high temperature electrolysis.

Table 4.8. Energy products offered by water-cooled SMRs*

SMR [Source]	Technology line	Electricity MWe (net)	Heat GCal/h	Desalinated water m^3/day	Process steam t/h (°C)
QP300 [4.9]	PWR	300	No	No	No
CNP-600 [4.5]	PWR	610	No	No	No
KTL-40S [4.29]	PWR	2x35	2x25 at 2x35 MWe	20 000-100 000 option	No
CAREM-25 [4.30]	PWR	27 (gross)	No	10 000 at 18 MWe option	No
CAREM-300 [4.1]	PWR	300 (gross)	No	No	No
SMART [4.1]	PWR	90	150 at 90 MWe option	40 008	No
IRIS [4.1]	PWR	335 (gross)	option	option	option
IMR [4.1]	PWR	350 (gross)	option	option	option
ABV [4.2]	PWR	2x7.9	Up to 2x12	Up to 20 000 option	No
VBER-300 [4.1]	PWR	302	150	option	No
mPower [4.7]	PWR	125-750 or more, depending on the number of modules	No	No	No
NuScale [4.8]	PWR	540 (12 module-plant)	No	option	209.2 (264°C) option
NHR-200 [4.30]	PWR	Option	168	option	330 (127°C)
VK-300 [4.1]	BWR	250 (gross)	400 at 150 MWe	option	No
CCR [4.1]	BWR	400	option	option	option
CANDU-6 [4.27]	HWR	670	No	No	No
EC6 [4.28]	HWR	700	No	No	No
PHWR-220 [4.9]	HWR	202	No	6 300 option	No
AHWR [4.1]	AHWR	300	option	500 (using reject heat)	No

* If the production rate of, say, heat or desalinated water is not followed by the indication of an electric power level at which it is achieved, it should be viewed as the maximum rate that would require a reduction in the electric output level compared to that indicated in the tables.

Table 4.9. Energy products offered by non-water-cooled SMRs

SMR [Source]	Technology line	Electricity MWe (net)	Heat GCal/h	Desalinated water m^3/day	Hydrogen t/day	Process steam t/h (°C)
HTR-PM [4.1]	HTGR	210* (two-module plant)	No	No	No	No
PBMR (previous design) [4.1]	HTGR	660 (4-module plant) 1 320 (8-module plant)	No	No	option	No
GT-MHR [4.1]	HTGR	287.5* (per module)	No	42 000	200 at 600 MWth	option
GTHTR300 [4.1]	HTGR	274*	option	option	126	option
4S [4.2]	Na cooled FR	10 *	option	34 008 option	6.5 option	option
SVBR-100 [4.2]	Pb-Bi cooled FR	100-1 600, depending on the number of modules	520 at 380 MWe (4-module plant 400 MWe)	200 000 at 9.5 MWe per module option	No	No
PASCAR [4.14]	Pb-Bi cooled FR	35	option	option	option	option
New Hyperion Power Module [4.15]	Pb-Bi cooled FR	25* (per module)	option	option	option	option

* Gross electric output

A somewhat cautious attitude of SMR designers to the inclusion of non-electrical applications in the designs of their FOAK plants reflects the fact that some recent market surveys have shown electricity applications to be in prime demand worldwide for the next decade [4.26]. With this in mind, the designers are pursuing the fastest deployment of the electricity-only versions of their SMRs, reserving the non-electrical applications for a more distant future.

4.5 Load following operation and compatibility with electricity grids

Many SMRs addressed in this section are designed (or are being designed) for both baseload as well as load-following operation. Where specified, the magnitude and rate of (daily) power variations and number of power level switches for SMRs do not differ much from those of the state-of-the-art large reactors[21]. The SMR derived from marine reactors may even have better manoeuvring capabilities than large reactors, since the original propulsion reactors are specifically designed to allow rapid power variations in a wide power range. However, the precise information on manoeuvring capabilities of advanced SMRs is currently not available.

For some co-generation plants with SMRs, e.g., the NuScale [4.8], it is proposed to change the ratio of electricity and desalinated water production at a constant thermal output of the reactor, which is expected to enable load-following operation precisely matching hourly load changes during the day.

Regarding non water-cooled SMRs, load following capability is in fact linked to the low linear heat rate of the fuel elements. For example, load-following is generally not considered for large capacity sodium cooled reactors where the linear heat rate of fuel elements can be as high as 485 W/cm. In the small sodium cooled 4S (see Section 4.2.5) the linear heat generation rate is only

[21] For example, the EC6 (see Section 3) has a proven capability of daily load cycles from 100% to 60% of rated power, and can continue operation with loss of line to grid [4.41]. Some of the currently operated large French reactors (*e.g.* REP-1300 MWe, N4 design of 1 450 MWe) use daily cycles from 100% to 40% of rated power. Moreover, both the EPRI Utility Requirements Document and the European Utility Requirements (EUR) stipulate that the reactors should be capable of daily load cycles from 100% to 50% (or even 20%) of rated power [4.43].

39 W/cm, which is said to enable load-following operation with controlled changes to the reactor power level[22].

Regarding the compatibility with electricity grids, the general “rule of thumb” is that the unit size of a power plant should not exceed 10% of the overall grid capacity[23] [4.42]. This requirement could, perhaps, be relaxed by some appropriate smart grid designs, but this is still subject to research. By definition NPPs with SMRs can be more easily deployed using existing grid capacity, when compared to large reactors or any other large sources of power.

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5. Small and Modular Reactors ("Mini" Reactors) and their Attributes

Recently the so-called "mini" or small and modular reactors have attracted much attention. Since 2008, several private companies have been created in the United States to support the design development, patenting, licensing and commercialisation of several new SMR concepts. Typically, the companies were created following the R&D and design development activities carried out by the US national laboratories and consulting companies. Eventually bigger private companies (including some propulsion reactor manufacturers) have followed the trend [5.1].

Table 5.1 lists the US concepts of small and modular reactors that were announced in the last few years. Table 5.1 includes the three SMR design concepts addressed in more detail in Section 4 of this report (the NuScale, the mPower, and the New Hyperion Power Module) and another design concept which is at an early design stage with prospects of further financing still unclear (the ARC-100).

Table 5.1. Small and modular reactors under development in the United States

	NuScale [5.2]	mPower [5.1]	Westinghouse SMR	New Hyperion Power Module [5.3]	ARC-100 [5.4]
Designer, Country	NuScale Power, USA	Babcock & Wilcox, USA	Westinghouse, USA	Hyperion Power Generation, USA	Advanced Reactor Concepts LLC, USA
Technology line	PWR	PWR	PWR	Lead-bismuth cooled fast reactor	Sodium cooled fast reactor
Electric output (gross), MWe	48	125	>225	25	50-100

The attributes of small and modular reactors mentioned cumulatively in [5.1, 5.2, 5.3, and 5.4] are:

- Small reactor size allowing transportation by truck (as well as by rail or barge) and installation in proximity to the users, such as residential housing areas, hospitals, military bases, or large governmental complexes.

- Small absolute capital outlay and an option of flexible capacity addition/removal through modular approach to plant design, deemed attractive to private investors.

- Individual containments and turbine generators for each of the reactor modules.

- High levels of safety and security boosted by the underground location of the reactor module(s), see examples at Figure 5.1 and Figure 5.2.

- Factory assembly of the complete nuclear steam supply system (NSSS) and, therefore, short construction duration on site.

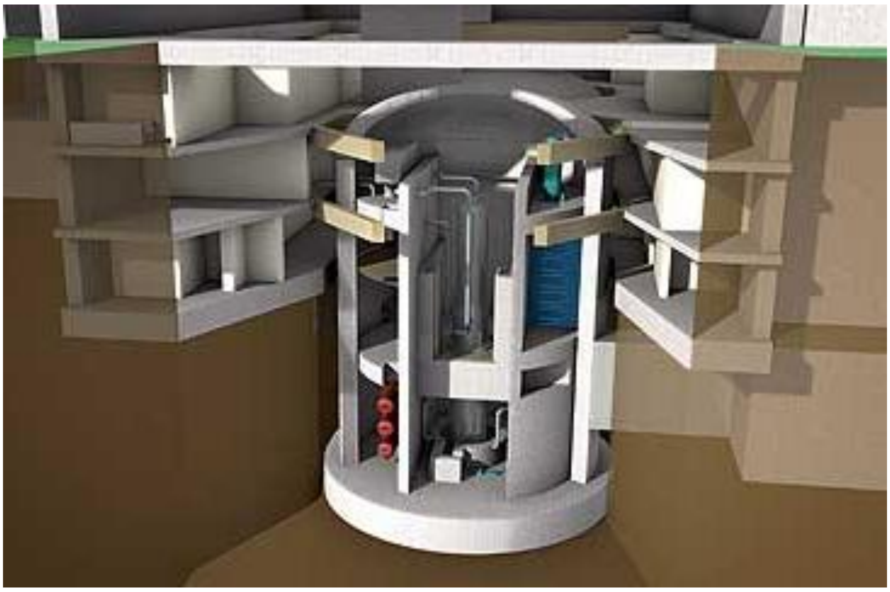
- Long refuelling interval and once-at-a-time whole core reloading on the site or at a centralised factory (as a future option).

- Simplified decommissioning limited to disconnection and removal of the transportable modules.

- Provision for flexible co-generation options (generating electricity with co-production of heat, desalinated water, synthetic fuels, hydrogen, etc.).

Figure 5.1. Reactor module configuration of the mPower [5.1]

Integral modular reactor



Single module reactor inside underground containment

Figure 5.2. Reactor module configuration of the NuScale [5.2]

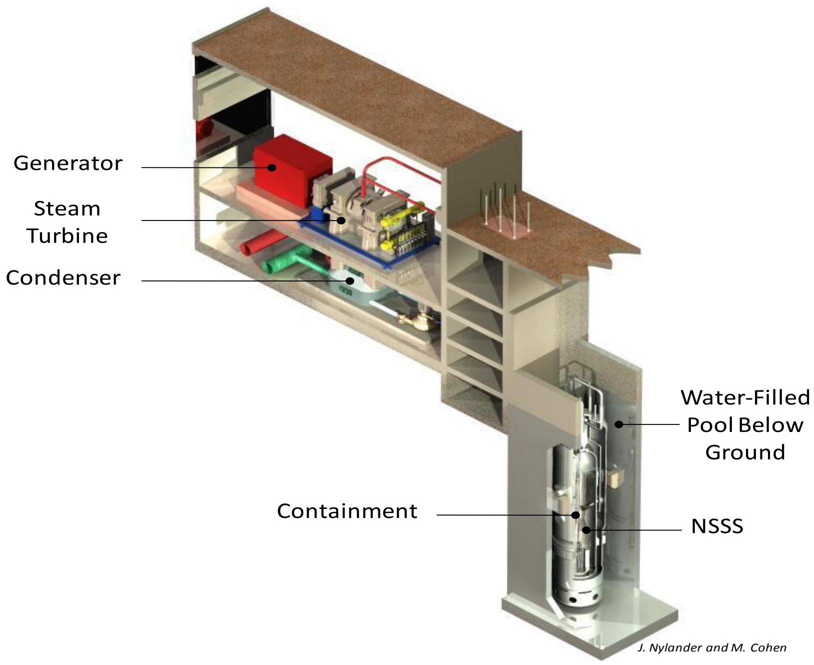


Table 5.2 shows how the above mentioned cumulative attributes are distributed among the US small and modular reactor designs.

Table 5.3 shows how the same attributes are distributed among the non-US small and modular reactor designs considered in this report.

Table 5.2. Design attributes of small and modular reactors under development in the United States

	NuScale [5.2] *Table 4.1*	mPower [5.1] *Table 4.1*	Hyperion Power Module [5.3] *Table 4.6*	ARC-100 [5.4]
Technology line	PWR	PWR	Lead-bismuth cooled fast reactor	Sodium cooled fast reactor
Electric output (per module), MWe	125	48	25	50-100
Factory assembly and delivery of NSSS	Yes	Yes	Yes	No information
Long refuelling interval, once-at-a-time whole core reloading on the site or factory refuelling	No	Yes	Yes	Yes
Multi-module plant option	Yes	Yes	Yes	No
Flexible capacity addition/removal	Yes	Yes	Yes	No
Underground location of reactor modules	Yes	Yes	Yes	Yes

Table 5.3. Design attributes of small and modular reactors under development in countries other than the United States

	KLT-40S Russia	ABV Russia	4S Japan	SVBR-100 Russia	PASCAR Republic of Korea
Technology line	PWR	PWR	Sodium cooled fast reactor	Lead-bismuth cooled fast reactor	Lead-bismuth cooled fast reactor
Electric output (per module) MWe	35	8.5	10	101.5	37
Factory assembly and delivery of NSSS	Yes	Yes	Yes	Yes	Yes
Long refuelling interval, once-at-a-time whole core reloading on the site or factory refuelling	No	Yes	Yes	Yes	Yes
Multi-module plant option	Twin-unit	Twin-unit	No	Yes	No
Flexible capacity addition/ deletion	No	No	No	Yes	No
Underground location of reactor modules	No	No	Yes	Partly embedded underground, (see Figure 5.4)	No information

The data presented in Table 5.1, Table 5.2 and Table 5.3 indicate that:

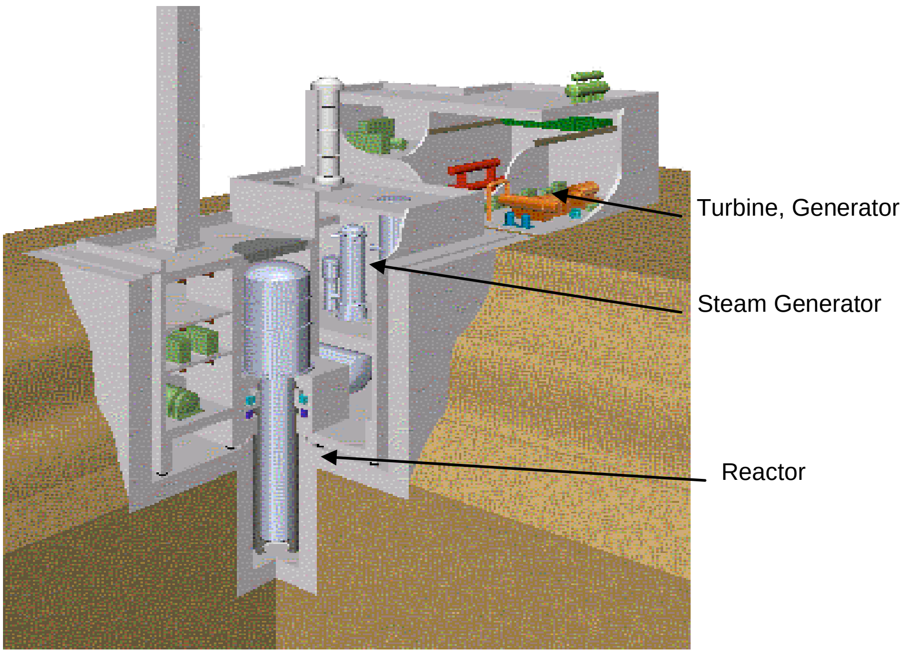
- The new small and modular ("mini") reactor concepts being developed in the United States fit well into the technology lines described in Chapter 4.
- The new US small and modular reactors (NuScale, mPower, New Hyperion Power Module, and ARC-100) share many of their design attributes with other small reactor design concepts being developed in other countries.
- However, three attributes that distinguish most of the new US small and modular reactors from other small reactor concepts developed elsewhere in the world, are namely:
  - multi-module plant option;
  - option of flexible capacity addition/removal; and
  - underground reactor modules.

- Some of the SMR designs developed outside the United States offer plant configurations similar to those envisaged for the US small and modular reactors. As an example, the Japanese 4S offers an underground location for the reactor module but does not provide for a multi-module plant, see Figure 5.3; As another example, 4,-6- and 16-module plant options have been considered for the Russian SVBR-100. Some of these plant configurations provide partly-underground location for the reactor modules, see Figure 5.4.

- Even though some of the non-US SMR design concepts (as well as the US ARC-100) do not offer a flexible multi-module plant configuration, an option to cluster several plants on the same site still exists, potentially yielding certain economic benefits related to the sharing of auxiliary equipment and communications, and learning. Alternatively, single module or twin-unit plants with SMRs could be reconfigured for a flexible multi-module plant configuration at later design stages.

- Sheltered underground location for reactor modules adds a degree of protection against aircraft crash but may pose challenges with respect to other site-specific external events, such as floods, see discussions in Section 6.8.2.

Figure 5.3. The 4S plant of 10 MWe [5.6]

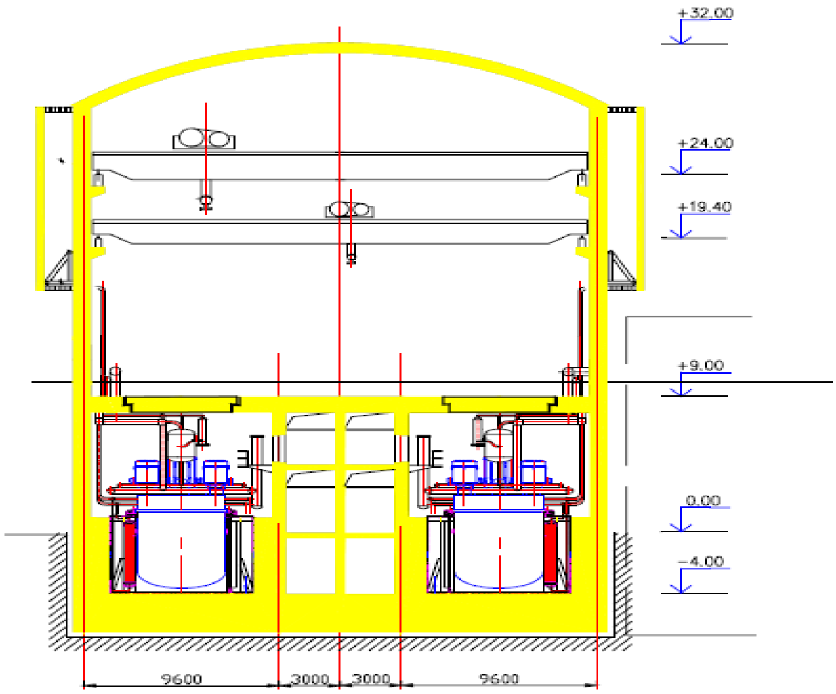


The fast spectrum sodium- and lead-bismuth cooled SMRs from Table 5.2 and Table 5.3, with the exception of the Korean PASCAR, share another common attribute - they provide for an initial fuel load based on enriched uranium rather than an uranium and plutonium mixture. The uranium enrichment is slightly below 20%.

The SVBR-100, the New Hyperion Power Module, and the ARC-100 are reported to be capable of operation with the initial uranium fuel load including a fraction of non-reprocessed spent nuclear fuel from present day light water reactors (with fission products). For the SVBR-100 this fraction is evaluated as 12%$_{weight}$ [5.6], while for the ARC-100 - as 25%$_{weight}$ [5.4].

Generically, all fast spectrum small and modular reactors are being designed to operate in a closed nuclear fuel cycle[1]. Because of a long refuelling interval (10-30 years) they do not pose a requirement for near-term availability of the reprocessing technologies, leaving a time lag for such technologies to be developed and mastered on a commercial scale. The conversion ratio is typically high, slightly below 1.0, which means that the reactor breeds almost as much fissile material as it consumes during operation. The spent fuel, after cooling and reprocessing, can be reloaded in the core with an addition of natural or depleted uranium. The reprocessing would then be limited to removal of the fission products without further separation of heavy nuclides.

Figure 5.4. Vertical cross section of a 6-module plant with SVBR-100 reactor modules [5.5]



The attributes of small and modular reactors, such as small upfront capital investments, short on-site construction time (with the cost of financing accordingly reduced) and flexibility in plant configuration and applications, make such reactors attractive for private investors. However, since the nuclear industry is heavily regulated by public authorities, the public-private partnership seems to be the most probable form of cooperation to develop projects with small and modular reactors.

In the Russian Federation, the Joint Stock Company (JSC) "Evrosibenergo" and the State Atomic Energy Corporation "Rosatom" have created a public-private joint venture company “AKME Engineering” to advance the development, licensing and commercialization of the SVBR-100 project of a small lead-bismuth cooled reactor [5.8]. The near-term goal is to deploy the prototype on the site of the NIIAR research centre in Dimitrovgrad (Russian Federation) by 2017.

In the United States, formation of public-private partnership and licensing for the small and modular reactors is being supported by the Small and modular reactor programme of the Office of Advanced Reactor Concepts belonging to the Office of Nuclear Energy of the Department of Energy (DOE) [5.9]. This programme, started in May 2011, has a near-term priority to support licensing of

[1] Some recently announced concepts of small fast reactors for waste incineration, such as the fast-spectrum gas cooled EM2 of 240 MWe (being proposed by the General Atomics in the United States [5.7]), abandon fuel reprocessing and suggest that the spent fuel could be stored within the disconnected reactor module on the site or in a repository.

two US designs of water cooled small and modular reactors. The target is to have these designs licensed for operation on the US territory by 2015 and to have them deployed by 2018. In the United States, development and deployment of small and modular reactors is viewed as a benefit to national industry as all (relatively small) components of such reactors could be produced indigenously [5.9].

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6. Factors Affecting the Competitiveness of SMRs

6.1 Introduction and designers' cost data for SMRs

6.1.1 Introduction and definition of Levelised Unit Electricity Cost (LUEC)

In order to assess the economics of different SMR projects and their deployment potential, this chapter provides the analysis and evaluation of the various economic factors affecting the competitiveness of SMRs.

The main figure of merit used in this chapter, as well as in the following Chapter 7, is the Levelised Unit Electricity Cost (LUEC). The LUEC formula and definitions are taken from reference [6.1] which mentions that:

> the notion of levelised costs of electricity (LUEC[1]) is a handy tool for comparing the unit costs of different technologies over their economic life. It would correspond to the cost of an investor assuming the certainty of production costs and the stability of electricity prices. In other words, the discount rate used in LUEC calculations reflects the return on capital for an investor in the absence of specific market or technology risks.

All SMR deployment foreseen in the next decade would mainly take place in regulated electricity markets with loan guarantees and with more or less strictly regulated prices (see Figure 4.2), which justifies the selection of LUEC as a figure of merit for the competitiveness assessment of nearer-term SMRs.

The LUEC formula suggested in reference [6.1] reads:

$$\mathrm{LUEC} = \frac{\sum_t \frac{(\mathrm{Investment}_t + O\&M_t + \mathrm{Fuel}_t + \mathrm{Carbon}_t + \mathrm{Decommissioning}_t)}{(1+r)^t}}{\sum_t \left(\frac{\mathrm{Electricity}_t}{(1+r)^t}\right)} \qquad (6.1)$$

where;

$\mathrm{Electricity}_t$:	The amount of electricity produced in year "t";
r:	Annual discount rate;
$\mathrm{Investment}_t$:	Investment cost in year "t";
$O\&M_t$:	Operations and maintenance cost in year "t";
Fuel_t:	Fuel cost in year "t";
Carbon_t:	Carbon cost in year "t";
$\mathrm{Decommissioning}_t$:	Decommissioning cost in year "t".

[1] In [6.1], a term LCOE - levelised cost of electricity is used. We use another abbreviation - LUEC - that is equivalent to LCOE, to be consistent with the literature on SMRs.

The subscript “t” denotes the year in which the electricity production takes place or the expenses are made. The various assumptions used in deriving the formula (6.1) are discussed in detail in reference [6.1].

We summarise in Table 6.1 the structure of a nuclear generation cost, based on the data reported in reference [6.1]. It should be noted that those data refer mostly to NPPs of unit power higher than 1 000 MWe.

Table 6.1. Structure of nuclear electricity generation cost (for large reactors), based on [6.1]

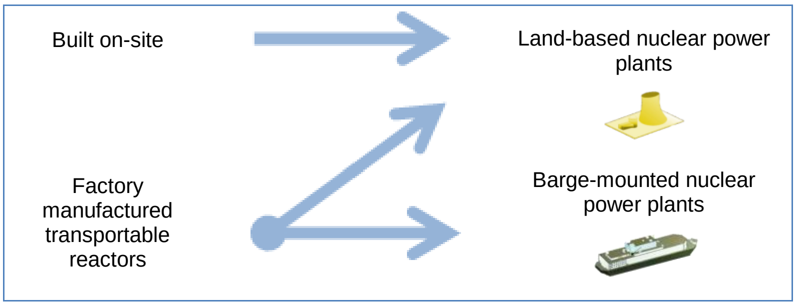
	5% discount rate	10% discount rate
Total investment cost	58.6%	75.6%
O&M	25.2%	14.9%
Fuel costs*	16.0%	9.5%
Carbon costs	0.0%	0.0%
Decommissioning	0.3%	0.0%

* Fuel costs comprise the costs of the full nuclear fuel cycle including spent fuel reprocessing or disposal [6.1].

Table 6.1 indicates that the total investment cost is a major constituent of LUEC for nuclear technology, with the O&M cost and the fuel cost making the next meaningful contributions. Carbon cost is zero since nuclear power plants emit no CO_2 in operation. Finally, the contribution of the decommissioning cost (usually taken as about 15% of the overnight costs) to LUEC is always very small once discounted over 40-60 years, the typical operational lifetime of a nuclear plant.

As has been shown in the previous chapters, SMRs could be divided in to two major categories: “traditional” land-based nuclear power plants and barge-mounted plants (see Figure 6.1). Land-based reactors could be either factory-manufactured and assembled on-site, or fully built on-site. These realisations may have very different effects on the competitiveness of each particular project.

Figure 6.1. Different SMR realizations



The objective of the following sections is to analyse and, where possible, to quantify the various factors affecting the competitiveness of SMRs (in terms of LUEC). An important concern while analysing the economics of SMRs, is the lack of data regarding their construction cost and the differences between SMR projects. In order to avoid those difficulties, we decided to adopt a scaling-law methodology [6.4] using the reliable data available for NPPs with large reactors (that have been deployed in recent years or are being deployed at the time of this report). The analyses performed are mostly based on comparative assessment of the impacts of the various factors on the economy of a NPP with SMR and that of a NPP with a large reactor.

After a brief summary of the designers' LUEC values for SMRs in the following sub-section 6.1.2, we analyse in section 6.2 the factors affecting the investment cost, which are responsible for the major differences in the economies of SMRs and larger reactors.

The main factor negatively affecting the investment component of LUEC for all SMRs is the economy of scale. Depending on the power level of the plant, the specific (per kWe) capital costs of SMRs are expected to be tens to hundreds of percent higher than that for large reactors. While the economy of scale increases the specific capital costs and, therefore, the investment component of the LUEC for SMRs, other economic factors may tend to improve it. As an example:

- **Construction duration.** According to the vendors' estimates the construction duration of SMRs is shorter than for large reactors.

- **First-of-a-kind factors and economy of subsequent units on the site/multi-module plants.** Building several reactors on the same site is usually cheaper than building a NPP with single units. This factor is the same for large reactors and SMRs. However, many SMRs are intended to be built in multiple modules and, thus, this factor can potentially play a larger role for SMRs than for large reactors.

- **Economy of subsequent factory fabricated units.** Different from large reactors, some SMRs could be manufactured and fully factory assembled, and then transported to the deployment site. This could potentially allow a decrease in the production cost (owing to the effects of production organisation and learning) and contribute positively to the competitiveness of SMRs.

- **Design simplification.** Some SMRs could offer a significant design simplification with respect to large reactors. If simplifications are possible, this would be a positive contribution to the competitiveness of SMRs.

To the extent possible, numerical estimates of each of the factors and their combined action are provided.

6.1.2 Designers' cost data for SMRs

The SMR designers' cost data (converted to 2009 USD) for various SMRs described in Chapter 4 are given in Table 6.2 and Table 6.3.

Where not indicated, the designers' overnight costs do not take into account the interest rates during construction. In most of the cases, the discount rate used in designers' LUEC calculation[2] is 5%. Several caveats should be understood:

- Regarding the CCR [4.1], the cost target is stated as "comparable to the state-of-the-art Japanese ABWR". The CCR electricity cost data in Table 6.2 correspond to the ABWR cost projection for 2010 from reference [4.31].

- For mPower, the cost data from [6.16] has been used.

[2] However, it cannot be guaranteed that the interest rate for the LUEC calculations used by the vendors were all the same.

- For the NuScale and the New Hyperion Power Module the designers indicate generation cost targets as equal or better than for current LWRs. This being rather ambiguous, no data for the NuScale and the New Hyperion Power Module are included in the tables below.

Table 6.2. Cost data for water cooled SMRs (in 2009 USD)*

SMR	Unit power MWe	Overnight capital cost USD per kWe	LUEC** USD per MWh	Levelised heat cost USD per GCal	Levelised desalinated water cost USD cent per m³
PWRs					
ABV [6.2]	8.5	9 100	≤120	≤45	≤160
CAREM-25 [6.8, 6.19]	27	3 600***	~42 at 8% discount rate	n/a	81 at 8% DR
KLT-40S [6.17]	35	3 700-4 200	49-53	21-23	85-95
NHR-200 [6.8]	200 MWth	809	n/a	-	66-86
SMART [6.8]	100	-	60	n/a	70
mPower [6.16]	125	-	47-95		
CAREM-125 [4.8]	125	1 900	-	n/a	n/a
CAREM-300 [6.8]	300	1 200	-	n/a	n/a
VBER-300 twin-unit [6.8]	325	2 800 barge 3 500 land	33 barge 35 land	18	n/a
QP300 two units average [6.18]	325	2 800 Pakistan	-	n/a	n/a
IRIS [6.8]	335	1 200-1 400 IC	34-45	n/a	n/a
BWRs					
VK-300 [6.8]	750	1 100	13	4	n/a
CCR	423	3 000-4 000	50	n/a	n/a
HWRs/AHWRs					
PHWR-220 [6.19]	220	1 400-1 600	39 50 at 7% discount rate	n/a	100-110 at 7% DR
AHWR [6.8]	300	1 300 F	25 single 24 four plants	-	n/a
CANDU-6 twin-unit [6.18]	715	3 600	35 Canada 32 China	n/a	n/a

* IC - investment cost, F - first-of-a-kind plant, N - n^{th}-of-a-kind plant, barge - barge-mounted plant, land - land-based plant.

** At a 5% discount rate by default.

*** In the latest official announcement a range of 8 000 - 14 000 USD per kWe is quoted (see http://en.mercopress.com/2011/04/29/argentina-will-press-ahead-with-plans-to-develop-small-scale-nuclear-reactors).

Table 6.3. Cost data for non water cooled SMRs (in 2009 USD)

SMR	Unit power MW_{th}	Overnight capital cost, USD per kWe	O&M cost, USD per MWh	Fuel cost, USD per MWh	LUEC* USD per MWh	Levelised heat cost, USD per GCal	Levelised desalinated water cost, US cent/m^3	Levelised hydrogen cost, USD per kg
HTGRs								
HTR-PM [6.8]	250	<1 500	9	12	51	n/a	n/a	n/a
PBMR (previous design) [6.8]	400	<1 700	1.0 O&M+Fuel	1.0 O&M+Fuel	As large LWR	n/a	n/a	-
GT-MHR [6.8]	600	1 200	4	9	36	n/a	-	1.9
GTHTR300 [6.8]	600	<2 000	-	-	<40	-	-	-
Sodium cooled fast reactors								
4S [6.2]	30	-	-	-	130-290	n/a	-	-
Lead-bismuth cooled fast reactors								
PASCAR [6.20,6.21]	100	-	-	-	100	n/a	n/a	n/a
SVBR-100 [6.2]	280	1 200 prototype	-	-	19 for 1600 MWe plant; 42 for 400 MWe plant	-	88 for 400 MWe plant	n/a

* At a 5% discount rate by default.

Table 6.4 presents the ranges of energy product costs for SMRs of different technology lines, based on the data from Table 6.2 and Table 6.3. For comparison, the median case of the projected generating costs in operating nuclear and non-nuclear plants is included, based on the data from reference [6.1]. Also, Table 6.4 gives a comparison of the designers' data on LUEC to the projected costs of generating electricity by large nuclear power plants in relevant countries in 2010 [6.1].

Table 6.4. Ranges of energy product costs for different technology lines of SMR (in 2009 USD)

SMR	LUEC USD per MWh	Levelised heat cost USD per GCal	Levelised desalinated water cost at 5-8% DR USD cent per m^3	Levelised hydrogen cost USD per kg
PWR (without very small ABV)	33-60	18-23	66-95	-
PWR-ABV	≤ 120	≤45	≤ 160	-
BWR[2]	50	-	-	-
HWR/AHWR	24-39	-	100-110	-
HTGR	36-51	-	-	1.9
Sodium cooled fast reactors (very small 4S)	130-290	-	-	-
Lead-bismuth cooled fast reactors (without very small PASCAR)	18-42	-	88	-
Lead-bismuth cooled fast reactors (very small PASCAR)	100	-	-	-

IEA-NEA/OECD projections for electricity generating costs in 2010
(Table 5.2 of reference [6.1], Median case)

Technology**	Nuclear	CCGT	SC/USC Coal	Onshore wind	Solar PV
Levelised cost of electricity at 5% discount rate, USD per MWh	58.5	85.8	65.2	96.7	41.1

* The VK-300 designers' data was not included as abnormally low. ** CCGT - Combined cycle gas turbine; SC/USC Coal - Supercritical/Ultra-supercritical coal-fired plants, PV - Photovoltaic.

The designers' cost data for SMRs show that:

- The generating cost (LUEC) for some very small (well under 100 MWe) nuclear power plants intended for distributed deployment exceeds the median case projection of the cost of generating electricity by nuclear power plants roughly by a factor of two.

- For all other SMRs the designers' evaluations of the generating costs appear to be close to, or below the median case projection.

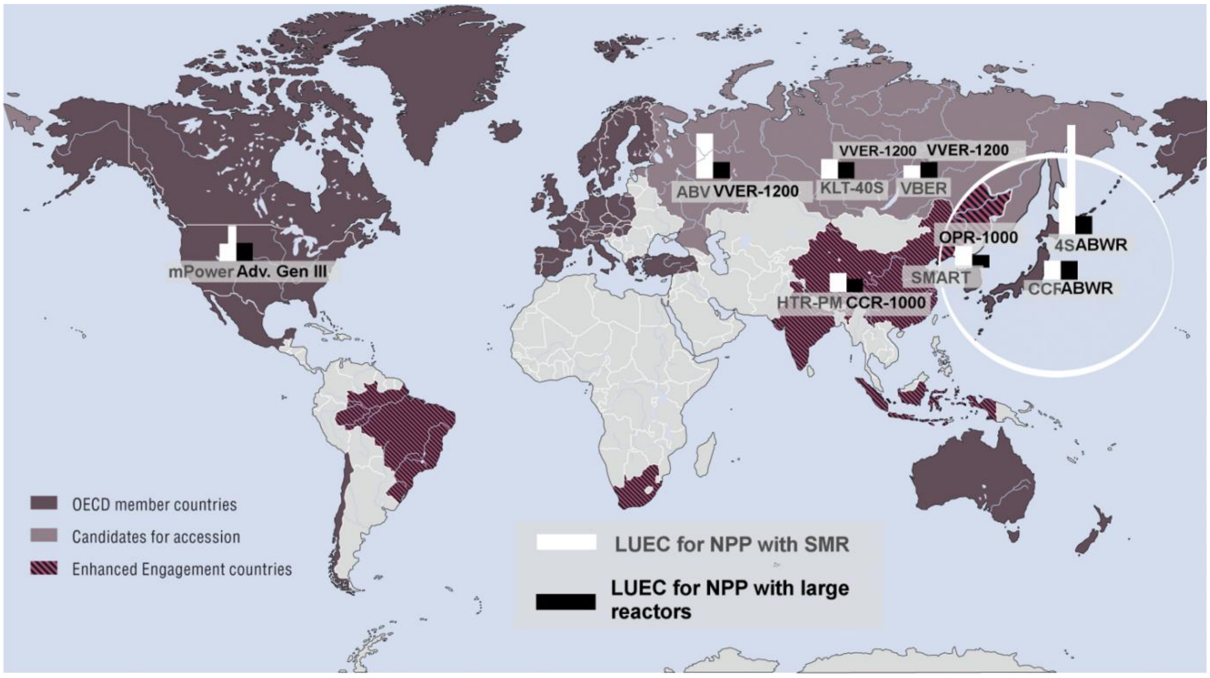
- On a country-by-country level, the designers' evaluations of generating costs are in many cases higher than the projected costs of generating electricity by large nuclear power plants in the countries where SMRs are designed.

The vendors' cost data indicate that the designers of advanced SMRs generally intend to compete with larger nuclear power plants (see Figure 6.2). The exceptions are very small (below 100 MWe) NPPs that are being designed for distributed deployment in remote off-grid locations where the electricity costs could be much higher compared to the areas with common electricity grids.

As SMRs do not benefit from the economy of scale, the designers have to rely on other factors to reach the economic targets. These factors and their possible impact on SMR economy are analysed and quantified further in this chapter.

In Chapter 7 independent estimates of LUEC for the selected "typical" NPP configurations with SMRs are obtained and then compared to the designers' data on LUEC given in this section.

Figure 6.2. Comparison of the designers' data on SMR LUEC (Table 6.2 and Table 6.3) to the projected costs of generating electricity by nuclear power plants in the corresponding countries (Table 3.7a in [6.1])



6.2 Factors affecting the investment cost of SMRs

The investment component of LUEC (the investment cost in Table 6.1) reads:

$$\text{LUEC}_{\text{inv}} = \frac{\sum_t \left(\frac{\text{Investment}_t}{(1+r)^t}\right)}{\sum_t \left(\frac{\text{Electricity}_t}{(1+r)^t}\right)} \quad (6.2)$$

The main factors affecting the investment cost are:

- The investments spread over construction years (their sum is often referred to as the "overnight capital cost") depending on the construction schedule, and
- The discount rate *r* defining the interest on investments, also known as the cost of financing.

An additional important factor is the contingency costs, i.e., cost increases resulting from unforeseen technical or regulatory difficulties. According to reference [6.1], the contingencies for a nuclear option constitute 15% of the investment costs in all countries, except France, Japan, the Republic of Korea, and the United States, and are typically included in the investments attributed to the last year of construction. For countries with a large number of operating nuclear power plants (like France) the contingency rate is often taken as approximately 5% (similar to other technologies, see reference [6.1]), because the technical and regulatory procedures could be considered as running in a well established way. In the case of factory manufactured SMRs the contingency rate would probably be lower than for large nuclear power plants, once the production of units is mastered.

The investment cost is the largest component of LUEC, and its share grows with the increase of the discount rate, see Table 6.1. Therefore, the factors that impact the investment cost are of prime importance for the competitiveness of any NPP. The following sections reflect on how these factors may affect the economy of SMRs, with a focus on the comparative assessment of NPPs with large reactors and those with SMRs.

6.2.1 Economy of scale

The specific, per kWe of installed capacity, overnight capital cost is known to be reduced as the plant size is increased. This is due to economies of raw materials and optimisation that could be realised while building larger reactors.

Reference [6.4] suggests the following scaling function that can be used to illustrate the effect of changing from a unit size P_0 to P_1 (see Figure 6.3) for the same design but different capacity:

$$\text{Cost}(P_1) = \text{Cost}(P_0)\left(\frac{P_1}{P_0}\right)^n \quad (6.3)$$

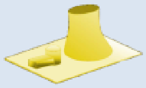
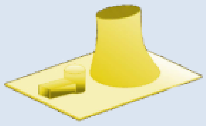
where

Cost (P_1) = Cost of power plant for unit size P_1,

Cost (P_0) = Cost of power plant for unit size P_0, and

n = Scaling factor, obtained for reactors with unit power from 300 to 1 300 MWe, is in the range of 0.4 to 0.7 for the entire plant

Figure 6.3. The scaling law for the cost of NPPs

	→	
Power P_0	→	Power P_1
Cost (in USD)		
$Cost(P_0)$	→	$Cost(P_1)=Cost(P_0)\left(\frac{P_1}{P_0}\right)^n$
Specific cost (in USD per kWe)		
$\frac{Cost(P_0)}{P_0}$	→	$\frac{Cost(P_1)}{P_1}=\frac{Cost(P_0)}{P_0}\left(\frac{P_1}{P_0}\right)^{n-1}$

Example

Consider a single-reactor NPP of P_0=1 000 MWe having a cost equal to Cost (1 000 MWe). Then a larger single-reactor power plant of similar design, say, of 1 500 MWe, would cost (for $n = 0.5$):

$$\text{Cost (1 500 MWe)= Cost (1 000 MWe)}\times(1.5)^{0.5} \approx 1.2\times \text{ Cost (1 000 MWe)}.$$

Thus, the total cost of a larger plant is higher than the cost of a smaller plant. At the same time the specific cost (per kWe) of the larger NPP would be19% less than that of a smaller 1 000 MWe plant.

There are some important caveats regarding the use of the scaling law (6.3):

- The scaling law is only true if no significant design changes take place on transition to a larger or smaller capacity plant. If such changes take place (for example, the complexity of the plant design is reduced or increased), this results in a transition to another scaling law curve which may be located below or above the original one [6.5].

- According to reference [6.4], "the economy of scale may be limited due to the physical limitation to increase dimensions of some systems or components (*e.g.* reactor core, fuel rods and turbine blades). …The maximum size of units in an electrical grid is limited in consideration of grid stability, demand pattern, spinning reserve or other specific characteristics of the system".

- One should keep in mind that an overall power scaling law for the entire plant is only approximate, because different components may have very different scaling exponents (for example, see Table 6.6), and thus the cost as a function of the plant unit power P is actually a polynomial of P, and it is approximated in (6.3) by a monomial.

The value of the scaling factor n is not fixed, and can be quite different for different NPPs:

- For example, for Korean NPPs of generally similar design OPR-1000 and APR-1400 this factor is 0.45, see Table 6.5.

- Another study, based on a French experience, gives a more detailed evaluation of the scaling factors, shown in Table 6.6. According to Table 6.6, the scaling parameter n is close to 0.6 for direct costs and is about 0.3 for the indirect costs including contingencies and owner's costs. Also, it could be noted that the value of n increases with the increase in plant capacity, i.e., for two smaller capacity plants it is smaller than for two larger capacity plants. The total scaling factor from Table 6.6 is 0.51.

- A third study performed for the AP1000 and AP600 plants gives *n* = 0.6 for scaling of the direct costs, see reference [6.7].

Table 6.5. Scaling factor for NPPs produced in the Republic of Korea (table 3.7a in [6.1]

Technology	Net Capacity, MWe	Overnight capital cost, USD/kWe	Scaling Factor *n*
OPR-1000 (Korea)	954	1 876	0.45
APR-1400 (Korea)	1 343	1 556	0.45

Table 6.6. Capital investment decomposition as percentage of the total overnight cost for 300-1350 MWe PWR units [6.6]

Cost components	300 MWe	650 MWe	1 000 MWe	1 350 MWe	Scaling factor *n*
Land and land rights and site utilities	2.8	2.9	3	3.1	*0.07*
Buildings and structures	14.8	21.6	26.7	31	*0.49*
Steam production and discharge processing	23.5	39.4	53.5	66.8	*0.69*
Turbines and alternators	10.5	17.7	23.7	29.1	*0.68*
Electrical, instrumentation and control	5.6	8.9	11.5	13.8	*0.60*
Miscellaneous plant equipment	2.5	3.2	3.7	4.1	*0.33*
Water intake and discharge structures	1.9	3.6	5	6.4	*0.81*
Sub-total for direct costs	**61.5**	**97.3**	**127.2**	**154.2**	**0.61**
Engineering and design	13.3	16.4	18.9	21.1	*0.31*
Construction services	6.2	7.1	7.8	8.5	*0.21*
Other indirect costs	4	4.7	5.4	6	0.27
Sub-total for indirect costs	**23.4**	**28.2**	**32.1**	**35.6**	**0.28**
Contingencies	2.7	4.1	5.2	6.2	*0.55*
Owner's costs	12.3	15.4	17.5	19.1	*0.29*
Total overnight cost	**100%**	**145%**	**182%**	**215%**	**0.51**

Based on the above mentioned data, for the purposes of the present report it was assumed that the most probable values for the factor *n* are in the interval 0.45-0.6[3], with an average of n=0.51.

Table 6.7 illustrates the range of possible impacts of the scaling law (6.3) on the specific (per kWe) capital costs of SMRs compared to a nuclear power plant with large reactors. The data in Table 6.7 indicate the scaling law to be an important factor negatively affecting the specific capital cost and, consequently, the LUEC of SMRs. For example, if it were applied directly, replacing a large 1 200 MWe reactor with four small reactors of 300 MWe, it would require an investment 75-155% higher.

At the same time, there are other economic factors that could be favourable to smaller reactors and compensate, to a certain extent, the negative impact of the economy of scale. These factors and their impact are analysed in the following sub-sections.

[3] It is noted that the contributors to this report were unable to find any reference with the example of a NPP scaling law with *n* = 0.7 (the upper range suggested in [6.4]).

Table 6.7. Influence of the scaling law (6.3) on specific capital cost of small reactors at different values of *n*. Large 1200 MW reactor is taken as reference

Plant capacity, MWe	1 200	600	300	100
n=0.4	1.0	1.52	2.30	4.44
n=0.5	1.0	1.41	2.00	3.46
n=0.6	1.0	1.32	1.74	2.70

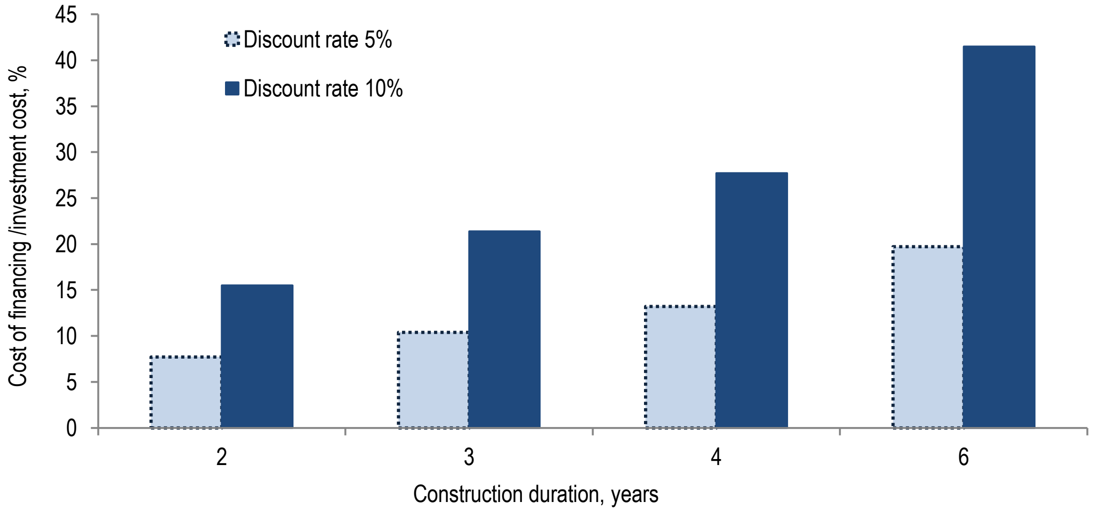
6.2.2 Construction duration

The construction duration has a significant impact on the total overall costs, because of the cost of financing. In general, reduction in the construction duration results in a decrease in interest during construction (i.e., the cost of financing), as illustrated by an example in Figure 6.4. The data for this figure was calculated with an assumption of the overnight capital cost of USD 2 000 per kWe uniformly distributed over the construction period, at 5% and 10% discount rates.

With respect to SMRs, Figure 6.4 shows that, for example, if the construction duration for a small plant is three years instead of six years for a large plant, the saving due to lower interest during construction will be 9.3% at a 5% discount rate and 20% at a 10% discount rate. Thus, the reduction in investment costs due to shorter construction period increases considerably with the growth of the discount rate.

The effect of a reduction in interest due to a shorter construction period, illustrated by Figure 6.8, applies to both on-site construction and factory manufacturing of the plants.

Figure 6.4. Cost of financing as a function of construction duration and interest rate (an example with the uniform financing schedule)



6.2.3 The simplification of design

In some cases the SMR designs can be simplified compared to large reactors belonging to the same technology line, by incorporating certain design features that are peculiar to smaller reactors.

As an example, a PWR SMR with integral design of the primary circuit[4] eliminates large break LOCA by design and also reduces the effect of other LOCA-type accidents, resulting in fewer and simpler safety systems (as discussed in section 4.2.1).

Other examples include the Russian marine derivative reactors that achieve a significant economy of construction materials because of a compact modular design of the nuclear steam supply system (see section 4.2.1).

Fewer safety systems and materials are considered for the boiling water reactor with compact containment, CCR, see the discussion in Section 4.2.2.

Reference [6.5] gives an evaluation of the design simplification factor for the 335 MWe IRIS - a PWR with the integral primary circuit design being developed by the Westinghouse Electric Company (United States). The factor is conservatively estimated by the designer as:

[Design simplification factor for integral design PWR] = 0.85 (6.4)

Factor (6.4) is a correction factor for the overnight cost increase resulting from the application of scaling law (6.3).

The Annex 7 of reference [6.8] contains the comparative economic data pointing to a very similar design simplification factor for the Russian marine derivative design VBER-300 of 325 MWe:

[Design simplification factor for the Russian marine derivative PWR] = 0.84 (6.5)

In both cases, the estimated design simplification factors allow a reduction in the SMR overnight capital costs by ~15%.

6.2.4 First-of-a-kind factors and economy of subsequent units on the site

Building reactors in series usually leads to a significant per-unit cost reduction. This is due to better construction work organisation, learning effect, larger volumes of orders for the plant equipment and other factors. However, the first-of-a-kind (FOAK) power plant is usually considerably more expensive than subsequent units.

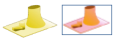
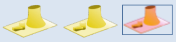
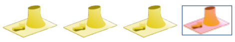
Reference [6.4] suggests an algorithm, based on the French experience, (see Table 6.8) to calculate FOAK plant effects in the overnight capital cost and cost reductions from building more than one serial plant on a site:

The main parameters of this algorithm are:

−x: FOAK extra cost parameter
−y: parameter related to the gain in building a pair of units.
−z: parameter related to the gain in building two pairs of units on the same site.
−k: industrial productivity coefficient.

[4] Characterized by the in-vessel location of the steam generators and by the absence of large diameter piping.

Table 6.8. Productivity and programme effects of building NPPs in series, [6.4]

Plant configuration	Productivity effect (multiplicative factor)	Cost of the last unit (in a box)	Total cost of the plant
 FOAK	-	$(1+x)T_0$	$(1+x)T_0$
	-	yT_0	$(1+x+y)T_0$
	$\frac{1}{1+k}$	zT_0	$\left(1+x+y+\frac{z}{1+k}\right)T_0$
	$\frac{1}{(1+k)^2}$	yT_0	$\left(1+x+y+\frac{z}{1+k}+\frac{y}{(1+k)^2}\right)T_0$
The industrial productivity coefficient k=0%-2%, FOAK extra cost parameter x=15-55%, Parameter related to the gain in building a pair of units y=74%-85%, Parameter related to the gain in building two pairs of units on the same site z=82%-95%			

The coefficients *x*, *y* and *z* correspond to the "programme" effect, and the coefficient *k* is related to the "productivity" effect described below. The main assumptions of the algorithm are as follows:

- The first unit built bears all of the extra FOAK cost (expressed as a factor [1+x]).
- The cost of engineering specific to each site is assumed to be identical for each site.
- The cost of facilities specific to each site is assumed to be identical for each site.
- The standard cost (excluding extra FOAK cost) of a unit includes the specific engineering and specific facilities for each unit.

Programme effect (construction of several units on the same site):

If T_0 is the standard cost (excluding extra FOAK cost) of the sole unit on a site (see Table 6.8):

- Cost of the first unit: $T= (1+x)T_0$
- Cost of the following units (if programme of 1 unit/site): T_0.
- Cost of the 2nd unit on a site with one pair: yT_0 (6.6)
- Cost of the 3rd unit on a site with two pairs: zT_0
- Cost of the 4th unit on a site with two pairs: yT_0 ,

where it is assumed that the cost of the 2nd unit of a pair is independent of the rank of the pair on the site.

Productivity effect

It is considered that a productivity effect only occurs as of the 3rd unit of a series. If n is the rank of the unit in the series, and T_n is the cost which results from taking into account the sole programme effect, it follows that:

$$T'_n = \frac{T_n}{(1+k)^{n-2}}, \quad \text{as of } n>2 \qquad (6.7)$$

Reference [6.4] suggests the following values of the parameters (based on the French experience):

x=15% to 55%, according to the nature and amount of changes in the design.

y=74%-85%

z=82%-95%

k=0%-2% (6.8)

According to (6.6) and (6.8), the FOAK plant could be 15% to 55% (35% on average) more expensive than the next ones (built at a site).

For the first and second pair of non-FOAK twin-units on the site, based on (6.6) and (6.8), the per-unit cost reduction factors would be:

$$\text{Per unit cost reduction factor for twin units (first pair)} = \frac{1+y}{2} = 0.87 - 0.93$$
$$\text{Per unit cost reduction factor for twin units (second pair)} = \frac{1}{2} \times \left(\frac{z}{1+k} + \frac{y}{(1+k)^2}\right) = 0.76 - 0.9 \qquad (6.9)$$

If two pairs of non-FOAK twin-units are built on the site, the per unit overnight cost reduction may be as substantial as:

$$\frac{1}{4} \times \left(1+y+\frac{z}{1+k}+\frac{y}{(1+k)^2}\right) = 0.81\text{-}0.9 \qquad (6.10)$$

A reduction such as (6.10) is quite significant but it would not be sufficient to compensate the specific investment cost increase because of the scaling law (6.3).

Example: The cost of 4 non-FOAK 300 MWe versus 1 non-FOAK 1200 MWe

As an example, let us consider four non-FOAK 300 MWe PWRs (integral design or marine-type) built on the same site, and compare them to one large non-FOAK 1200 MWe PWR. In this case one should include the effects of economy from building subsequent units on the same site (equation [6.10]), simplification of the design (6.4) or (6.5), take into account the decrease of the cost of financing (due to reduction of the construction period from 6 to 3 years, see Figure 6.4), and multiply the result by the scaling factor (from 1 200 MWe to 300 MWe, see Table 6.7). The results are given in the Table 6.9.

From Table 6.9 it could be seen that, within the assumptions made, four integral type or marine derivative PWRs of 300 MWe class (and not FOAK) built on the same site may have the effective per unit specific overnight capital costs of about 10-40% higher (at n=0.5-0.6 and a 5% discount rate) compared to those of a NPP with a single large PWR of 1 200 MWe.

Similar results for almost identical case studies were obtained by the Westinghouse Electric Company [6.5]. In their case, the construction duration was assumed to be five years for the large plant and three years for each of the SMRs, the annual interest rate was 5%, and the scaling factor used (1.74) corresponds to n=0.6. They found that the specific capital cost of a 300 MWe PWR versus specific capital cost of a 1 200 MWe reactor of the same type would be increased by about 4% (compared to 10-22 % in our case, see Table 6.9 at n=0.6 and a 5% discount rate).

Table 6.9. Effective per unit specific (per kWe) overnight capital cost for the case of four 300 MWe marine derivative or integral design PWRs built on one site for different parameters of the scaling law

	Factors			
Scaling exponent and the corresponding factor	n=0.4: **× 2.30**	n=0.5: **× 2.00**	n=0.6: **× 1.74**	n=0.7: **× 1.52**
Economy on cost of financing due to construction period reduction from 6 to 3 years	Interest rate 5%: **× 0.92**		Interest rate 10%: **× 0.86**	
Economy from building 4 subsequent units on the same site	**× (0.81-0.9)**			
Design simplification factor	**× 0.85**			
Specific capital cost of a 300 MWe PWR versus specific capital cost of a 1 200 MWe reactor belonging to the same technology line				
	Total factor between 4 SMRs of 300 MWE and one large reactor of 1 200 MWe (product of the above factors)			
	n=0.4	n=0.5	n=0.6	n=0.7
Interest rate 5%	1.46-1.62	1.27-1.41	1.10-1.22	0.96-1.07
Interest rate 10%	1.36-1.51	1.18-1.32	1.03-1.14	0.90-1.00

The effects defined by the parametric equations (6.6), (6.7) and (6.8) include both, learning in construction (parameters x and *z*) and in factory fabrication (parameter *k*), and sharing of common facilities and systems on the site (parameters *y* and *z*). An important assumption regarding learning is that the costs of engineering and facilities for each site are identical, which means similarity of the sites. Otherwise, the learning effects may be not observed.

The international and national NPP build experience, specifically, that of the Russian Federation and Canada [6.5] indicates that learning will not apply:

- if NPPs are consequently built in different countries;
- if there are regulatory changes in a country during the next NPP build;
- if siting conditions for the consecutive plants are essentially different; and
- if the interval between building consecutive plants is too long.

The last effect of a "too long" interval between consecutive plants building is illustrated by Figure 6.5. It is based on the OKBM Afrikantov[5] experience in factory fabrication of the marine propulsion reactors in the Russian Federation [6.9]. As it can be seen from the figure, for the case of full factory fabricated nuclear plants the requirements of continuity are quite strict, with notable increase in labour intensity observed even for a one-year break in the production process (unit number 3 on Figure 6.5).

[5] OKBM Afrikantov is a principal Russian design organisation for nuclear propulsion reactors: http://www.okbm.nnov.ru/.

Figure 6.5. Impact of production process continuity on labour intensity in the production of marine propulsion reactors [6.9]

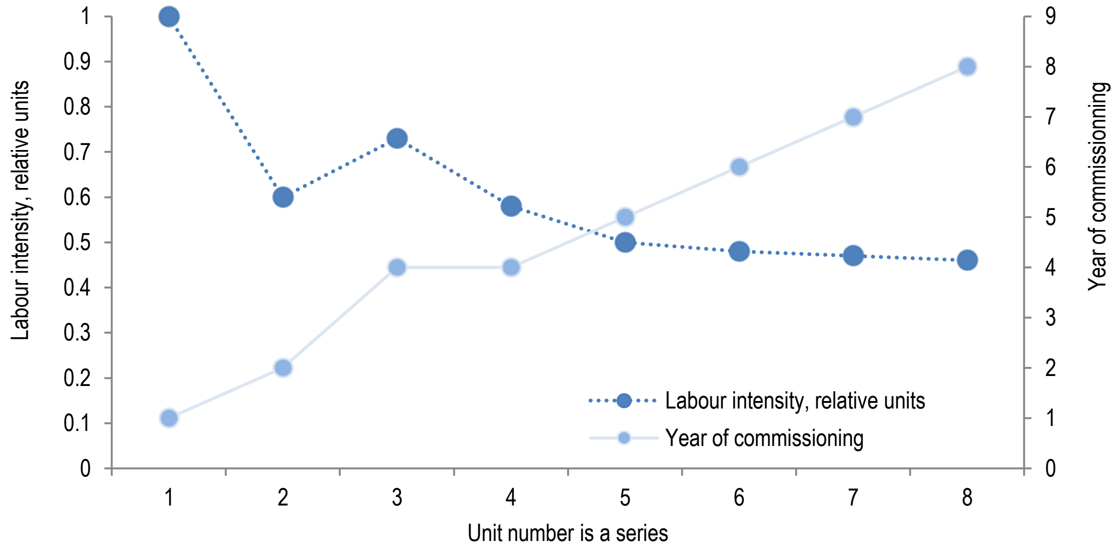


Table 6.10. Effective per module specific (per kWe) overnight capital cost for the case of a five- or a six-module NPP with 300 MWe marine derivative or integral design PWR modules

	Factors	
Scaling exponent and the corresponding factor	n=0.5: **× 2.24**	n=0.6: **× 1.904**
Economy on cost of financing due to construction period reduction from 6 to 3 years	Interest rate 5%: **× 0.92**	Interest rate 10%: **× 0.86**
Economy from building 5 subsequent units on the same site	Factor (1+y)/2 reduced by 15-17%: **× (0.72-0.79)**	
Design simplification factor	**× 0.85**	
Specific capital cost of a 300 MWe PWR versus specific capital cost of a 1 500 MWe reactor belonging to the same technology line		
	Total factor between 5 SMRs of 300 MWE and one large reactor of 1 500 MWe (product of the above factors)	
	n=0.5	n=0.6
Interest rate 5%	1.26 – 1.38	1.07 – 1.18
Interest rate 10%	1.17 – 1.29	1.00 – 1.10

6.2.5 Economy of multi-module plants

While twin-units of nuclear power plants exist and the cost reduction factors for them are known and defined by equations (6.9) and (6.10), no experience data is currently available for multi-module nuclear plants. The apparent reason is that multi-module nuclear power plants have never been built. However, with reference to the current safety rules that prohibit safety system sharing among different reactor modules [6.10], near term multi-module plants could be reasonably approximated by sequentially built twin-units. Then, the evaluations provided in Sections 6.2.1-6.2.4 would apply.

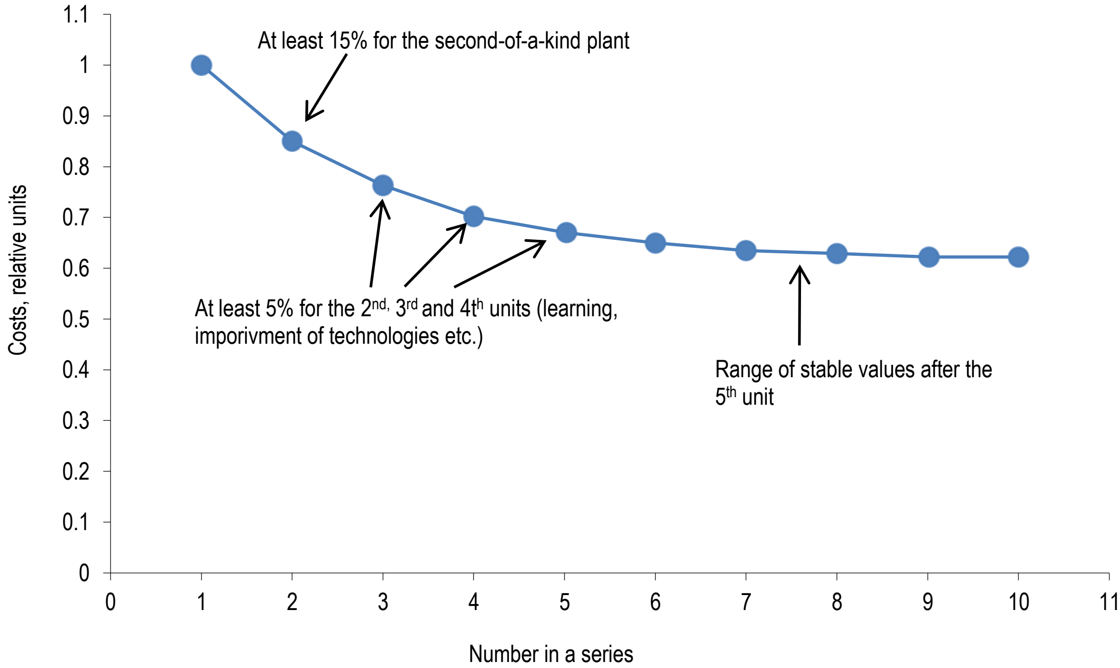
In addition to this, reference [6.1] mentions that "for a 5-6 unit plant capital costs may be 15-17% lower than for the basic two-unit plant". If we apply this to a 300 MWe marine derivative or the integral design PWR discussed in Section 6.2.4 and use the same assumptions, a five-module NPP with such reactors may have the overnight capital costs that are about 7 - 38 % higher (at a 5% discount rate) compared to those of a NPP with a single large PWR of 1 500 MWe, see Table 6.10.

6.2.6 Economy of factory fabricated units

Some reactor components, systems or modules are entirely factory-fabricated and are subsequently transported and assembled on-site. For example, some small capacity nuclear plants foresee factory fabrication of the full nuclear steam supply system. In this case, the above-mentioned parameters y and z cannot apply and the productivity effect (factor k) becomes dominant.

Figure 6.6 presents the OKBM Afrikantov experience data on cost reduction in serial factory production of the nuclear propulsion plants [6.9]. After a certain number in the series, no additional gain in productivity is supposed.

Figure 6.6. Costs of equipment fabrication and assembly in serial production of nuclear propulsion reactors [6.9]



Using the data presented in Figure 6.6 and the equations (6.6) and (6.7):

$$\mathrm{T} = (1+\mathrm{x})\mathrm{T}_0 \text{ and } \mathrm{T}_n' = \frac{\mathrm{T}_n}{(1+k)^{n-2}} \quad (n = 2),$$

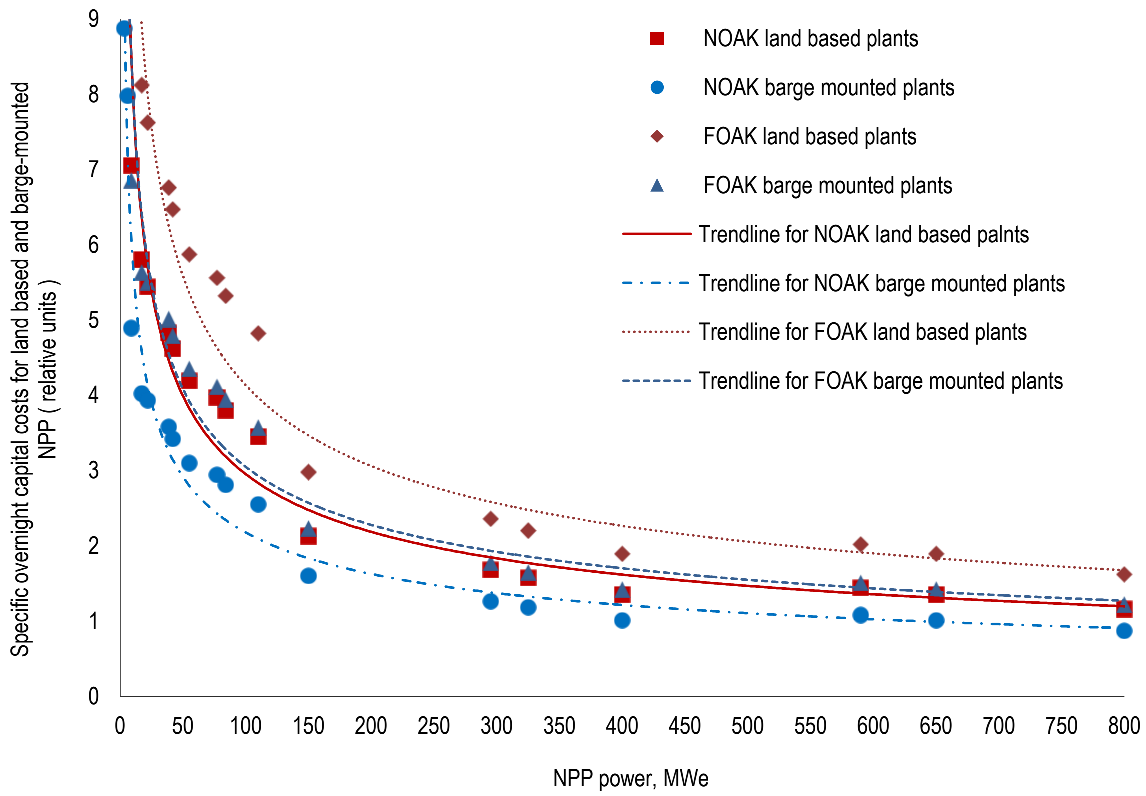
and assuming that for the fully factory fabricated plants the only relevant factor is *k* (6.7) one could derive the values of *x* and *k* for the marine propulsion reactor case of Figure 6.6:

x=15%

k=5-7% (6.11)

Although *k* is the principal factor for full factory assembled propulsion (as well as barge-mounted power) reactors, and the evaluated value of this factor is ~3 times higher than that recommended in [6.4] (see equation [6.11]), the overall cost reductions for each subsequent factory-fabricated nuclear propulsion plant shown in Figure 6.6 appear to be well within the ranges defined by equations (6.6) and (6.7) for conventional land-based plants built mostly on the site. This fact is independently confirmed by the OKBM Afrikantov in reference [6.9].

Figure 6.7. Specific (per kWe) overnight capital costs for land-based and barge-mounted NPPs of different power, including first-of-a-kind (FOAK) and n^th^-of-a-kind (NOAK) plants, [8.12]



6.2.7 Overnight capital costs for land-based versus barge-mounted SMRs

Reference [9.11] provides a direct comparison of the overnight costs for a twin-unit land-based and a twin-unit barge-mounted NPP with the VBER-300 reactors of 325 MWe gross electric output each. According to the data provided by the vendors (see Table 6.2), the overnight capital cost for a barge-mounted plant is 20% lower than those for a land-based plant. However a barge-mounted plant would need factory repairs and maintenance (mostly related to the barge) every 12 years and thus bears higher O&M costs. According to Table 6.2, the overall LUEC for barge-mounted VBER-300 is thus reduced by only 6% with respect to a land-based version[6].

Reference [6.12] provides a more detailed evaluation of the specific overnight capital costs for land-based and barge-mounted NPPs, presented in graphic form as Figure 6.7.

6.3 Operation and maintenance and fuel costs

Table 6.11 presents the data on operation and maintenance (O&M) and fuel costs for some of the SMRs addressed in this report. For comparison, included are similar data for the representative large reactors from reference [6.1].

[6] However, this explanation is based on a single set of data and thus should be viewed with caution.

The O&M and fuel costs are directly available only for a few SMRs, while for the majority of SMRs only the LUEC and the overnight cost were available. Where possible, we inferred the data for O&M and fuel costs using the formula (6.1) and neglecting the decommissioning costs, for a limited number of PWR- and HTGR-type SMRs. This estimate cannot give the breakdown between O&M and fuel costs.

The data presented in Table 6.11 leads to the following observations:

- There is a considerable spread of data on O&M and fuel costs even for NPPs with large reactors presented in reference [6.1]. The corresponding sums of O&M and fuel costs vary from 16.9 to 25.8 USD/MWh.

- The sums of O&M and fuel costs for SMRs vary between 7.1 and 36.2 USD/MWh. Both of the values exceeding 30 USD/MWh belong to SMRs with a long refuelling interval:

  – 36.2 USD/MWh belongs to the IRIS version with a 96-month refuelling interval; and

  – 33.5 USD/MWh belongs to the ABV with a 144-month refuelling interval (see Table 4.1 in Section 4.2.1).

- In both cases the increase is probably linked with a less effective fuel utilisation associated with the long refuelling intervals. For SMRs with conventional refuelling intervals, the sums of O&M and fuel costs are between 7.1 and 26.7 USD/MWh, being basically within the range for the considered NPPs with large reactors.

- The example of VBER-300 indicates that the sum of O&M and fuel costs for a barge-mounted reactor is ~50 % higher compared to the land-based one. As already mentioned, this could be explained by a larger volume of the O&M essentially required for the barge. In particular, the barge is assumed to be towed to the factory each ~12 years to undergo factory repair and maintenance.

The designers of advanced SMRs often indicate that O&M costs could be lower than those of large reactors owing to a stronger reliance of SMRs on inherent and passive safety features and to the resulting decrease in the number and complexity of safety systems [6.2, 6.8].

Regarding the fuel costs, SMRs generally offer lower degree of fuel utilisation compared to the state-of-the art large reactors, mainly because of the poor neutron economy due to small reactor core [6.2, 6.8]. Lower degrees of fuel utilisation result in higher fuel costs[7], which is most sharply manifested for SMRs with long refuelling interval, e.g., the ABV or the IRIS with a long refuelling interval (see Table 6.11).

[7] Fuel costs also include fuel cycle costs, but here the predominant SMR strategy is to start all reactors in a currently mastered open fuel cycle with low enriched uranium as a fuel load. This strategy is also typical for all SMRs with fast reactors, except the Korean PASCAR (see Tables A1.6 and A1.7 in Appendix 1). Although a closed fuel cycle with the reprocessing of spent fuel is foreseen for most of the advanced SMRs presented in this report, SMRs are most likely to make a transfer to the new fuel cycles only when such cycles are well mastered for all other reactors. Specifically, all of the fast SMRs addressed in this report offer long refuelling intervals from 7 to 30 years, which offers a time lag for the fuel reprocessing technology to be proved and developed on a commercial scale.

Table 6.11. O&M and fuel cost data for SMRs and some large reactors (in 2009 USD)

Reactor	Unit power MWe (net)/Plant lifetime (years)	Overnight capital cost USD per kWe	O&M cost, USD per MWh	Fuel cost, USD per MWh	O&M+Fuel costs, USD per MWh	LUEC at 5 % discount rate USD per MWh
Large reactors (from reference [6.1])						
EPR (France) [6.1]	1 600/ 60	3 860	16	9.3	25.3	56.4
Advanced Gen. III +(USA) [6.1]	1 350/ 60	3 382	12.8	9.3	22.2	48.7
ABWR (Japan) [6.1]	1 330/ 60	3 000	16.5	9.3	25.8	49.7
VVER-1150 (Russia) [6.1]	1 070/ 60	2 930	16.7	4	20.7-20.9	43.5
APR1400 (Korea) [6.1]	1 343/ 60	1 570	9	7.9	16.9	29.1
Integral design PWR SMRs						
CAREM-300 [6.8]	300*/ 60	1 200	-	-	14.1	-
IRIS [6.8]	335*/ >60	1 200-1 400 (investment cost)	-	-	26.7-36.2 *recovered from LUEC*	34-45
Marine derivative PWR SMRs						
KLT-40S (twin-unit barge-mounted) [6.17]	30/ 40	3 700-4 200	-	-	10.7-9.2 *recovered from LUEC*	49-53
ABV (twin-unit barge-mounted) [6.2]	7.9/ 50	9 100	-	-	33.5 *recovered from LUEC*	120
VBER-300 (twin-unit barge-mounted) [6.8]	302/ 60	2 800	-	-	10.7 *recovered from LUEC*	33
VBER-300 (twin-unit land-based) [6.8]	302/ 60	3 500	-	-	7.1 *recovered from LUEC*	35
HTGR SMRs						
HTR-PM [6.8]	105*/ 40	<1 500	8.6	12.3	20.9	51
PBMR (previous design) [6.8]	165/ 35	<1 700	-	-	10.2	As large LWR
GT-MHR [6.8]	287.5*/ 60	1 200	3.5	8.7	12.2	36.3

* Gross electric output

6.4 Decommissioning costs

The absolute values of decommissioning costs are not available for any of the SMRs addressed in this report. However, the designers of SMRs often mention that decommissioning costs are expected to be relatively low, with respect to large-size reactors.

Generally speaking decommissioning appears technically easier for full factory-assembled reactors, as they could be transported back to the factory in an assembled form, in the same way as they were brought to the site for operation [6.2]. The dismantling and recycling of the components of a decommissioned NPP at a centralised factory is expected to be cheaper compared to the on-site operations, in particular, due to the economy of scale associated with the centralised factory [6.2]. The decommissioning of barge-mounted reactors seems particularly simplified since they could be towed back to the factory leaving no traces of plant operation on the site.

Even if the absolute value of the decommissioning cost is important, the impact of the decommissioning cost on the LUEC is small (less than a percent, see Table 6.1) since it is discounted over a long period of time (40-60 years) corresponding to the operation of the plant.

6.5 Co-generation with non-electrical applications (heat credit model)

Although large nuclear reactors could be used for non-electrical applications (such as the production of heat for district heating or desalinated water), smaller reactors are often presented to better fit this market. The main arguments are the following:

- Co-generating SMR designs are in fact considered for replacement of existing (fossil fuel) plants in the power range of 250-700 MW_{th}. The corresponding distribution infrastructure cannot be easily changed to accommodate a large reactor, and in many cases there is even no demand for larger capacities.

- SMR sites are expected to be located closer to the final consumer than large reactors (see the discussion in Section 9.3, and thus energy losses and the associated costs due to long-distance transport of hot water or desalinated water could be significantly reduced.

- Regarding hydrogen production, the HTGR reactors needed for this can only be small for safety reasons (see Section 4.2.3).

Many advanced SMRs provide co-production of non-electrical products. These products also have their value and, for power plants operating a co-generation mode, "… one cannot impute the total generating costs to power alone" [6.1].

Reference [6.1] suggests that "…parcelling out cost shares … is highly impractical since heat and power are genuine joint products". Instead, reference [6.1] adopts the convention "to impute to power generation the total costs of generation minus the value of the heat produced. In order to arrive at a CHP[8] heat credit per MWh of electricity, one thus needs to establish first the total value of the heat produced over the lifetime of the plant by multiplying total heat output by its per unit value. The total value of the heat output is then divided by the lifetime electricity production to obtain the per MWh heat credit". For plants operated in a co-generation mode, referred to in reference [6.1] as the combined heat and power plants (CHPs), a heat credit is then subtracted from total unit costs to establish an equivalent of the levelised costs of producing only electricity.

Table 6.12 presents the LUEC estimates for several of the SMRs addressed in this report taking into account the values of non-electrical energy products by applying the heat credit model described above. The estimates are based on the designers' cost data (see section 6.1.2) and on the design specifications for the relevant SMRs given in Appendix 1. Included are the SMRs for which consistent[9] data on co-production of heat (non-electrical products) along with the electricity are available in the tables of Appendix 1.

The data in Table 6.12 indicates the heat credit to be quite substantial (~22-33%) in co-generation NPPs with SMRs producing heat for district heating and desalinated water.

[8] CHP = combined heat and power.

[9] Analysis of the Appendix 1 data has shown that most of the designers specify the production rates for non-electrical products without specifying the electric output of the plant matching exactly these production rates.

Table 6.12. LUEC evaluation for advanced SMRs taking into account heat credit (in 2009 USD)

SMR	Energy products	Non-electrical product cost	LUEC, USD per MWh	Heat credit: Cost of heat/ Cost of electricity
KLT-40S (barge-mounted)	35 MWe plus 25 Gcal/h of low-grade heat output [8.13]	21-23 USD/GCal	49-53	28.3-33.5%
VBER-300 (barge-mounted or land-based)	302 MWe plus 150 GCal/h of heat for district heating	18 USD/GCal	33-35	25-27%
SMART	90 MWe plus 1 667 m^3/h of desalinated water	70 USD cent/m^3 of desalinated water	60	21.6%

6.6 SMRs in liberalised energy markets

Although the specific (per kWe) overnight capital costs and investment costs tend to be higher for SMRs, as discussed in Section 6.2, the corresponding absolute capital outlay (in currency units, such as USD) is always significantly smaller for small reactors.

Projects with small capital outlay could be more attractive to private investors operating in liberalised markets in which the cost of financing and capital at risk are as important as the levelised unit product cost assuming the certainty of the production costs and the stability of the product prices.

Although the world electricity markets are still mainly regulated (see Section 6.1), the tendency is toward more liberalisation (see reference [6.14]) and, therefore, it is useful to examine the investment related performance of SMRs according to figures of merit alternative to the levelised unit electricity cost (LUEC).

The examinations of the above mentioned kind are being performed by a research team at the Politecnico di Milano (Italy) in collaboration with the Westinghouse Electric Company (United States), see reference [6.15]. The studies are focused on comparison of the incremental deployments of SMRs versus large reactors in terms of cash flow profiles and also include sensitivity analyses. The preliminary conclusions presented in reference [6.15] are as follows:

- Incremental capacity increase with SMRs reduces the front-end investment and the capital-at-risk compared to capacity increase with large reactors, see Figure 6.8.
- Lower interest during construction of SMRs helps compensate the higher specific overnight capital costs.
- SMRs may more easily attract investment.
- Notwithstanding the higher specific overnight capital costs, incrementally deployed SMRs could be comparable to large reactors in terms of profitability.
- The deployment schedules for incrementally built SMRs need to be carefully optimised to avoid delays which shift the cash inflow forward.

Two deployment scenarios have been considered in [6.15]: Four 300 MWe SMRs incrementally deployed according to different construction schedules, versus one large 1 200 MWE reactor (Figure 6.8). Comparison of the scenarios of Figure 6.8 shows that a more staggered build of SMRs reduces the capital-at-risk (maximum negative values of the cash flow), but moves the cash inflow forward in time.

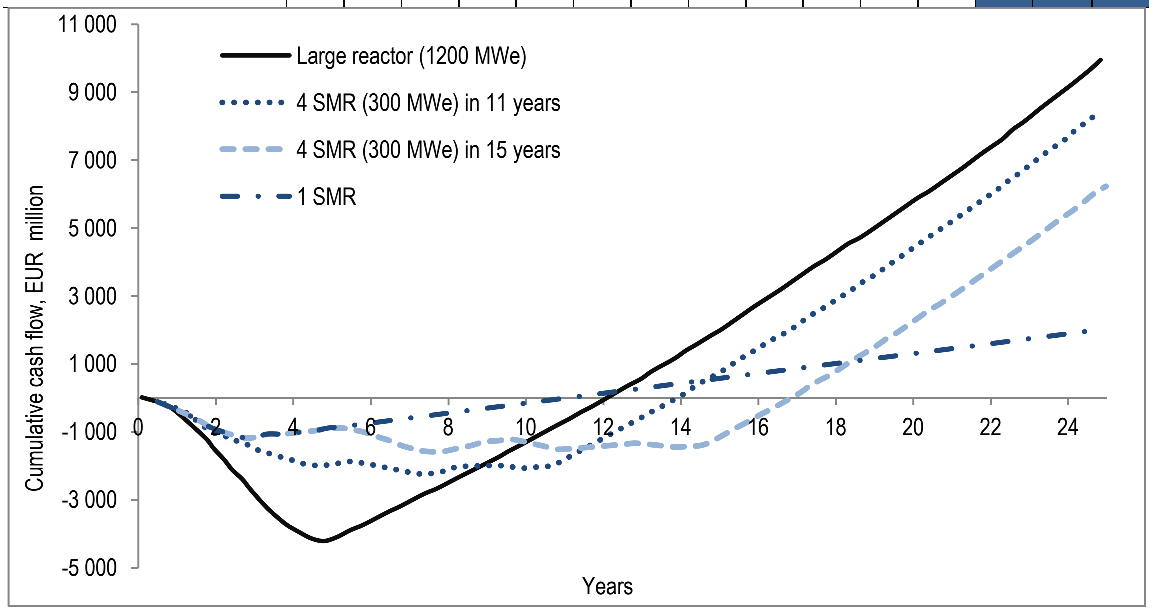
Figure 6.9 and Figure 6.10 from [6.15] show that the staggered build of SMRs enables a partial self-financing of the subsequent SMR projects (at the expense of the profits obtained from sales of electricity from the already built and commenced units). The more staggered the SMR build is, the broader the options for self-financing. This feature of incremental capacity increase could be attractive to those utilities who wish to increase the installed capacity using mostly their own funds, with minimum reliance on external loans.

An assessment or a detailed analysis of the results presented in reference [6.15] is beyond the scope of this report, in which the LEUC has been selected as a figure-of-merit to analyse nearer-term deployments of advanced SMRs, see the discussion in Section 6.1. However, studies such as [6.15] could facilitate broader involvement of private investors (specifically, those from non-nuclear sector) to support development and deployment of advanced SMRs and, therefore, should be encouraged.

Figure 6.8. Construction schedules (top) and cumulative cash flows (bottom) for the deployment of four 300 MWe SMRs versus one 1200 MWe large reactor (an example of calculations performed in reference [6.15])

Deployment of four 300 MWe SMRs over 11 years versus one 1 200 MWe large reactor in 5 years															
Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Large reactor (1 200 MWe)															
SMR #1															
SMR #2															
SMR #3															
SMR #4															

Deployment of four 300 MWe SMRs over 15 years versus one 1 200 MWe large reactor in 5 years															
Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Large reactor (1 200 MWe)															
SMR #1															
SMR #2															
SMR #3															
SMR #4															



As for large nuclear power plants, the public-private partnership is an attractive option for financing the project. In the case of SMRs, the private-public partnerships involving private investors from a non-nuclear sector already have some history, since the capital requirements are smaller than for very large nuclear projects. As it has been noted in Chapter 5, the State Atomic Energy Corporation "Rosatom" and the private JSC "Evrosibenergo" have formed a public-private joint venture company "AKME Engineering" to develop and deploy the SVBR-100 small lead-bismuth cooled reactor (see Section 4.2.6) by 2017. Within this joint venture company the financing is provided by the privately owned JSC "Evrosibenergo".

Public-private partnerships are also being considered for development of new small and modular reactors in the United States, see Section 5.

Figure 6.9. Sources of SMR financing for the first deployment scenario of Figure 6.8 (an example of calculations performed in reference [6.15])

4 SMRs (300 MWe) over 11 years

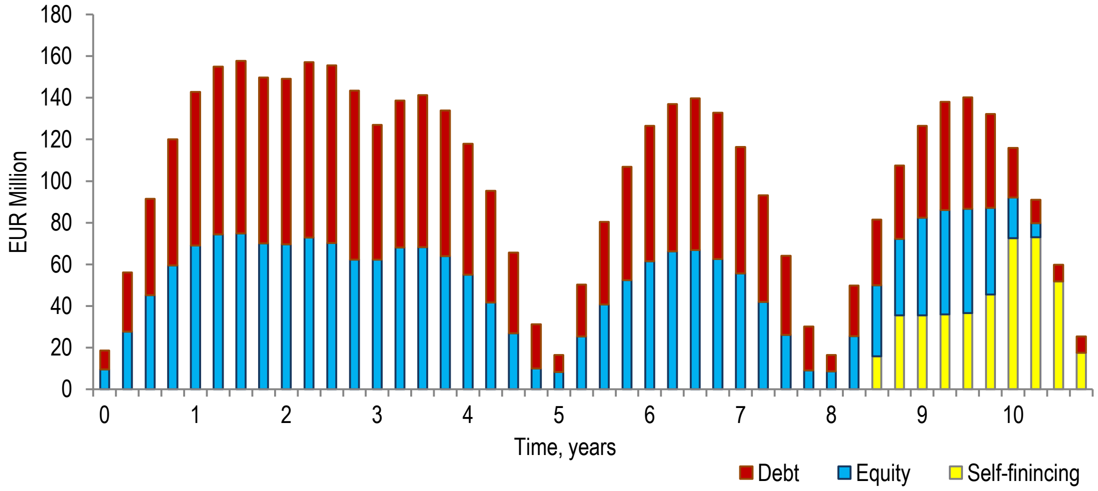
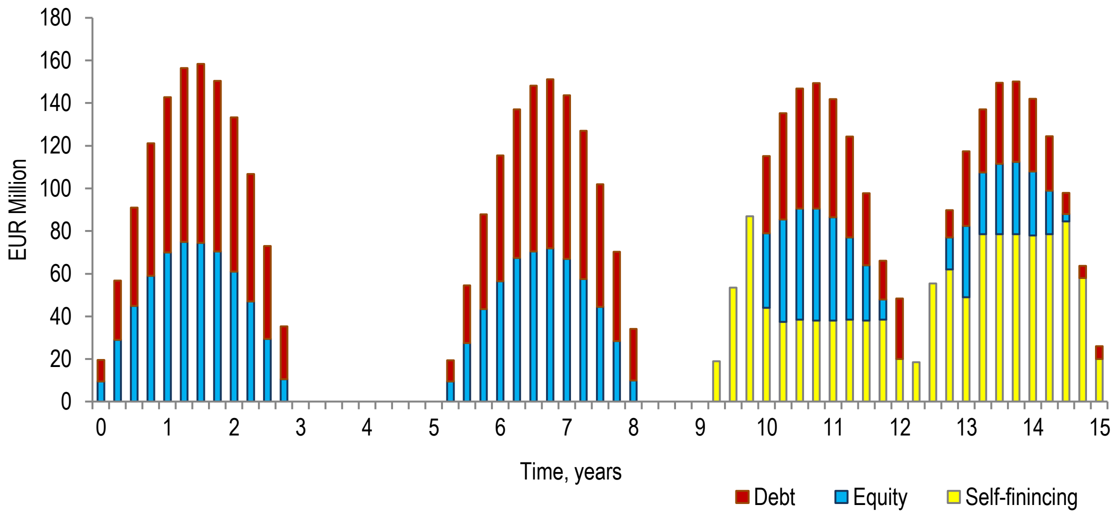


Figure 6.10. Sources of SMR financing for the second deployment scenario of Figure 6.8 (an example of calculations performed in reference [6.15])

4 SMRs (300 MWe) over 15 years



6.7 Summary of the factors affecting SMR economy

In Chapter 6 the non-site-specific factors affecting the competitiveness of SMRs have been reviewed. The review focused on a relative impact of each of the considered factors on the economy of a NPP with SMRs versus that of a NPP with a large reactor.

One of the main factors negatively acting on the competitiveness of SMRs is the economy of scale. Depending on the power level, the specific (per kWe) capital cost of SMRs are expected to be tens to hundreds percents higher than for large reactors.

Other factors tend to ameliorate the capital costs of SMRs. These are:

- The reduction of the construction period resulting in a significant economy in the costs of financing. This is particularly important if the interest rate is high.

- The savings from building subsequent units on the same site and from serial production of factory-built SMRs ("learning in construction" and "sharing of common facilities on the site").

- The design simplification due to inherent properties of particular SMRs.

In some cases, additional design specific factors allow further reduction of capital costs, e.g., for the barge-mounted plants.

However, even taking all above factors into account, one can conclude that the specific capital costs of SMRs would probably be higher than those of a large plant. As an example, four integral type or marine derivative PWRs of 300 MWe (and not FOAK) built on the same site may have the effective per unit specific overnight capital costs of about 10-40% higher compared to those of a NPP with a single large PWR of 1 200 MWe. As another example, a five-module NPP with such 300 MWe reactors may have overnight capitals costs that are about 7-38% higher compared to those of a NPP with a single large PWR of 1 500 MWe.

A very important benefit of SMRs is that they could be incrementally deployed in shorter time frames. This allows a significant reduction in front-end investment and capital-at-risk compared to capacity increase with large reactors.

The levelised unit cost of electricity generated by SMRs and large reactors is design- and site-specific. However, several conclusions on the factors influencing the LUEC could be made:

- The LUEC share of O&M and fuel costs for SMRs (17-41%) is noticeably below that of large reactors (45-58%).

- Co-production of heat or desalinated water leads to a significant credit expressed in USD per MWh. This credit could be subtracted from the total unit cost to establish an equivalent of the levelised cost of producing only electricity. In this case the values of LUEC could be improved by about 20-30% (for some SMR designs).

In the following chapter, several design- and site-specific estimates of the capital cost and LUEC will be performed, in order to illustrate the competitiveness of SMRs compared to the alternative energy sources in some electricity and heat markets around the world.

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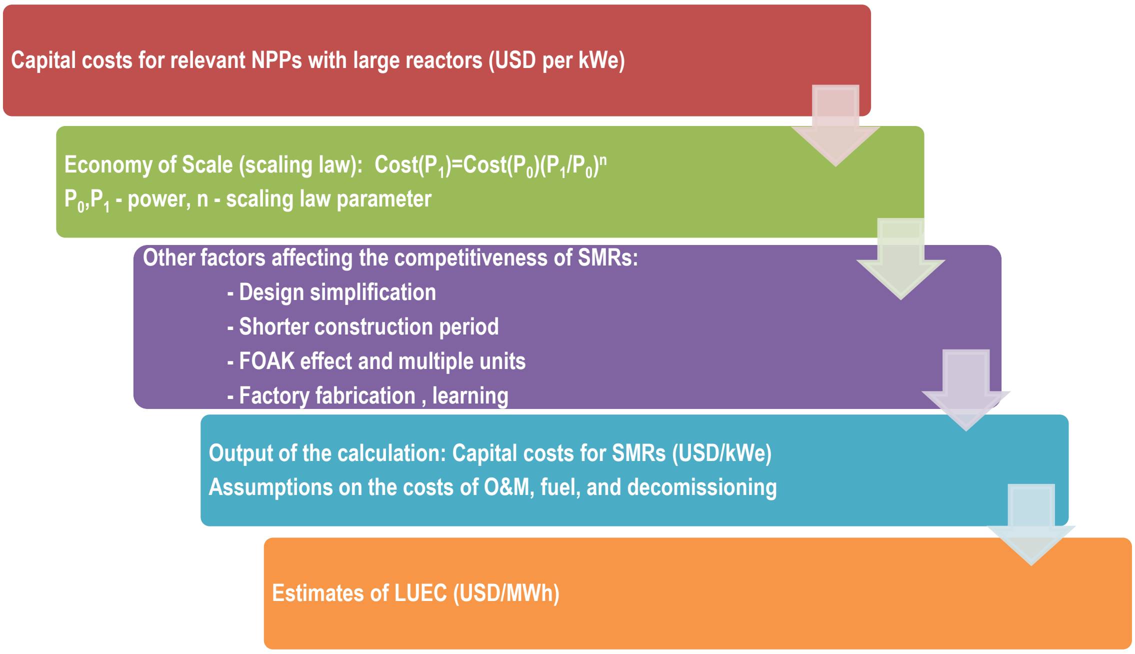
7. Assessment of the Deployment Potential of the Various Proposed SMR Designs

7.1 Independent estimates of LUEC for typical SMRs

7.1.1 SMR selection and assumptions for the estimates

The primary aim of the estimates of LUEC performed and presented in this chapter is to obtain an independent LUEC value for next-of-a-kind SMRs starting from a reliable evaluation of overnight capital cost, operation and maintenance (O&M) and fuel costs for some reference large reactors. The scaling law and the correction factors analysed in Chapter 6 have been used for this analysis (see Figure 7.1). The resulting evaluations were then compared to the designers' cost data in 2009 USD given in Table 6.2. Such a comparison was found useful to understand the various factors influencing the economics of the SMRs, and also to highlight the points that would probably require further clarification.

Figure 7.1. Schematic description of the LUEC methodology applied



While using the approach mentioned above it should be kept in mind that the available economic data on nuclear power plants has a large degree of uncertainty which is, in particular, related to the implicit impact of the non-quantifiable factors.

Also, the algorithms of the scaling law and the correction factors described in Chapter 6 are necessarily approximate, include essential simplifications, and reflect only the experience of certain types of NPPs that have been built in the past. For those reasons, we made the following assumptions in the study:

- We consider only SMRs based on pressurised water reactor technology, which have the highest potential of being deployed within the current decade. Within this technology reasonably reliable data on the overnight capital costs, O&M and fuel costs are available for NPPs with large reactors recently deployed (or being constructed) in several countries.

- The evaluations were performed for some "model" SMRs denoted as PWR-X, (where X stands for the electric output), rather than for actual SMR designs. However, each of such "model" SMR reflects the characteristics of specific SMR designs. The PWR-X and the basic designs were selected:

  – To cover the whole range of unit electrical outputs, from 8 to 335 MWe.
  – To cover a variety of possible plant configurations, including single module plants, twin-units and pairs of twin-units, multi-module plants, and barge-mounted and land-based plants.
  – To represent the ongoing developments in several countries.
  – It is assumed that these "model" PWR-X SMRs have reached industrial maturity and thus no path to development is analysed in this chapter.

- Reference NPPs with large reactors were selected based on the following criteria:

  – Availability of the necessary economic data (overnight capital costs, O&M and fuel costs) in the OECD report *Projected Costs of Electricity Generation, 2010 Edition* [7.1] used as reference in the current study.
  – Matching the country of origin of a particular SMR corresponding to the PWR-X for which the independent LUEC estimate was obtained.

To cater for possible uncertainties associated with the method used for LUEC estimation, two reference NPPs with different large reactors were attributed to the same PWR-X in one case. The selection of particular NPPs with large reactors for those cases is explained in the following paragraphs.

Table 7.1 presents the SMRs that have been analysed in this chapter (PWR-X) and the reference plant used as a basis for the LUEC estimation. As was already mentioned, reference NPPs with large reactors were typically selected to come from the same country of origin as the corresponding SMRs used as a basis for a PWR-X. In the case of the PWR-90, based on Korean SMART, two different NPPs with large reactors were considered, both of Korean origin. Comparison of the PWR-90(1) and (2) then makes it possible to evaluate the uncertainty related to the selection of a particular large reference NPP for scaling.

For PWR-125 (based on the mPower project) and for PWR-335 (based on the IRIS project), the choice of reference NPP with a large reactor was the Advanced Gen. III+ from [7.1]. Such a choice reflects the fact that the designers of the mPower are currently concentrating on the deployment of their design in the United States [7.3].

For PWR-8,-35,-302 corresponding to the Russian marine derivative reactors, the reference NPP with a large reactor was the VVER-1150 from [7.1].

Formula (6.1) for LUEC given in Section 6.1 was used in the evaluations. For the purposes of the present chapter and following the discussion in section 6.3, the sums of the O&M and fuel costs for land-based SMRs were taken equal to the corresponding sums for NPPs with the reference large reactors. For barge-mounted plants, the corresponding sums were multiplied by a factor of 1.5 reflecting the assumption of a higher O&M costs owing to the need of periodical factory repairs of a barge. Further specific assumptions made in the evaluation of particular LUEC components are highlighted in the following sections.

Table 7.1. SMRs and plant configurations for which independent LUEC estimates were obtained and the overnight costs (OVC) for single-SMR plants

	PWR-8	**PWR-35**	**PWR-90(1)**	**PWR-90(2)**
Electric output (net), MWe	7.9	35	90	90
Construction period/ Plant lifetime, years	4/50	4/40	3/60	3/60
Availability, %	80	85	90	90
SMR of relevance from Table 4.14	ABV	KLT-40S	SMART	SMART
Large reactor used a basis for scaling [7.1]	VVER-1150	VVER-1150	APR-1400	OPR-1000
Plant configurations considered for SMR	Twin-unit barge-mounted plant	Twin-unit barge-mounted plant	Single unit land-based plant	Single unit land-based plant
Electric output for large reactor, MWe	1 070	1 070	1 343	954
OVC for large reactor, USD/kWe	2 933	2 933	1 556	1 876
OVC for SMR, scaled with *n=0.51*, USD per kWe	32 500	15 700	5 850	5 970
Design simplification factor	0.85			
OVC for single-SMR plant, USD per kWe	27 600	13 300	4 970	5 070
Total OVC for single-SMR plant, USD million	2×218	2×465	447	456

	PWR-125	**PWR-302**	**PWR-335**
Electric output (net), MWe	125	302	335
Construction period/ Plant lifetime, years	3/60	4/60	3/60
Availability, %	90	92	96
SMR of relevance from Table 4.14	mPower	VBER-300	IRIS
Large reactor used a basis for scaling [7.1]	Advanced Gen III+	VVER-1150	Advanced Gen III+
Plant configurations considered for SMR	five module plant	- Twin-unit barge-mounted plant; - Twin-unit land-based plant	- Two twin-unit land-based plant
Electric output for large reactor, MWe	1 350	1 070	1 350
OVC for large reactor, USD/kWe	3 382	2 933	3 382
OVC for SMR, scaled with *n=0.51*, USD per kWe	10 853	5 450	6 695
Design simplification factor	0.85		
OVC for single-SMR plant, USD per kWe	9 225	4 630	5 690
Total OVC for single-SMR plant, USD million	1 153	2×1 398	1 906

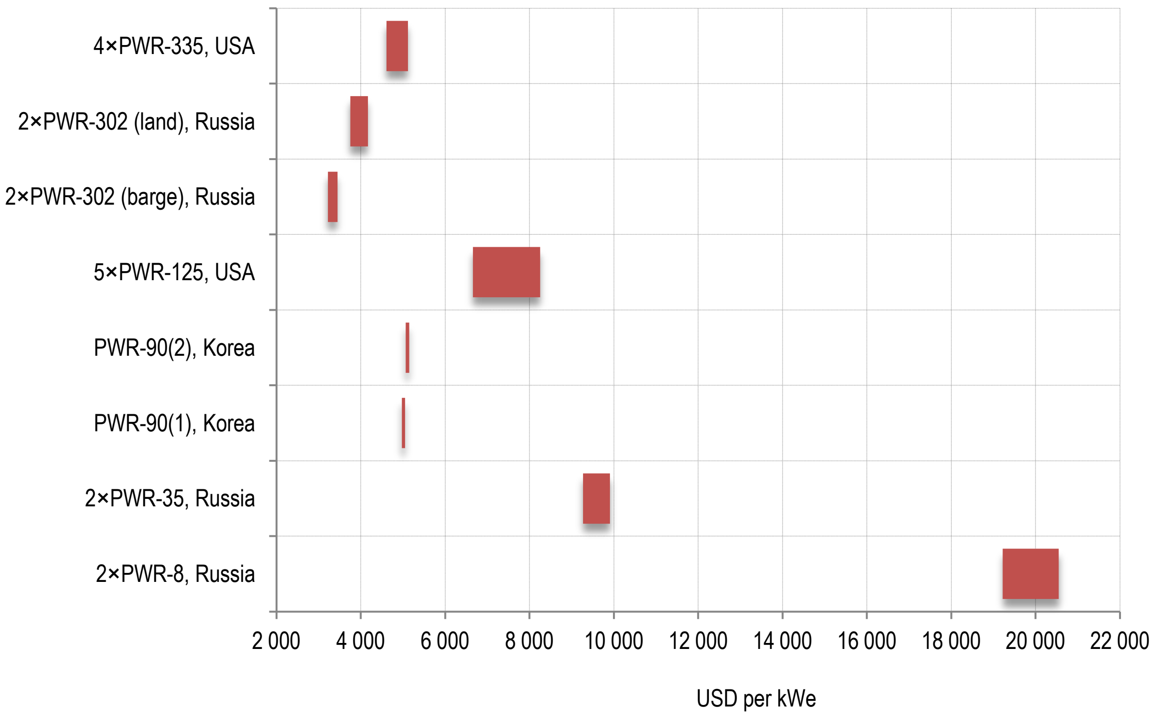
7.1.2 Investment cost estimate

Investment cost for a single SMR PWR-X has been estimated applying the methodology described in Section 6.2 and summarised in Figure 7.1.

Following the discussion in Section 6.2, the overnight cost of a single SMR was obtained using a scaling law with n=0.51;

As a second step, the overnight costs for the plant configurations (defined in Table 7.1) were estimated. These estimates used different factors accounting for possible cost reductions in a twin-unit, a multi-module and a barge-mounted plant. The details of the calculation are given in Appendix 3(Table A3.4). As many of the factors are specified as ranges, the resulting overnight capital costs most often also appear as ranges rather than single values. Those results are graphically illustrated in Figure 7.2.

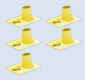
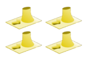
Figure 7.2. Overnight costs for various NPP configurations with SMRs (data from Table A3.4)



Following the calculation of overnight costs for the various SMR plant configurations, the corresponding investment costs were estimated. The investments were assumed to be spread uniformly over the whole construction period and were evaluated separately at a 5% and at a 10 % discount rate. Estimates of the investment costs for the SMR plant configurations in Table 7.1 are given in Table 7.2. This table provides both the specific investment costs in USD per kWe and the total investment in USD.

From Table 7.2 it can be seen that, while the specific investment costs (per kWe) are in some cases quite high, the total investments in USD are relatively small for a small reactor. For single-SMR plants with the electric output below 125 MWe the total investments are well below USD 1 billion (see Table 7.1).

Table 7.2. Investment costs for the various plant configurations

Plant configuration	Total electric output of the plant, MWe	OVC of the plant configuration *Table A3.4* USD/kWe	Construction duration, years	Investment cost for 5 % discount rate USD per kWe	Investment cost for 5 % discount rate USD billion	Investment cost for 10% discount rate USD per kWe	Investment cost for 10% discount rate USD billion
PWR-8 twin-unit barge 	2x7.9=15.8	19 200-20 600	4	21 800-23 300	0.34-0.37	24 500-26 200	0.39-0.41
PWR-35 twin-unit barge 	2x35=70	9 270-9 910	4	10 500-11 200	0.73-0.79	11 800-12 700	0.83-0.89
PWR-90(1) single module 	90	4 970	3	5 490	0.49	6 040	0.54
PWR-90(2) single module 	90	5 070	3	5 600	0.50	6 150	0.55
PWR-125five modules 	5 x 125	6 661-7 292	3	7 350-8 046	4.6-5	8 085- 8 851	5.1-5.5
PWR-302 twin-unit barge 	302x2=604	3 230-3 450	4	3 650-3 900	2.20-2.36	4 120-4 400	2.49-2.66
PWR-302 twin-unit land-based 	302x2=604	3 750-4 170	4	4 250-4 720	2.57-2.85	4 790-5 320	2.89-3.22
PWR-335(2) two twin-units 	670x2=1 340	4 610-5 122	3	5 086-5 651	6.8-7.57	5 594-6 216	7.5-8.3

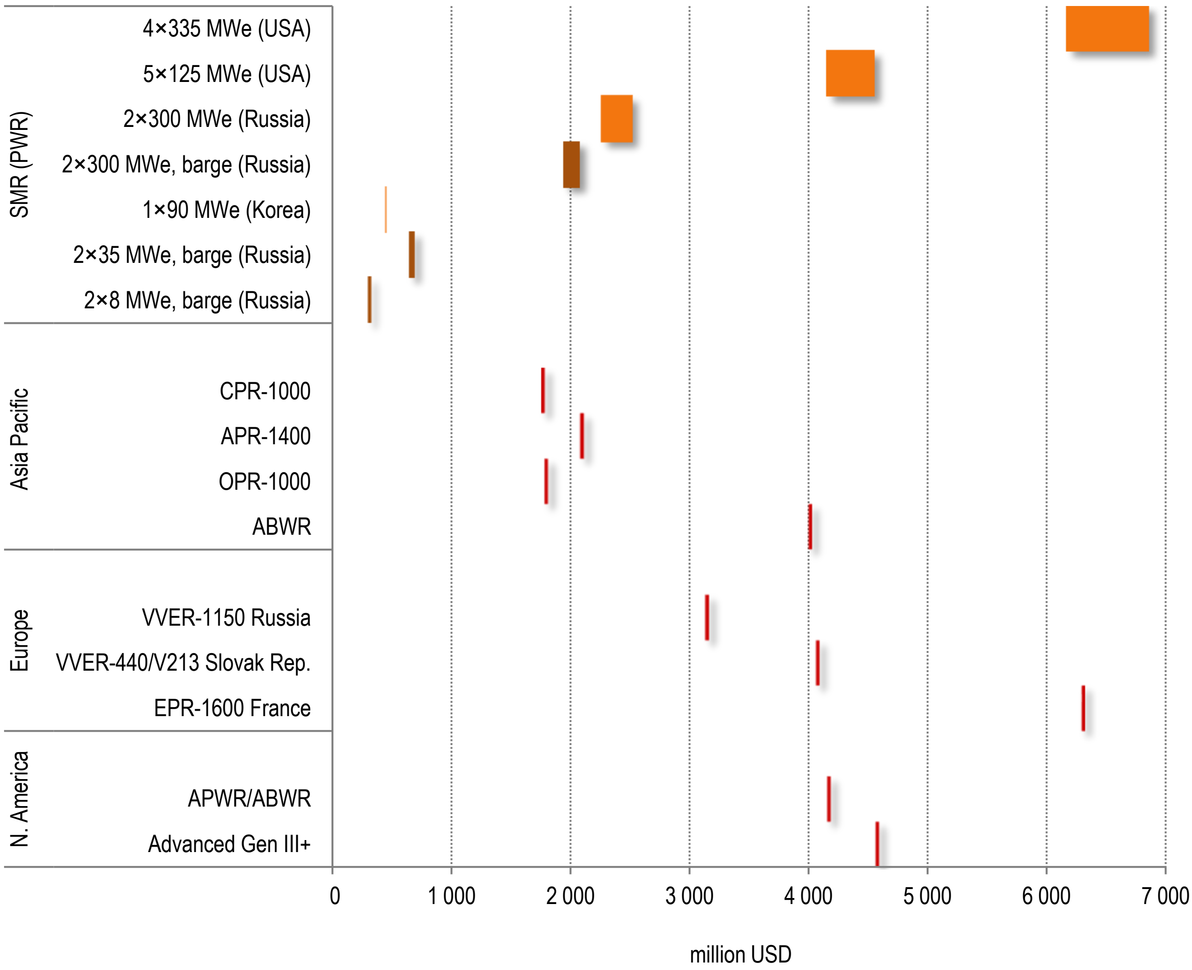
In Figure 7.3, the overnight costs for the various plant configurations with SMRs are compared with the overnight costs for NPPs with large reactors currently available in the world. It could be seen that the projects with several SMR units, yielding significant overall amounts of electric power, seem to have overnight costs comparable to those for some NPPs with large reactors in Europe and in North America. In Asia, the construction of NPPs with large reactors requires significantly less capital than in Europe and North America, and all of the plant configurations with SMRs would be more expensive to build (except some very small, including the one developed in the region - 1×90 MWe, the Republic of Korea).

7.1.3 O&M and fuel cost estimate

For the purposes of the present chapter and following the discussion in section 6.3, the sums of the O&M and fuel costs for land-based SMRs were taken equal to the corresponding sums for NPPs with the reference large reactors. For barge-mounted plants, the corresponding sums were multiplied by a factor of 1.5 reflecting the assumption of a higher O&M costs owing to the need of periodical factory repairs of a barge[1], see the discussion in Section 6.3. The resulting O&M and fuel costs (components of the LUEC) for SMRs plant configurations considered are given in Appendix 3 (Table A3.6).

[1] As discussed in Section 6.3, this assumption is based on the analysis of only one set of consistent data and, therefore, cannot be considered as reliable. Using this assumption may, therefore, add a certain degree of conservatism to LUEC evaluation for barge-mounted plants.

Figure 7.3. Estimated overnight cost for the various SMR and large reactor deployment projects [7.1]



7.1.4 Decommissioning cost estimate

In view of the negligible contribution of decommissioning costs to LUEC [7.1] (see the discussion in section 6.4), the decommissioning costs were set to zero for all SMR plant configurations estimated in this section.

7.1.5 LUEC estimate

First, the investment component of LUEC for SMR plant configurations was estimated. The calculations were performed[2] using formula (6.2) given in Section 6.2.

Next, all LUEC components given in Table A3.6 and Table A3.5 in Appendix 3 were summed yielding the final LUEC estimate in USD/MWh, shown in Table 7.3.

[2] The input data and the results are presented in Table A3.5 in Appendix 3 for the discount rates of 5% and 10%.

Table 7.3. LUEC estimates for the various SMR plant configurations (5% discount rate)

Plant configuration	Total electric output of the plant (net) MWe	Pant lifetime Years/ Availability	Investment cost *	Investment component of LUEC**	O&M + fuel component of LUEC**	LUEC**
PWR-8 twin-unit barge-mounted	15.8	50/80%	21 800-23 300	161-172	31.1	192-203
PWR-35 twin-unit barge-mounted	70	40/85%	10 500-11 200	78-83	31.1	109-114
PWR-90(1) single module plant	90	60/90%	5 490	35	16.9	52
PWR-90(2) single module plant	90	60/90%	5 600	36	18.3	54
PWR-125 five module plant	625	60/90%	7 350-8 046	47-51	22.2	69-73
PWR-302 twin-unit barge-mounted	604	60/92%	3 650-3 900	23-24	31.1	54-55
PWR-302 twin-unit land-based	604	60/92%	4 250-4 720	26-29	20.7	47-50
PWR-335 two twin-units	1 340	60/96%	5 086-5 651	30-34	22.2	53-56

* for 5 % discount rate, USD per kWe.

** at 5% discount rate, USD per MWh.

Table 7.4. LUEC estimates for the various SMR plant configurations (10% discount rate)

Plant configuration	Total electric output of the plant (net) MWe	Plant lifetime Years/ Availability	Investment cost*	Investment component of LUEC**	O&M + fuel component of LUEC**	LUEC**
PWR-8 twin-unit barge-mounted	15.8	50/80%	24 500-26 200	321-343	31.4	352-374
PWR-35 twin-unit barge-mounted	70	40/85%	11 800-12 700	148-158	31.4	179-189
PWR-90(1) single module plant	90	60/90%	6 040	70	16.8	87
PWR-90(2) single module plant	90	60/90%	6 150	71	18.3	89
PWR-125 five module plant	625	60/90%	8 085- 8 851	94-102	22.2	116-125
PWR-302 twin-unit barge-mounted	604	60/92%	4 120-4 400	47-50	31.4	78-81
PWR-302 twin-unit land-based	604	60/92%	4 790-5 320	54-60	20.9	75-81
PWR-335 two twin-units	1 340	60/96%	5 594-6 216	61-67	22.2	83-90

* for 10% discount rate, USD per kWe.

** at 10% discount rate USD per MWh.

7.1.6 Comparison with the designers' data

To compare the LUEC estimates obtained with the designers' data, the LUEC values from Table 7.3 were first converted to USD/MWh and then divided by the corresponding designers' data in 2009 USD taken from Table 6.2. The results are presented in Table 7.5.

Table 7.5. **LUEC estimates versus the designers' data at a 5% discount rate**

Plant configuration	Total electric output of the plant (net) MWe	SMR of relevance Table 7.1	LUEC estimate at 5% discount rate Table 7.3 USD per MWh	Designers' data on LUEC USD per MWh	Ratio LUEC estimate/Designers' LUEC
PWR-8 twin-unit barge-mounted	15.8	ABV (Russia)	192-203	≤120	1.6-1.7
PWR-35 twin-unit barge-mounted	70	KLT-40S (Russia)	109-114	49-53	2-2.3
PWR-90(1) single module plant	90	SMART (Korea)	52	60	0.9
PWR-90(2) single module plant	90	SMART (Korea)	54	60	0.9
PWR-125 five module plant	625	mPower (USA)	69-73	47-95	0.72-1.6
PWR-302 twin-unit barge-mounted	604	VBER-300 (Russia)	54-55	33	1.6-1.7
PWR-302 twin-unit land-based	604	VBER-300 (Russia)	47-50	35	1.3-1.4
PWR-335 two twin-units	1 340	IRIS (USA)	53-56	34-45	1.2-16

The data from Table 7.5 leads to the following observations:

- The estimates of LUEC are higher than the designers' data for all plant configurations with PWRs based on the Russian marine derivative designs (by 60-70%, and for the PWR-35 by 100-130%).
- The estimates of LUEC are overlapping the designers' data for the PWR-125 multi-module plant based on the US mPower design.
- The estimates of LUEC are slightly lower than the designers' data for the integral type PWR based on the Korean design SMR (by 10%).
- LUEC estimates for the PWR-90 obtained with the two different Korean NPPs with large reactors used as reference are nearly equal.

Assuming that some SMR designers may explicitly include the heat credit in the LUEC values specified for their designs, an evaluation of the possible impact of such an inclusion was performed. The heat credit values for several SMRs were taken from Table 6.12. The ratios of the independent LUEC estimates and the designers' data on LUEC for the corresponding SMRs from Table 7.5 were then adjusted taking into account the heat credit values, with the results shown in Table 7.6.

Table 7.6. LUEC estimates for selected SMRs versus the designers' data at a 5% discount rate (heat credit taken into account)

Plant configuration	Total electric output of the plant (net) MWe	SMR of relevance	LUEC estimate/Designers' LUEC *Table 7.5, without heat credit*	Heat credit *Table 6.12*	Ratio LUEC estimate/Designers' LUEC *With heat credit*
PWR-8 twin-unit barge-mounted	15.8	ABV	1.6-1.7	28.3-33.5%*	1.26-1.42
PWR-35 twin-unit barge-mounted	70	KLT-40S	2-2.3	28.3-33.5%	1.7-1.96
PWR-90(1) single module	90	SMART	0.9	21.6%	0.7
PWR-90(2) single module	90	SMART	0.9	21.6%	0.7
PWR-302 twin-unit land-based	604	VBER-300	1.3-1.4	25-27%	1.03-1.15

* Not available from Table 6.12, considered as equal to PWR-35.

From Table 7.6 one can conclude that:

- With the assumption of a heat credit explicitly included in the LUEC, the LUEC estimates for PWR-90 and PWR-302 show reasonably good agreement with the designers' data given in Table 4.14. The estimate for PWR-8 is 26-42% higher than the designer' values.

- No explanation was found for the observed difference between the LUEC estimate for the barge-mounted plants with the two PWR-35 based on the Russian KLT-40S and the designers' data for this plant. Even with heat credit taken into account the LUEC estimate appears to be 26-96 % higher than the designers' data.

An important factor affecting the LUEC estimation carried out in this report is parameter *n* in the scaling law (6.3) discussed in Section 6.2.1. For the estimates presented in Table 7.1 to Table 7.6 of this section the value $n = 0.51$ was used corresponding to the average[3] from Table 6.6. To evaluate the uncertainty associated with the selection of *n*, Figure 7.4 graphically represents the difference between the LUEC estimates and the designers' data on LUEC (maximal values) for different values of the parameter *n*, ranging from 0.45 to 0.6[4].

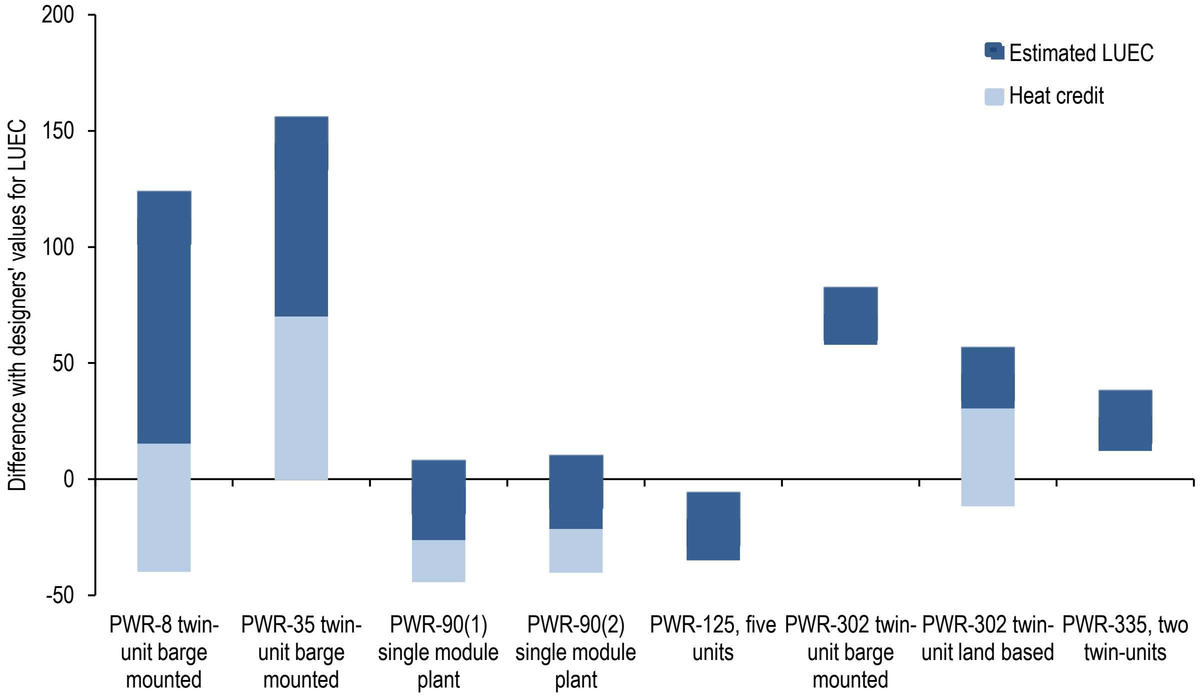
Figure 7.4 shows that the LUEC estimates are quite sensitive to the selection of parameter *n* in the scaling law (6.3) and taking (or not taking) into account the heat credit. If heat credit is not taken into account (where it could apply) the majority (5 out of 8) of the independent LUEC estimates are significantly higher compared to the designers' data on LUEC. If heat credit is taken into account, the majority (5 out of 8) of the independent LUEC estimates envelope the designers' data on the LUEC.

The independent LUEC estimates obtained in this section (Table 7.3) are used in Section 7.2 to evaluate the deployment potential of SMRs in a number of electricity and electricity and heat markets around the world.

[3] In Table 6.6 $n = 0.51$ corresponds to an average between the direct and the indirect costs of a NPP.

[4] Corresponds to the range of *n* in Table 6.7 .

Figure 7.4. Difference (in %) between estimated LUEC and the designers' maximal values for LUEC at different values of n ranging from 0.45 to 0.6.



7.2 Evaluation of SMR deployment potential

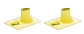
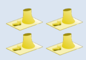
7.2.1 SMR designs selected for the evaluation of deployment potential in niche markets

Deployment potential was evaluated for typical SMRs of the PWR type presented in Table 7.1. The independently estimated ranges of LUEC values given in Table 7.3 were used for the evaluation. Table 7.7 summarises the plant configurations with SMRs for which the evaluations were performed. For convenience, letter codes were attributed to each of the SMRs to denote plant configuration. The letter codes are decrypted as follows:

- PWR - pressurised water reactor;
- number, for example, -8 or -335, - electric output per reactor module;
- S - plant with a single reactor module;
- T - twin-unit plant;
- TT - two twin-unit plants;
- M - modular plant (with 5 or 6 reactor modules);
- B - barge-mounted plant;
- L - land-based plant;

The LUEC estimates in Table 7.7 are given for 5 % and a 10 % discount rate, and also with or without taking into account the heat credit from Table 7.6, to enable evaluation of the deployment potential of SMR plants operating in a co-generation mode.

Table 7.7. Advanced SMRs (PWRs) for which the evaluations were performed taking into account the heat credit (where applies)

Plant configuration		Total electric output of the plant (net) MWe	Based on	LUEC at 5% discount rate, USD per MWh	LUEC at 5% discount rate, USD per MWh*	LUEC at 10% discount rate, USD per MWh	LUEC at 10% discount rate, USD per MWh*
PWR-8TB twin-unit barge-mounted		15.8	ABV (Russia)	192-203	128-145	352-374	234-268
PWR-35TB twin-unit barge-mounted		70	KLT-40S (Russia)	109-114	72-82	179-189	119-136
PWR-90SL single module plant		90	SMART (Korea)	52-54	41-42	87-89	68-70
PWR-125ML five module plant		625-750	mPower (USA)	69-73	n/a	116-125	n/a
PWR-302TB twin-unit barge-mounted		604	VBER-300 (Russia)	54-55	n/a	78-81	n/a
PWR-302TL twin-unit land-based		604	VBER-300 (Russia)	47-50	34-38	75-81	55-61
PWR-335TTL two twin-units		1 340	IRIS (USA)	53-56	n/a	83-90	n/a

*Taking into account the heat credit

7.2.2 Competition with other technologies (electricity generation in "on-grid" locations)

To evaluate a deployment potential of NPPs with SMRs in regulated markets, the LUEC estimates for SMRs based plants presented in Table 7.7 were compared to the LUEC values for electricity generating plants based on the following other technologies:

- nuclear power plants with large reactors;
- coal-fired plants;
- gas-fired plants;
- renewable plants, including onshore wind, offshore wind, solar, biomass and biogas, and large hydroelectric power plants.

The LUEC data for the power plants using technologies other than SMRs were taken from tables 3.7(a-d) of reference [7.1] and correspond to the most recent projections for electricity generation costs (for the year 2010).

With data from [7.1] used as a reference, the evaluation performed in this and the following sections is limited to the generation of electricity, co-generation of electricity and heat in areas with large interconnected electricity grids ("on-grid" locations). Another segment of electricity markets associated with isolated or remote locations with small, local electricity grids or with no grids at all ("off-grid" locations) will be considered in more detail in Section 7.2.5.

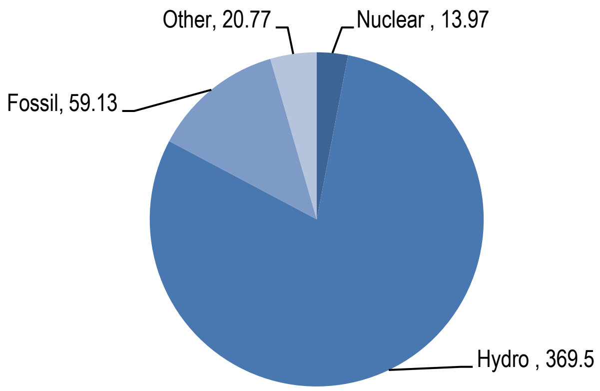
The evaluations were performed for several electricity markets in Brazil, China, Japan, the Republic of Korea, the Russian Federation, and the United States, separately at a 5% and 10% discount rate. The selected countries represent both developed and transitional economies. No countries from the European Union were considered since SMRs are currently not considered for near term deployment in this region of the world.

7.2.2.1 Brazil

In Brazil about 80% of electricity is generated by hydropower with relatively low generating costs, see Figure 7.5 and Table 7.8. The second main source of electricity in Brazil is fossil fuel. In 2008, about 6.26% of electricity was generated from natural gas, 5.25% from wood and 3.79% from oil [7.4].

Figure 7.5. Sources of electricity generation in Brazil [7.4]

Gross electricity production (in TWh) by source in 2008



The data from Table 7.8 indicates some advanced SMRs could be competitive with the currently deployed electricity generating plants in Brazil. However, hydroelectric power plants are more competitive than any nuclear source.

Competition with other nuclear power plants should be viewed with caution. The LUEC values for nuclear in Table 7.8 are estimates with regards to the completion of the Angra 3 project. Should new NPPs with modern large reactors be considered for Brazil, SMRs would probably not be competitive.

However, some SMRs appear to be competitive with the coal- and gas-fired plants[5], as well as with some renewable plants (in the case of Brazil - biogas). The majority of the coal- and gas-fired plants operated worldwide have a capacity between 300 and 700 MWe [7.1] matching the capacity range of SMRs. In view of that, SMRs may provide a competitive replacement for decommissioned power plants in these categories not requiring an enhancement of the electricity grids, the addition of a spinning reserve, or a transition to the new site. For example, SMRs could be competitive when previously used sites do not have sufficient amounts of water for cooling towers of a large power plant. As a replacement, SMRs could effectively use the basic infrastructure remaining on the sites of

[5] The LUEC values for coal and gas in Table 7.8 do not include carbon pricing

the decommissioned small and medium-sized coal- and gas-fired plants. In addition to this, plants with advanced SMRs could provide a reasonable alternative to the newly planned coal- and gas-fired plants, especially in the case of the introduction of carbon taxes.

Table 7.8, as well as the following tables in the section 7.2.2, indicates no options for competitive deployment of barge-mounted plants with very small twin-unit PWRs of 8 and 35 MWe (per unit).

Table 7.8. LUEC for SMR and other technologies (electricity generation, Brazil)

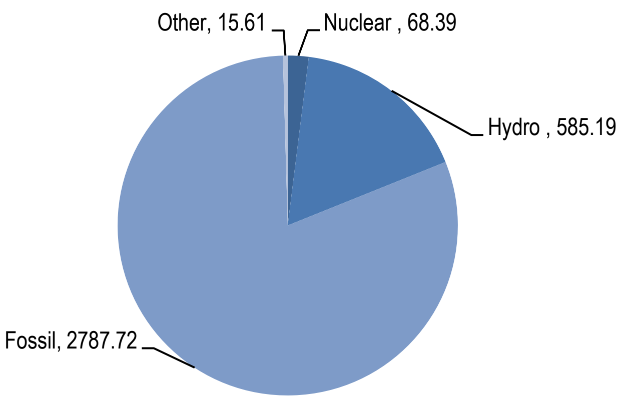
Technology (other than SMRs)	5% discount rate		10% discount rate	
	LUEC, reference [7.1] USD per MWh	Competitive SMRs (*from Table 7.7*)	LUEC, reference [7.1] USD per MWh	Competitive SMRs (*from Table 7.7*)
Nuclear plants (*Table 3.7a[7.1]*)	65.29	PWR-90SL,PWR-302TB,PWR-302-TL,PWR-335TTL	105.29	PWR-90SL,PWR-302TB,PWR-302-TL,PWR-335TTL
Coal-fired plants (*Table 3.7b[7.1]*)	63.98	PWR-90SL,PWR-302TB,PWR-302-TL,PWR-335TTL	79.02	PWR-302TB
Gas-fired plants (*Table 3.7c[7.1]*)	83.85	PWR-90SL,PWR-125ML,PWR-302TB,PWR-302-TL,PWR-335TTL	94.84	PWR-90SL,PWR-302TB,PWR-302-TL,PWR-335TTL
Renewable power plants (*Table 3.7d [7.1]*):				
Large Hydro	17.41-38.53	No SMRs	33.13-61.46	No SMRs
Biomass	77.73	PWR-90SL,PWR-125ML,PWR-302TB,PWR-302-TL,PWR-335TTL	102.60	PWR-90SL,PWR-302TB,PWR-302-TL,PWR-335TTL

7.2.2.2 China

The main primary source of electricity in China is coal (more than 78%). The remaining part in 2008 was shared between hydropower (about 17%) and nuclear power (about 2%), see Figure 7.6.

Figure 7.6. Sources of electricity generation in China [7.4]

Gross electricity production (in TWh) by source in 2008



In the case of China the costs of generating electricity at coal-fired and gas-fired power plants are so low (without carbon pricing) that neither SMRs nor state-of-the-art large reactors can currently compete (neither at a 5% nor at a 10% discount rate). However, nuclear power plants are currently being intensively built in China, showing that the economic factors are not the only ones in decision making.

In the Chinese case, small reactors could be competitive only with renewable plants (onshore wind, solar).

Table 7.9. LUEC for SMRs and other technologies (electricity generation, China)

Technology (other than SMRs)	5% discount rate		10% discount rate	
	LUEC, reference [7.1] USD per MWh	Competitive SMRs (*from Table 7.7*)	LUEC, reference [7.1] USD per MWh	Competitive SMRs (*from Table 7.7*)
Nuclear plants (Table 3.7a[7.1])	29.82-36.31	No SMRs	43.72-54.61	No SMRs
Coal-fired plants (Table 3.7b[7.1])	29.42-30.16	No SMRs	33.26-34.43	No SMRs
Gas-fired plants (Table 3.7c [7.1])	35.81-36.44	No SMRs	39.01-39.91	No SMRs
Renewable power plants (Table 3.7d [7.1])				
Onshore wind	50.95-89.02	PWR-90SL,PWR-125ML,PWR-302TB,PWR-302-TL,PWR-335TTL	72.01-125.80	PWR-35TB, PWR-90SL,PWR-125ML,PWR-302TB,PWR-302-TL,PWR-335TTL
Large Hydro	11.49-29.09	No SMRs	23.28-51.50	PWR-302-TL
Solar	122.86-186.33	PWR-35TB, PWR-90SL,PWR-125ML,PWR-302TB,PWR-302-TL,PWR-335TTL	186.54-272.04	PWR-35TB, PWR-90SL,PWR-125ML,PWR-302TB,PWR-302-TL,PWR-335TTL

7.2.2.3 Japan

About 24% of electricity was generated by nuclear power plants in Japan in 2008, approximately 65.7% from fossil sources (natural gas, coal and oil), and 7.7% by hydropower plants [7.4].

According to Table 7.10, advanced SMRs are not competitive with large nuclear power plants. However, because of the very high costs of generating electricity on coal- and gas-fired plants[6], SMRs - as well as NPPs with large reactors - are competitive in these segments of the electricity market. In such conditions the choice between SMRs and large reactors would, *inter alia*, be defined by the site availability and characteristics. In the case of Japan, clustering of NPPs with large reactors on the sites has been considered more effective, resulting in a complete abandonment of the national SMR option.

If the interest rate is increased up to 10% (which is not the current case in Japan), some SMRs seem to become competitive, especially those with short construction periods (e.g. multi-module plants).

Because of complicated geographical conditions and high level of seismic design requirements, nuclear power plants in Japan strongly compete with large hydroelectric plants, see Table 7.10.

[6] Japan imports all the fossil fuel needed for these plants.

Table 7.10. LUEC for SMRs and other technologies (electricity generation, Japan)

Technology (other than SMRs)	5% discount rate		10% discount rate	
	LUEC, reference [7.1] USD per MWh	Competitive SMRs (*from Table 7.7*)	LUEC, reference [7.1] USD per MWh	Competitive SMRs (*from Table 7.7*)
Nuclear plants (Table 3.7a[7.1])	49.71	No SMR	76.46	No SMRs
Coal-fired plants (Table 3.7b[7.1])	88.08	PWR-90SL, PWR-125ML, PWR-302TB, PWR-302-TL, PWR-335TTL	107.03	PWR-90SL, PWR-302TB,PWR-302-TL,PWR-335TTL
Gas-fired plants (Table 3.7c[7.1])	105.14	PWR-90SL, PWR-125ML, PWR-302TB, PWR-302-TL, PWR-335TTL	119.53	PWR-90SL, PWR-302TB,PWR-302-TL,PWR-335TTL
Renewable power plants (Table 3.7d [7.1]):				
Large Hydro	152.88	PWR-35TB, PWR-90SL, PWR-125ML, PWR-302TB, PWR-302TL, PWR-335TTL	281.51	PWR-35TB, PWR-90SL,PWR-125ML,PWR-302TB,PWR-302-TL,PWR-335TTL

7.2.2.4 Republic of Korea

In 2008, about 64.5% of electricity in the Republic of Korea was generated from fossil fuels (coal and natural gas), and approximately 34% from nuclear power plants. The contribution of hydropower and other sources is below 2% [7.4].

The pattern of SMR competitiveness in the Republic of Korea (Table 7.11) is generally similar to the one in Japan (Table 7.10). No data on renewable plants is available in reference [7.1] for the Republic of Korea.

Table 7.11. LUEC for SMRs and other technologies (electricity generation, Republic of Korea)

Technology (other than SMRs)	5% discount rate		10% discount rate	
	LUEC range, reference [7.1] USD/MWh	Competitive SMRs (*from Table 7.7*)	LUEC range, reference [7.1] USD/MWh	Competitive SMRs (*from Table 7.7*)
Nuclear plants (Table 3.7a[7.1])	29.05-32.93	No SMRs	42.09-48.38	No SMRs
Coal-fired plants (Table 3.7b[7.1])	65.86-68.41	PWR-90SL, PWR-302TB,PWR-302-TL,PWR-335TTL	71.12-74.25	No SMRs
Gas-fired plants (Table 3.7c[7.1])	89.80-90.82	PWR-90SL, PWR-125ML,PWR-302TB,PWR-302TL,PWR-335TTL	93.63-94.70	PWR-90SL, PWR-302TB, PWR-302-TL, PWR-335TTL
Renewable power plants (Table 3.7d[7.1])	No reference data	n/a	No reference data	n/a

As in the previous cases, nuclear plants are generally competitive with coal- and gas-fired plants[7], and NPPs with large reactors outperform those with SMRs. However, SMRs could be chosen

[7] The LUEC values for coal and gas in Table 7.10 do not include carbon pricing

as a replacement or alternative to power plants using fossil fuel based on the siting considerations like the grid capacity, spinning reserve requirements, or the availability of water for cooling towers of a NPP.

7.2.2.5 Russian Federation

In the Russian Federation, the electricity is mainly generated using natural gas and coal as a primary energy source. In 2008, about 68% of the electricity in the Russian Federation was from fossil sources, and the remaining part almost equally shared between nuclear and hydropower, see Figure 7.7.

Figure 7.7. Sources of electricity generation in the Russian Federation [7.4]

Gross electricity production (in TWh) by source in 2008

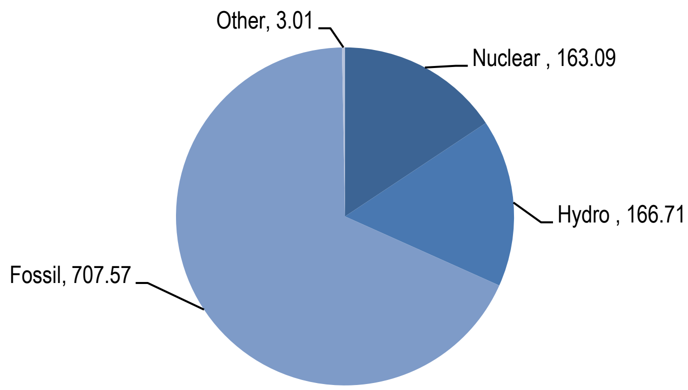


Table 7.12. LUEC for SMRs and other technologies (electricity generation, the Russian Federation)

Technology (other than SMRs)	5% discount rate		10% discount rate	
	LUEC, reference [7.1] USD per MWh	Competitive SMRs (*from Table 7.7*)	LUEC, reference [7.1] USD per MWh	Competitive SMRs (*from Table 7.7*)
Nuclear plants (Table 3.7a [7.1])	43.49	No SMRs	68.15	No SMRs
Coal-fired plants (Table 3.7b [7.1])	50.44-86.82	PWR-90SL, PWR-125ML, PWR-302TB, PWR-302TL, PWR-335TTL	65.15-118.34	PWR-90SL, PWR-302TB,PWR-302TL, PWR-335TTL
Gas-fired plants (Table 3.7c [7.1])	57.75	PWR-90SL, PWR-302TB, PWR-302TL, PWR-335TTL	65.13	No SMRs
Renewable power plants (Table 3.7d [7.1]):				
Onshore wind	63.39	PWR-90SL, PWR-302TB, PWR-302TL, PWR-335TTL	89.60	PWR-90SL, PWR-302TB, PWR-302TL, PWR-335TTL

The situation in the Russian Federation is notable for the actual discount rate being closer to 10% than to 5%. Despite this, the nuclear option competes well with all the available technologies producing electricity, see Table 7.12.

It should be noted that small floating NPPs with the PWR-8 and PWR-35 twin-unit plants (based on the Russian ABV and the KLT-40S designs) do not compete in the conditions of the “on-grid” electricity generation addressed in this section. Possible niche markets for such small plants are analysed in Section 7.2.5.

From Table 7.12 it is noted that several SMR projects are competitive with the coal- and gas-fired plants at a 5% discount rate (but only with the coal-fired plants at a 10% discount rate). As in the previous cases, large reactors are more competitive, but smaller reactors could still be selected for particular sites (where large reactors could not be used).

7.2.2.6 United States

In the United States, fossil primary sources (mainly coal and gas) were used to generate more than 70% of electricity in 2008. About 19% of electricity was generated by nuclear power plants and about 6.5% by hydropower plants (see Figure 7.8).

Figure 7.8. Sources of electricity generation in the United States [7.4]

Gross electricity production (in TWh) by source in 2008

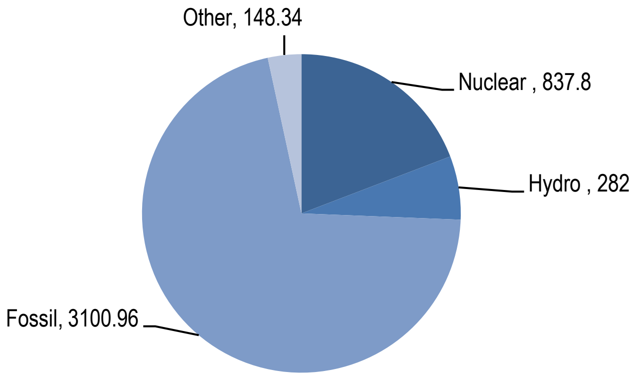


Table 7.13. LUEC for SMRs and other technologies (electricity generation, the United States)

Technology (other than SMRs)	5% discount rate		10% discount rate	
	LUEC, [7.1] USD per MWh	Competitive SMRs (*from Table 7.7*)	LUEC, [7.1] USD per MWh	Competitive SMRs (*from Table 7.7*)
Nuclear plants (Table 3.7a[7.1])	48.23-48.73	No SMRs	72.87-77.39	No SMRs
Coal-fired plants (Table 3.7b[7.1])	68.04-74.87	PWR-90SL, PWR-125ML, PWR-302TB, PWR-302TL, PWR-335TTL	87.68-93.92	PWR-90SL, PWR-302TB, PWR-302TL, PWR-335TTL
Gas-fired plants (Table 3.7c [7.1])	76.56-91.90	PWR-90SL, PWR-125ML, PWR-302TB, PWR-302TL, PWR-335TTL	82.76-104.19	PWR-90SL, PWR-302TB, PWR-302TL, PWR-335TTL
Renewable power plants (Table 3.7d [7.1]):				
Onshore wind	48.39-61.87	PWR-90SL, PWR-302TB, PWR-302TL, PWR-335TTL	70.47-91.31	PWR-90SL, PWR-302TB, PWR-302TL, PWR-335TTL
Offshore wind	101.02	PWR-90SL, PWR-125ML, PWR-302TB, PWR-302TL, PWR-335TTL	146.44	PWR-90SL, PWR-125ML, PWR-302TB, PWR-302TL, PWR-335TTL
Solar	136.16-215.45	All SMRs	202.45-332.78	PWR-35TB, PWR-90SL, PWR-302TB, PWR-302TL, PWR-335TTL
Biomass and biogas	32.48-53.77	PWR-90SL, PWR-302TL	63.32-80.82	PWR-302TB, PWR-302TL

In the US market, the nuclear option is competitive with other technologies for generating electricity (Table 7.13). Large reactors are more competitive than smaller ones. Although the NPPs with large reactors have smaller LUEC than SMRs, the latter could represent an attractive option in the case of a liberalised market (since they could be easier to finance, see the discussions in Sections 6.5 and 6.6) or for specific site conditions. Also, in the United States, there are other motivations than economics to develop SMRs (increasing exports of US companies, creation of jobs, replacement of small and medium size fossil plants, powering military bases, etc.) that are out of scope of the present report. More information could be found in [7.13].

7.2.3 Competition with other technologies (combined heat and power plants in "on-grid" locations)

In this section, the competitiveness of the SMRs is analysed for countries with interconnected electricity grids (i.e. for "on-grid" locations). Niche markets for SMRs in the remote and isolated ("off-grid") locations are analysed in Section 7.2.5.

The evaluation presented in the previous section was limited to SMRs and alternative technologies intended for generating electricity. Some of the power plants currently operating worldwide, as well as many advanced SMRs, provide for the simultaneous production of electricity and heat in a co-generation mode. Such plants are referred to as Combined Heat and Power Plants (CHPs) [7.1]. As the produced heat is transformed into a commercial product (heat for district heating, desalinated water, etc.) and sold along with the generated electricity, co-generation mode may contribute to the enhancement of the overall plant economy. The heat credit model proposed in reference [7.1] and discussed in Section 6.5 is used to take into account the associated benefits.

To evaluate the deployment potential of co-generating nuclear power plants with SMRs, the LUEC estimates for SMRs from Table 7.7 in Section 7.2.1 were compared to the LUEC values for the CHP from Table 3.7e of [7.1]. The latter publication takes into account the heat credit at a fixed rate of USD 45/MWh.

The evaluation results are summarised in Table 7.14, which generally has the same structure as Table 7.8-Table 7.13 of the previous section. Regarding these results one should note that:

- Countries rather than technologies are listed in the left column of the table, i.e., the specified ranges of LUEC for CHPs encompass all technologies specified in [7.1] for a particular country.
- All SMRs evaluated in this chapter (PWR SMRs) were considered as capable of producing heat in the co-generation scheme (and not only those for which heat credit data are specified in Table 7.6).

The main argument for the last point is that almost all SMR designers do not exclude the non-electrical applications and co-generation modes for their designs as discussed in Section 4.4. For the SMRs from Table 7.6 - PWR-8TB, PWR-35TB, PWR-90SL, and PWR-302TL - the LUEC estimates taking into account heat credit were taken from the Table 7.7, while for all other SMRs from the same table, the LUEC values used in the evaluation had no correction for the heat credit.

The data from Table 7.14 leads to the following conclusions:

- At least some SMRs could be competitive with other CHP technologies in China and in the Russian Federation at 5% discount rate[8]. As co-generation modes are typically not provided for in NPPs with state-of-the-art large reactors, NPPs with SMRs appear to be the only nuclear option for a CHP.

- It is noted that in the case of the Russian Federation, the SMR based CHPs are competitive with gas turbine and Combined Cycle Gas Turbine (CCGT) CHP that fill-in the upper part of the LUEC ranges specified in Table 7.14. Plants with SMRs cannot compete with the Russian coal-fired CHP for which the LUEC values (without carbon pricing) are at the lower boundary of the LUEC ranges of Table 7.14. In contrast, in the Chinese case, the specified co-generation NPPs with SMRs are competitive with the coal-fired CHPs.

- In the case of the United States, reference [7.1] includes the CHP LUEC data only for the two technologies, biomass and simple gas turbine. Both appear so cheap that no SMRs could compete with any of them at either a 5% or 10% discount rate.

- Similar to what was found in Section 7.2.2, the evaluation performed in this section has found no cases when small barge-mounted co-generation plants with the PWR-8 and PWR-35 twin-units (based on the Russian ABV and KLT-40S designs) are competitive (in the considered "on-grid" CHP applications).

Table 7.14. LUEC for SMRs and other technologies (combined heat and power plants [CHPs])

Country	5% discount rate		10% discount rate	
	LUEC, non-nuclear CHPs Table 3.7e [7.1] USD per MWh	Competitive SMRs (*from Table 7.7*)	LUEC, non-nuclear CHPs Table 3.7e [7.1] USD per MWh	Competitive SMRs (*from Table 7.7*)
China	48.73	PWR-302TL	52.70	No SMRs
Russian Federation	24.12-59.58	PWR-90SL, PWR-302TB, PWR-302TL, PWR-335TTL	45.40-72.73	No SMRs
United States	36.57-40.58	No SMRs	45.07-55.64	No SMRs

7.2.4 Summary of SMR competitiveness in "on-grid" applications

Figure 7.9 and Figure 7.10 summarise the estimated values of the SMR LUEC and estimates regional ranges for LUEC for large nuclear, coal, gas and wind power plants, at 5% and 10% discount rates. Ranges for SMR LUEC include the uncertainty associated with the selection of the scaling parameter n from 0.45 to 0.6 (shown graphically at Figure 7.4 and discussed in Section 6.2.1).

The general conclusions from the evaluation of the competitiveness of SMRs performed for the electricity markets (in "on-grid" applications) are similar to the general findings on nuclear power presented in the recent OECD study *Projected Costs of Electricity Generation, 2010 Edition* [7.1]. However, there are some important SMR-specific conclusions that are summarised below:

[8] Large number of assumptions made in the evaluation of competitiveness of SMR based CHPs makes it impossible to draw any meaningful conclusions regarding particular configurations and types of the SMR based plants.

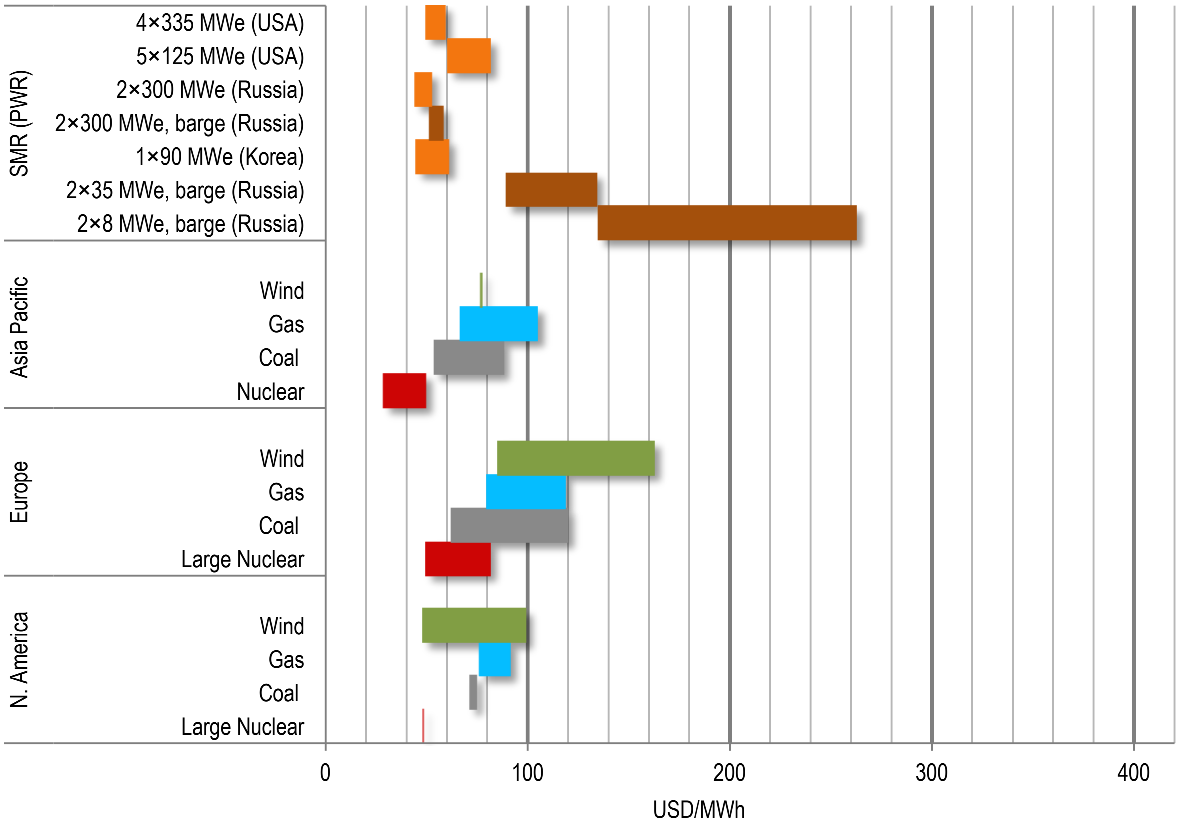
- Within the assumptions of the performed evaluation, the nuclear option in general (NPPs with large reactors or with SMRs) is competitive with many other technologies (coal-fired plants, gas-fired plants, renewable plants of the some types) in Brazil[9], Japan, the Republic of Korea, the Russian Federation and the United States, but not in China.

- SMRs, including twin-unit and multi-module plants, generally have higher values of LUEC than NPPs with large reactors (see Figure 7.9 and Figure 7.10). However, like NPPs with large reactors, some SMRs are expected to be competitive with several of the coal-fired, gas-fired and renewable plants of the various types, including those with small to medium-sized capacity (below 700 MWe).

- A plant with SMRs could be a competitive replacement for decommissioned small and medium-sized fossil fuel plants, as well as an alternative to newly planned such plants, in the cases when certain siting restrictions exist (such as limited free capacity of the grid, limited spinning reserve, and/or limited supply of water for cooling towers of a power plant). SMRs (like nuclear in general) could be more competitive if carbon taxes are emplaced.

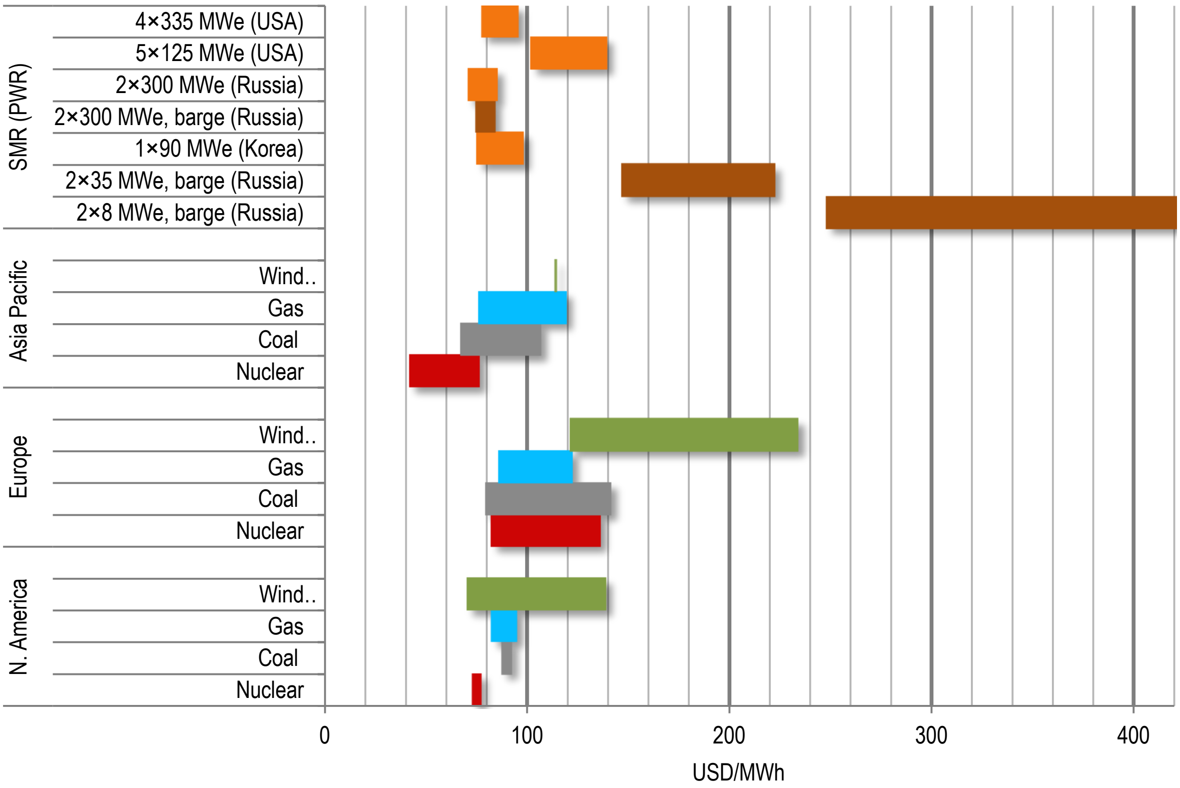
- In other words, SMRs are more competitive than many non-nuclear technologies for generating electricity in the cases when NPPs with large plants are, for whatever reason, unable to compete.

Figure 7.9. Regional ranges for LUEC and estimated values of the SMR LUEC (at a 5% discount rate).



[9] In Brazil, more that 70% of electricity is generated from hydroelectric power plants offering very low cost electricity. Other sources of electricity, including nuclear power plants (with large reactors or SMRs), have higher electricity generation costs.

Figure 7.10. Regional ranges for LUEC and estimated values of the SMR LUEC (at a 10% discount rate)



7.2.5 Specific applications and niche markets for SMRs in "off-grid" locations

Given the reference data [7.1], the evaluations performed in Sections 7.2.2 and 7.2.3 were limited to the generation of electricity (or the production of electricity and heat) in locations with large interconnected electricity grids. As noted in the previous sections, these evaluations showed that barge-mounted NPPs with small PWR-8 and PWR-35 twin-units (based on the Russian ABV and KLT-40S designs) would not be competitive in these conditions.

However, small and transportable NPPs (such as the KLT-40S and the ABV) are being developed for application in remote or isolated areas with difficult access and with no interconnected electricity grids (or even no grids at all) rather than in populated areas with the established grids of a large overall capacity. This section provides several evaluations of the competitive deployment options for NPPs with SMRs in the remote or isolated areas (conventionally referred to as "off-grid" locations). However, no market analysis has been performed.

7.2.5.1 Russian Federation

For the first evaluation case, Figure 7.11 presents a map showing the distribution of electricity tariffs along different regions of the Russian Federation in 2010 [7.4]. In the Northern and Eastern part of the country there are huge territories with lengthy coastal areas where the electricity tariffs are within the range of 78.7-291 USD/MWh. These territories are characterised by permanent frost, difficult climatic conditions, underdeveloped infrastructure and, at best, small local electricity grids. The access to many of these territories is only possible within a particular short season during the year. The customers in these areas are sparsely located enterprises (including gas production and transporting), military bases and small settlements that typically need heat as well as electricity to move on with their routine activities all year around.

A comparison of the data from Table 7.7 and Figure 7.11 indicates many options for the competitive application of both the PWR-8TB and PWR-35TB in these areas (at least, at a discount rate of 5%). If heat credit is taken into account (and heat supply is essential in these regions), the PWR-8TB becomes competitive at a 10% discount rate.

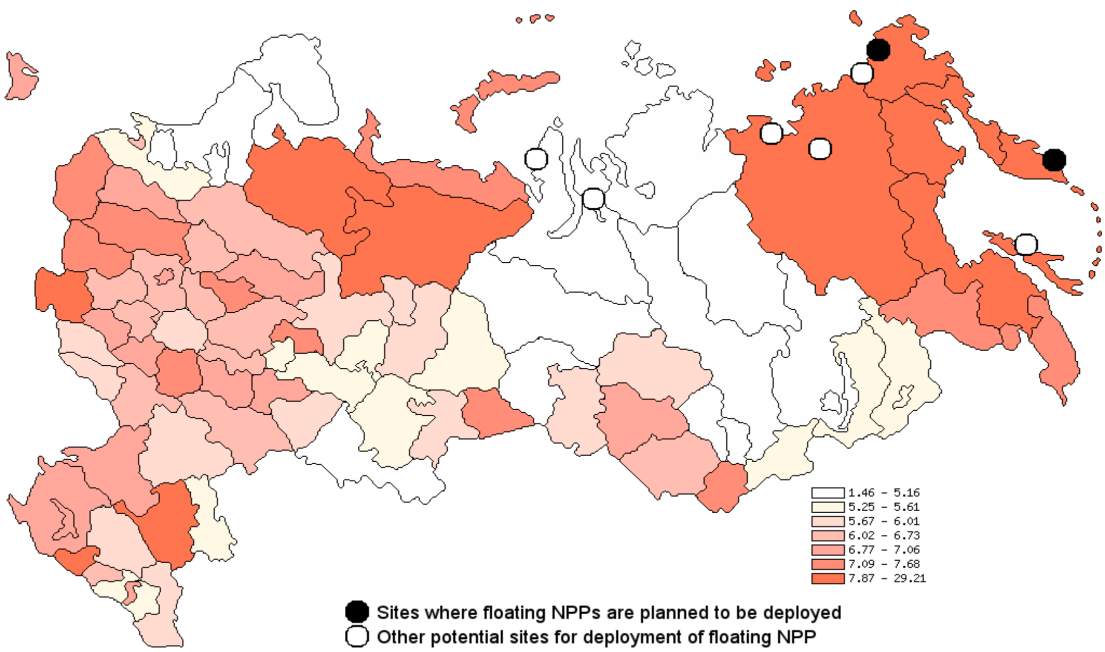
One could note that, from an economic standpoint, the territories with the electricity tariff range of 78.7-292 USD per MWh in Figure 7.11 might actually accommodate all of the SMRs listed in Table 7.7. However, the severe climate and the specific siting conditions with complicated access pose special requirements for NPPs, which include:

- Ability to operate safely within a small local grid or with no grid at all.
- Simplified operation and maintenance requirements and reduced staffing requirements, supported by very high levels of plant robustness and safety.
- Infrequent refuelling or, at least, exclusion of the need of frequent fuel delivery to the site.
- Transportability, to enable plant relocation in the case of a relocation or abandonment of the enterprise to which the NPP caters (for example, the lifespan of a mine development could be as short as 10-15 years).
- Co-generation option with the use of heat for residential heating or industrial applications.

The SMRs better suiting the above mentioned requirements for coastal areas and, probably, large rivers are barge-mounted NPPs (such as the PWR-8TB, PWR-35TB and PWR-302TB of Table 7.7 based on the Russian KLT-40S, ABV and VBER-300).

For the in-land areas away from the coast and the rivers land-based plants with small reactors having an infrequent refuelling interval (such as the mPower and the NuScale (see Section 4.2.1), the 4S (see Section 4.2.5), or SVBR-100, PASCAR and New Hyperion Power Module (see Section 4.2.6) could be appropriate.

Figure 7.11. Map of electricity tariffs (in USD cent per kWh) in the Russian Federation in 2010, [7.5]

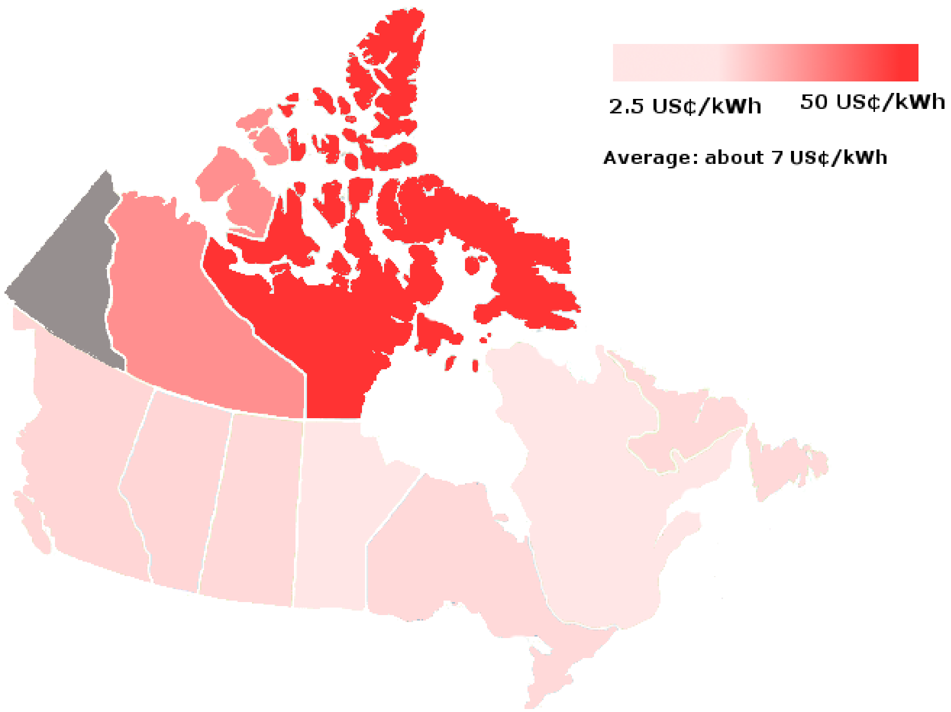


7.2.5.2 Canada

For the second evaluation case, Figure 7.12 presents a simplified map of the electricity tariffs in Canada, developed on the basis of the published regulated tariffs on electricity [7.6]. The simplification is due to the fact that in many regions of this country the electricity tariffs are regulated, but real tariffs can differ significantly from town to town inside each province. Nevertheless, Figure 7.12 indicates large territories in the northern part of the country where the electricity tariffs are as high as 500 USD/MWh and suggests a number of the territories where the electricity tariffs are much higher than 25 USD/MWh which is typical of a southern part of Canada.

The requirements for NPPs in the northern part of Canada are similar to those mentioned in Section 7.2.5.1 for the case of the Russian Federation. Additionally, these territories are rich in crude oil, the refinement of which requires process steam that could be produced by a NPP with SMRs operating in a co-generation mode. With the very high electricity tariffs in the northern part of Canada, all of the SMRs listed in Table 7.7 could be competitive in these territories on the condition they meet specific requirements arising from severe climatic and access conditions.

Figure 7.12. Simplified map of electricity tariffs in Canada in 2008, reference [7.6]



7.2.5.3 United States (Alaska)

For the third evaluation case, reference [7.7] indicates the generation costs across Alaska (US) vary between 9.3 and 450 USD/MWh (110-540 USD/MWh in 2009 USD), which exceeds the typical costs in the US contiguous forty eight states by factors of three to ten [7.8]. The climatic and siting conditions in Alaska are similar to those in the northern parts of the Russian Federation and Canada and, therefore, the requirements for NPPs would also be similar. From the economic standpoint, it can be seen that all of the SMRs from Table 7.7 that would meet these requirements could be competitive in particular territories of Alaska. For example, the 4S plant (see Table 4.5 in Section 4.2.5) was originally considered for deployment in the city of Galena in the Alaska state.

7.2.6 Summary of SMR competitiveness in "off-grid" applications

The evaluation performed in this section has identified several potential niche markets for SMRs, in particular remote areas with severe climatic conditions hosting mining, refinement enterprises or military bases, and the affiliated small settlements.

On a purely economic basis, isolated islands and small off-grid settlements in populated developing countries (e.g. Indonesia, India) could also become potential market[10].

It was shown that a variety of land-based and barge-mounted SMR plants with substantially higher LUEC could still be competitive on these markets on condition that the plants meet certain technical and infrastructure requirements defined by the specific climate, siting and access conditions of the targeted locations.

In these niche markets, SMRs are not competing with large reactors, the competition will be only with the non-nuclear energy options available or possible for the specific locations.

Co-generation appears to be a common requirement for SMRs in niche markets. More niche markets for advanced SMRs could probably be found if the investigations of this kind are continued.

The evaluation performed in this section, which considered the generation of electricity or the production of electricity and heat in remote or isolated "off-grid" locations, has found many cases when small barge-mounted NPPs with the PWR-8 and PWR-35 twin-units (based on the Russian ABV and KLT-40S designs) are competitive.

[10] Currently a very large part of the electricity generated in Indonesia is based on coal, oil and natural gas. Reference [7.10] indicates the growth rate of the electricity demand in Eastern Kalimantan of 12% per year to be unbalanced with the capabilities of the State Electricity Company which is able to provide only an 8.5% per year capacity growth rate using small and medium-sized power plants on organic fuel. The tariff for electricity produced by coal-fired plants could be as high as 110 USD/MWh. In addition to electricity, East Kalimantan also faces the unbalanced consumption and production of potable water. For example, in 2007 the demand for water in East Kalimantan was 437 221 m^3/day, while the local water company owned by the government was able to provide only 253 991 m^3/day of potable water causing a deficit of 183 300 m^3/day. Maximum plant capacity in East Kalimantan is limited by approximately 400 MWe from the conditions of compatibility with small electricity grids.

References

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8. Safety Designs of Advanced SMRs

8.1 Introduction

This chapter presents a summary of safety design features for advanced SMRs belonging to different technology lines categorised in Section 4.2. SMR designs that had already been deployed and gained some positive operating experience are not addressed, as the mere fact of their deployment and successful operation is a proof of their conformity to national safety norms. An exception is the KLT-40S floating plant which was still under construction at the time of this report. However, one should keep in mind that the safety features of SMRs will be re-analysed following the Fukushima Dai-ichi accident in order to take into account the lessons learnt from it.

In recent years a number of reports addressing safety designs and issues for advanced SMRs were published by IAEA [8.1, 8.2, 8.3, 8.4, 8.5, and 8.6]. Along with the IAEA safety standards and guides [8.7, 8.8, and 8.9] those provided valuable inputs for the consideration performed in this section.

This section makes a reference to Tables A2.1-A2.6 in Appendix 2 of this report, which provide a summary of information on safety design features for each of the addressed SMRs in the following format:

- inherent and passive safety features;
- reactor shutdown systems;
- decay heat removal and depressurisation systems;
- reactor vessel and containment cooling systems;
- seismic design;
- aircraft crash design;
- core damage frequency/large early release frequency;
- emergency planning zone radius (as evaluated by the designer);
- special events considered in safety design (for barge-mounted NPPs);
- compliance with the current regulations.

Reference is also made to Tables A1.2-A1.7 in Appendix 1 of this report, which contains design specifications for each of the SMRs considered.

The structure of this section is as follows. First, safety design features are explained in brief for each technology line, see Sections 8.2-8.7. Section 8.8 provides a summary of safety designs particularly on designs for internal and external events (Sections 8.8.1, 8.8.2), passive versus active safety systems (Section 8.8.3), and safety design versus economics (Section 8.8.4). Compliance with the current regulations and licensing issues that might be faced by some of the advanced SMR designs are then examined in Chapter 9.

8.2 Pressurised water reactors

Summary information on safety design features for each of the addressed SMRs - pressurised water reactors is provided in Tables A2.1(a) and A2.1(b) of Appendix 2. Both tables have identical structure. Table A2.1(a) presents data on the safety designs of the KLT-40S, CAREM-25, SMART, IRIS, and IMR, while Table A2.1(b) presents similar data for the VBER-300, ABV, mPower, NuScale, and NHR-200. Design specifications for the corresponding SMRs are provided in Tables A1.2(a) and A1.2(b) of Appendix 1.

All of the designs presented have relatively large primary coolant inventory and relatively high heat capacity of the primary circuit or nuclear installation as a whole, as compared to typical large PWRs. To illustrate this, Table 8.1 shows the comparative values of the estimates of the order of magnitude of the thermal inertia of the primary circuit in transients with reactor power changes:

$$\partial T_{av}/\partial t = W_{th} /(m \times C_p(T_{av})),\ [K\cdot s^{-1}] \qquad (8.1)$$

W_{th} - thermal output of the reactor;

C_p - heat capacity of the primary coolant;

m - mass of the primary coolant;

T_{av} - average temperature of the primary coolant;

for SMRs versus a reference large reactor (the EPR [8.10]).

Table 8.1. Ratio (8.1) for several SMR designs versus a large reactor

	EPR	IRIS	CAREM-25
W_{th}, MW	4 324	1 000	100
P, MPa	15.5	15.5	12.3
T_{av}, K	585	584	578
Average coolant density, kg/m^3	701	702	709
Primary coolant volume, m^3 [8.10]	460	380	39
C_p, J/(kg·K)	5 802	5 780	5 737
$\partial T_{av}/\partial t$, K/s	**2.3**	**0.65**	**0.63**

The data in Table 8.1 indicates that the thermal inertia of the primary circuit in transients is 3-4 times slower for the PWR SMR type with the integral design of the primary circuit, as compared to a large PWR.

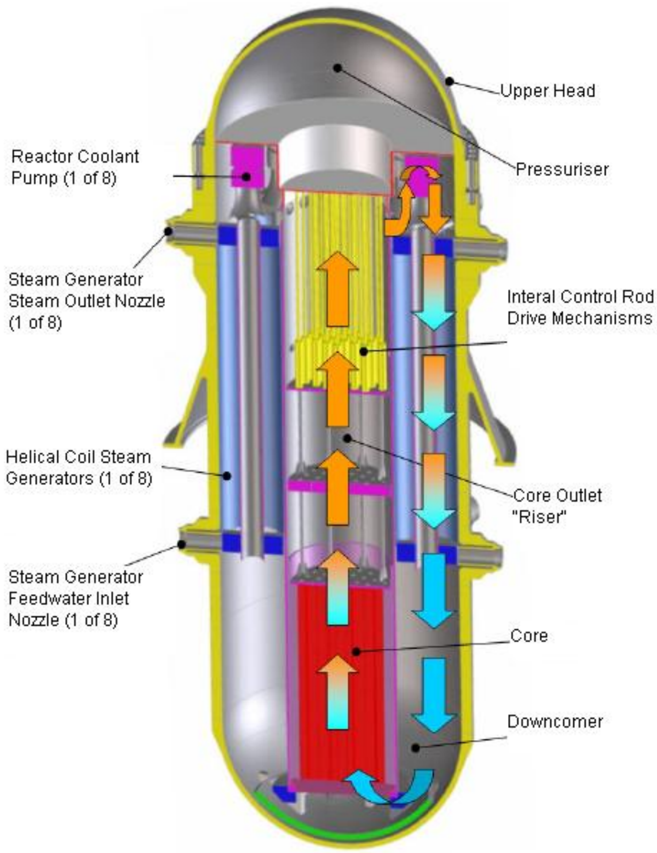
All of the SMR designs considered in this section provide for a level of primary natural circulation sufficient to remove decay heat passively from a shut down reactor.

Loss of coolant accidents (LOCA) are of prime concern for small and medium-sized PWRs, and Tables A2.1(a) and A2.1(b) in Appendix 2 indicate two distinct approaches pursued by SMR designers to eliminate or minimise LOCA by design.

The first approach is to use an integral design (see Figure 8.1 for an example) of the primary circuit with in-vessel location of the steam generators and steam space under the reactor vessel dome acting as a pressuriser. Such an approach is used in the designs of the CAREM-25, SMART, IRIS, Westinghouse SMR, IMR, mPower, NuScale, and NHR-200[1]. It helps minimise primary piping and eliminates large-break LOCA.

Some integral designs (CAREM-25, IRIS, IMR, mPower)[2] go further to use the in-vessel control rod drives, which additionally minimise the vessel penetrations, i.e., the probability and scale of LOCA, and also exclude an inadvertent control rod ejection in the case of a hypothetical control rod bar disconnection from the drive.

Figure 8.1. Integral layout of the IRIS [8.11]



The second design approach, limited to the Russian marine derivative designs KLT-40S and VBER-300, is to use a compact, modular, leak-tight primary coolant system, see Figure 8.2. With this approach nuclear installation appears as a compact array of modules (reactor, steam generator, pressuriser, and main circulation pump) connected with short pipes ("nozzles"). To minimise coolant outflow in breaks the primary pipelines are mostly connected to the "hot legs" of the circuit, and the nozzles incorporate small-diameter flow restrictors. The water chemistry and purification system is located within the primary pressure boundary, which is the justification to call the primary coolant system "leak-tight". The safety design approach of the KLT-40S and VBER-300 is based on operating experience of the Russian submarine and icebreaker reactors of more than 6 500 reactor-years.

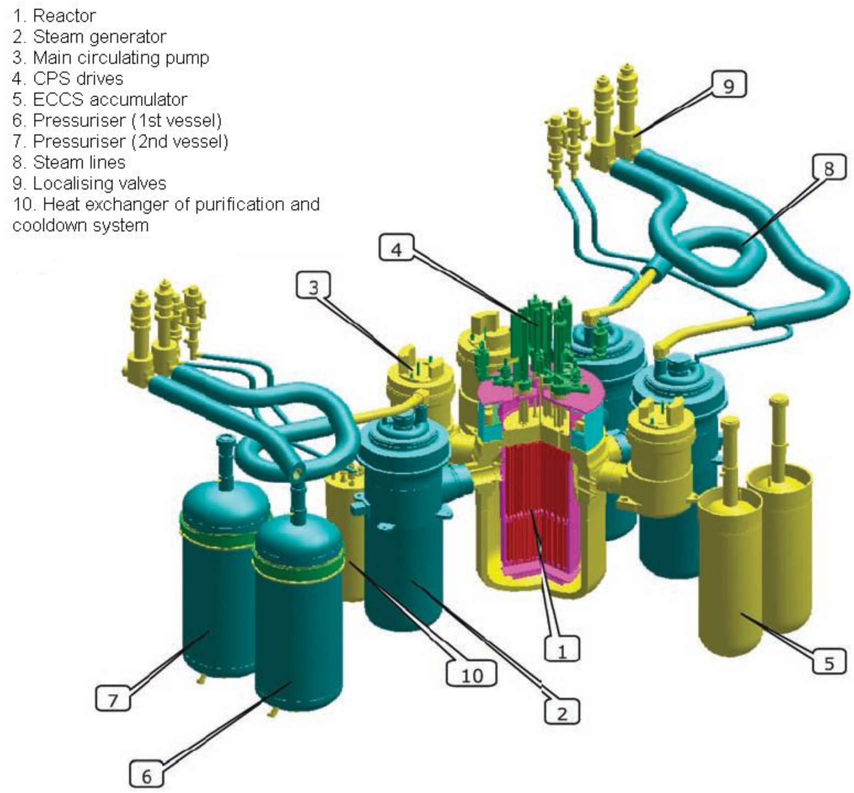
[1] It is noted that the Russian ABV design has internal steam generators but an external gas pressuriser.

[2] It is noted that the Chinese NHR-200 has hydraulic control rod drives located in a narrow gap between the reactor pressure vessel and the guard vessel.

If a LOCA still occurs, all designs provide features to prevent core uncovery. The Russian marine-derivative reactors rely on redundant trains of active and passive emergency core cooling systems. Some integral designs, e.g. the IRIS, use compact containment structures to ensure fast pressure equalisation and return of the coolant to the reactor vessel after a LOCA. The mPower, an integral design said to be backed by many-decades of experience in integral reactor design for nuclear submarines, uses a small diameter, tall reactor vessel with the bottom location of a small reactor core. In the NuScale, all reactor modules have individual vacuumed containments fully submerged in a common water pool.

In normal operation, small and medium-sized PWRs use either forced or natural convection of the primary coolant. The trend is to use natural convection in the designs of less than 150 MWe output. However, there are exceptions. A 125 MWe module of the mPower uses in-vessel canned pumps, while the IMR of 350 MWe uses natural convection of the primary coolant in all modes. The IMR is different from other PWR designs in that boiling of the primary coolant is allowed in the upper core part.

Figure 8.2. Primary coolant system of KLT-40S [8.5]



Burnable absorbers are used in all designs to compensate for burn-up reactivity swing, along with the mechanical control rods and, in some cases, a liquid boron system.

Reactor shutdown is accomplished by diverse mechanical control rods driven either by gravity, an electric motor, hydraulically, or by the force of springs. The second shutdown system is typically based on liquid boron injection, active or passive. The Russian marine-derivative designs are the exception; they avoid safety injections by using the diverse driving forces for the diverse mechanical control rods.

In normal shutdown the normal operation heat removal system is available to remove decay heat in all designs. In addition to this, all designs incorporate redundant and diverse passive or passive and active decay heat removal systems. A trend in the integral design PWRs, e.g., IRIS, CAREM-25, is to have all safety systems passive and safety grade, while keeping all normal operation active systems non-safety grade. Russian marine-derivative reactors (KLT-40S, ABV, and VBER-300) all use the combinations of active and passive decay heat removal systems. Each of these active and passive systems on its own is capable of removing 100% of the reactor core decay heat.

Steam generators in nearly all designs provide for secondary, lower pressure coolant flowing inside the tubes to minimise the probability of a steam generator tube rupture. An exception is the NHR-200, a dedicated reactor for heating, which has an intermediate heat circuit pressure higher than the primary pressure to keep the heating network free from radioactivity.

All designs incorporate the redundant and diverse passive and, in some cases (SMART) active reactor vessel and containment cooling systems. With large primary coolant inventory and, in many cases, relatively low core power density, all designers target the in-vessel retention of the core debris in severe accidents. Core catchers are not provided in any of the considered small and medium-sized PWRs. As an exception, the CAREM-25 provides for a sufficient under-reactor floor space with extra layers of concrete to cool the core debris in case some still exits the reactor vessel.

All of the designs incorporate containments or double containments. In the case of the Russian marine derivative reactors, as well as for some other designs, secondary containments are provided by the structures of the reactor premises/building. Reactor buildings of the mPower and the NuScale are located underground, while for the IRIS the reactor building is half-embedded underground. The containments, as well as the underground location of the reactor buildings (and in the case of the NuScale, additionally, a water pool with the submerged reactor modules) are expected to provide aircraft crash protection, even in the cases when it has not been explicitly addressed in the design (CAREM-25, IRIS).

All of the small and medium-sized PWRs incorporate seismic design for the operating basis earthquake and for the safe shutdown earthquake. For the latter, the horizontal peak ground acceleration (PGA)[3], where indicated, varies from 0.4 g to 0.7 g[4], i.e., is larger than the typical values for the currently operated NPPs [8.3]. The equipment and systems of the Russian marine-derivative reactors are designed for 3 g[5] peak ground acceleration.

The specified core damage frequencies (CDFs) are typically very low (10^{-6}-10^{-8}), i.e., at the level of, or below the values for the best large water cooled reactor designs. Large early release frequencies (LERFs) are typically one order of magnitude lower than CDFs. In most cases it is not explicitly specified whether CDFs were determined with respect to both internal and external events, or the internal events only. For the IRIS and KLT-40S, the CDFs are said to take into account both internal and external events. It is noted that for the KLT-40S, the CDF with respect to internal events is 10^{-7}, while for both internal and external events it is only 10^{-5}.

Safety designs of the Russian floating NPPs (KLT-40S, ABV, VBER-300) address additional external events that may result from on-water location of the plant, such as collision with other ships, debris blocking the water intakes, sinking of the floating power unit, and unit landing on rocky ground. The designs also address helicopter crash landing and collision of a 20 t plane falling at 200 m/s velocity (e.g., a military jet) at a frequency of 10^{-7} per year. Seismic stability and protection against storm waves and earthquake waves (including tsunamis) are provided by appropriate siting and natural or artificial barriers (islands, capes, breakwaters).

[3] Vertical peak ground acceleration is conventionally assumed to be 2/3 of the horizontal one or less.

[4] ~3.5-4.4 on the Japan Meteorological Agency (JMA) seismic intensity scale [6.12].

[5] ~6 on the JMA scale.

8.3 Boiling water reactors

Summary information on the safety design features for the two addressed SMRs - boiling water reactors (VK-300 and CCR) is provided in Table A2.2 of Appendix 2. Design specifications for the corresponding SMRs are provided in Table A1.3 of Appendix 1.

Both designs rely on natural circulation of the coolant in all operating modes, use the in-vessel separators and control rods with the top-mounted drives, to minimise the number of vessel penetrations and the coolant outflow rate in LOCA, as well as to exclude the loss of flow accidents by design.

Both SMRs have a relatively large coolant inventory in the reactor vessel provided to assure the core is not uncovered in accidents and secured by the use of the relatively large reactor pressure vessels.

The VK-300 uses a large low pressure reinforced concrete secondary containment within which the primary containment system is located, providing an effective condensation of steam and return of water to the reactor vessel under a LOCA. Additionally, the secondary concrete containment hosts large water tanks of the emergency core cooling system that could be used for passive flooding and cooling of the reactor core.

In contrast, the CCR incorporates a high pressure compact containment preventing a large coolant inventory loss from the reactor vessel in the case of a LOCA. Relatively small size of the high pressure containment secures fast pressure equalisation, effective condensation of steam (assisted by the isolation condenser) and gravity driven return of water to the reactor pressure vessel soon after a LOCA. Small size of the CCR containment is also expected to enable a reduction of the volume and mass of the reactor building components nearly proportional to the reactor output, if scaled down from a conventional large ABWR.

Burnable absorbers are used in both designs to compensate for burn-up reactivity swing, along with the mechanical control rods. Reactor shutdown is accomplished by the diverse mechanical control rod systems. The second shutdown system is a liquid boron injection system.

In normal shutdown, a normal operation heat removal system is available to remove the decay heat in both designs. In addition to this, the VK-300 incorporates a passive emergency core cooling system and a passive residual heat removal system. The CCR uses a residual heat removal system, an isolation condenser and the flooder lines to return water to the reactor pressure vessel.

Both designs include the reactor vessel and containment cooling systems; specifically, the CCR uses a permanently operated forced airflow cooling of the outer surface of the compact containment vessel.

Aircraft crash protection is provided by the double containment in both designs. A 20 t plane crash is considered for the VK-300.

The VK-300 is designed for a maximum shutdown earthquake of 7 on the MSK scale. The CCR seismic design will be similar to that of the state-of-the-art Japanese light water reactors (LWR).

The specified LERF is 10^{-8} per annum for the VK-300 and 10^{-6} per annum for the CCR, apparently reflecting the differences in the methodologies used to derive it, as well as differences in the design stages of these SMRs.[6] No information is available on whether these numbers take into account both internal and external events, or the internal events only.

Boiling water SMRs belong to the same technology line as the Fukushima Dai-ichi plants, therefore, a very thorough reassessment of their safety design will be needed to take into account lessons learnt from this severe accident.

8.4 Advanced heavy water reactors

Summary information on safety design features of the only entry in this category, AHWRs, is presented in Table A2.3 of Appendix 2. The design specifications of AHWRs are provided in Table A1.4 of Appendix 1.

The AHWR design strongly relies on natural circulation of the coolant in all operating modes, as well as on passive heat removal from all components of the nuclear island. Such a reliance results in a very large size of the containment - for the rated power output of 300 MWe plus some amount of potable water produced using the reject heat the containment size is around 55 m in diameter and 75 m in height[7].

The AHWR is a pressure tube reactor having no reactor pressure vessel. The inherent and passive features include a relatively low core power density, large coolant inventory in the main coolant system, large inventory of water in the gravity driven water pool located at the top of the containment and used to feed the passive core and containment cooling systems, and the use of heavy water moderator in the calandria as a heat sink.

With the on-line refuelling and, especially, when the original Pu-Th fuel is being used, AHWRs feature a low reactivity swing with burn-up. This low reactivity margin is compensated with the use of the burnable absorbers and the mechanical control rods.

The reactor incorporates two independent and diverse passive shutdown systems, one based on the mechanical control rods, and another one - a liquid poison injection in the low pressure heavy water moderator.

In normal shutdown, a normal operation passive heat removal system is available to remove the decay heat in AHWRs. In accidents, core cooling is performed by natural convection of the coolant assisted by a passive injection of the cooling water, first, from the accumulator, and later from the gravity driven water pool located at the top of the containment. Decay heat is transferred to the gravity driven water pool.

The AHWR incorporates passive containment isolation and cooling systems, a system of vapour suppression in the gravity driven water pool, and a system of reactor cavity flooding following a LOCA. All safety systems of AHWRs are passive and safety grade.

Aircraft crash protection is provided by a double reinforced concrete containment. The details of the seismic design are not available.

The specified CDF is 10^{-6} per annum and LERF is 10^{-7} per annum for both internal and external events and their plausible combinations.

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[6] Detailed design has been completed for the VK-300, while the CCR is still at a conceptual design stage.

[7] Plans to increase the AHWR output up to 500 MWe are being discussed.

8.5 High temperature gas cooled reactors

Summary information on the safety design features for each of the addressed high temperature gas cooled reactors (HTGRs) is provided in Table A2.4 of Appendix 2. This table has four inputs, the HTR-PM, PBMR (previous design), GTHTR300, and the GT-MHR. The design specifications for the corresponding HTGRs are provided in Table A1.5 of Appendix 1.

All HTGRs use the tri-isotropic (TRISO) fuel based on tiny (~0.5 mm in diameter) spherical fuel kernels with multi-layer ceramic coatings. Such fuel has a proven record of reliable long-term operation at high temperatures (1 600°C) and at very high burn-ups (120 MWday/kg), and can also effectively retain fission products in the short-term at temperatures as high as 2 100°C. Coated particles can be arranged within fuel designs of the two different types, a moveable pebble bed design and a fixed "pin-in-block" design. The TRISO fuel design options considered in the proposed HTGR designs are described in more detail Section 4.2.4 of this report. A principal passive safety feature of all HTGRs, independent of their fuel design, is the capability of passive decay heat removal from the reactor core to the outside of the reactor vessel using only natural processes of conduction, convection and radiation in all media, without radioactivity release beyond the coating boundary of the TRISO fuel. This capability, facilitated by a large volume of graphite inside the reactor vessel and small power density in the TRISO fuelled core, is retained even in the absence of the helium coolant. Moreover, early release of chemically inert and non-activating helium is a safety measure adopted in HTGR designs to prevent overpressure of the main heat transport system.

In passive decay heat removal to the outside of the reactor vessel, the vessel material appears to be a critical component preventing further increase of the reactor thermal output. With the currently known reactor vessel materials ~600 MWth appears to be the maximum possible unit size of HTGR, "by default" bringing all of the HTGRs into a SMR category.

On-line refuelling is used for the moveable pebble bed fuel, contributing to small burn-up reactivity swing in the HTR-PM and the PBMR. Reactivity control in operation is performed by the mechanical control rods inserted in the reflector area. Burnable absorbers are added to the fuel to minimise the reactivity change with burn-up.

All of the HTGRs have two independent reactor shutdown systems, one based on the mechanical control rods, preferably gravity driven, and another one based on the absorber pellets or balls dropped in a dedicated cavity in the reflector area.

In normal shutdown, a normal operation active heat removal system (with helium blowers) is available to remove the decay heat in all designs. In accidents, the passive decay heat removal mechanism described above is being exploited. To remove heat from the outside of the reactor pressure vessel the redundant passive reactor cavity cooling systems are provided. The preferred working medium is water, but in the case of the GTHTR300 it is proposed to use air.

Of the four designs presented, three (the PBMR (previous design[8]), GTHTR300 and the GT-MHR) are being designed as direct gas-turbine Brayton cycle reactors. One design, the HTR-PM, uses an indirect Rankine cycle on superheated steam and, therefore, incorporates steam generators designed to prevent the secondary water ingress into the reactor core. The HTR-PM incorporates a secondary water discharge system for the case of a steam generator tube rupture.

A citadel of the reactor building (in some cases, a double citadel) providing a path for helium release acts as containment in all of the HTGRs. In the GTHTR300 and the GT-MHR, the reactor buildings are located underground providing an additional protection against aircraft crash.

[8] The most recent PBMR design had reverted to an indirect Rankine cycle.

Where indicated, the seismic design is for 0.2-0.4 PGA (horizontal). The indicated LERF is 10^{-6}-10^{-8} per annum.

8.6 Sodium cooled fast reactors

Summary information on the safety design features of the only entry in this category, 4S, is presented in Table A2.5 of Appendix 2. The design specifications of the 4S are provided in Table A1.6 of Appendix 1.

The 4S design incorporates the inherent and passive safety features typical of a number of larger capacity pool type sodium cooled fast reactors with the integral primary circuit and metallic fuel, but also relies on a number of unique safety design features.

Among the features common with other sodium cooled reactor designs are low (near atmospheric) pressure of the primary coolant system, the sodium based intermediate heat transport system to exclude exothermic sodium water reaction near the reactor core, high thermal conductivity and low operating temperature of the metallic fuel, a pool type design with the intermediate sodium-sodium heat exchangers located in the primary sodium pool, and the large negative feedbacks on temperature and power, typical of a fast spectrum core, with an important role of the negative feedback from radial expansion of the reactor core. Altogether, these features secure a so-called "passive shutdown" capability of the reactor, i.e., the capability of a reactor to bring itself to a safe low power state with balanced heat production and passive heat removal, and with no failure to the barriers preventing radioactivity release into the environment; all relying on the inherent and passive safety features only, and with the indefinite (for practical purposes) grace period.

Among the unique features offered by the 4S are the relatively large specific primary coolant inventory and large thermal inertia of the primary coolant and shielding structure (owing, in part, to a low linear heat rate of the fuel). The unique features also include the double reactor vessel, and the double piping, double tubes and double vessels for the secondary sodium, including the double heat transfer tubes of the steam generator.

The designers have examined and found effective, for the selected primary circuit design, a mechanism of fuel carry-over from the reactor core in case of a fuel element cladding failure. Such a mechanism contributes to the prevention of the core re-criticality, which is a typical hazard for all fast spectrum reactors, resulting from the fast spectrum core not being an optimum critical configuration.

The reactivity control in operation of the 4S is executed solely by changing the water coolant flow rate in the power circuit, with self-adjustment of the core power via the reactivity feedbacks.

The 4S uses forced circulation of the working media in all circuits. In the primary circuit the circulation is provided by the electromagnetic pumps connected in series to ensure the optimum flow coast-down characteristics.

The 4S design provides a continuous core operation without the reloading or shuffling of fuel in the course of 30 years. The burn-up reactivity swing is compensated by the pre-programmed (out of operator control) very slow upward movement of the graphite based radial reflector. In case the reflector gets stuck, the reactor would operate for some limited time and then shut itself down via a negative reactivity feedback resulting from the fission product accumulation.

The 4S has two independent passive shutdown systems, one based on a gravity drop of several sectors of the reflector, and another - on a gravity driven insertion of the single "ultimate shutdown" rod, located in the centre of the reactor core.

In normal shutdown, a normal operation active heat removal system is available to remove decay heat in the 4S. In addition to this, the reactor incorporates two permanently operated independent passive decay heat removal systems. One of them, called the reactor vessel auxiliary cooling system (RVACS), uses natural draught of air to remove heat from the outer surface of the reactor guard vessel. Another one, for which options are being examined, removes heat from the primary or the intermediate sodium system, first, by natural circulation of sodium in a dedicated small loop and, then, through the out-of-the-vessel heat exchanger to the environmental air. This system is called either the primary or the intermediate reactor auxiliary cooling system (IRACS or PRACS, correspondingly).

Regarding seismic design, a horizontal seismic isolation of the reactor building is noted, as well as the tiny shape of the reactor vessel (~3.6 m in diameter and ~24 m height) which provides a protection against vertical shock owing to a higher characteristic frequency.

The reactor building is located in a concrete silo below the ground level. The containment is provided by the guard vessel, the silo walls and the top dome covering the concrete silo, which are all the features to protect the 4S against aircraft crash.

The specified CDF is 10^{-6} per annum.

8.7 Lead-bismuth cooled fast reactors

Summary information on the safety design features of the three considered lead-bismuth cooled fast spectrum SMRs (SVBR-100, PASCAR, and New Hyperion Power Module) is provided in Table A2.6 of Appendix 2. The design specifications for the corresponding SMRs are provided in Table A1.7 of Appendix 1.

The designs addressed are at significantly different development stages. The Russian Federation is the only country in the world with a positive experience in the design, construction and operation (80 reactor-years) of the lead-bismuth cooled reactors for nuclear submarines. The Russian SVBR-100, therefore, takes full advantage of this experience; however, it is a reactor with fast spectrum core while submarine reactors are reactors with epithermal or intermediate spectrum core. Nevertheless, the Russian experience involves the technologies for dealing with the corrosion problem (the principal problem for all heavy liquid metal cooled reactors) and with the volatile ^{210}Po generation[9]. An approach to the solution of the ^{210}Po problem, realised in all of the designs considered in this section, is full factory fabrication and fuelling/defueling of the reactor for its long operation on a site.

Heavy liquid metal cooled reactors could be designed in different output ranges; however, with the coolant being heavy, the size of the reactor vessel (and the unit output) is likely to be limited by the considerations of seismic design. Although there is no common view on this issue, the studies performed in Japan [8.4] indicate the maximum unit size of ~750 MWe for a lead-bismuth cooled reactor as securing the reactor integrity under plausible seismic impacts.

The inherent and passive safety features incorporated in all of the lead-bismuth cooled SMRs considered include a low pressure primary coolant system (the pressure is essentially defined by the weight of the lead-bismuth eutectics), chemical inertness of lead-bismuth in air and water, very high boiling point of the lead-bismuth eutectics (1 670 ^{o}C at atmospheric pressure), and excellent natural

[9] ^{210}Po is a volatile α-emitter produced via reaction ^{209}Bi + p → ^{209}Po + n; it has a half life of ~138 days and is lethal for a human being when inhaled or digested.

convection properties of the heavy liquid metal coolant contributing to passive heat removal from the core.

The properties of a heavy liquid metal coolant and the designs of the lead-bismuth cooled SMRs considered substantially exclude LOCA owing to a very high boiling temperature of the coolant, use of the guard vessel, and placing of the pressure vessel in a water pool[10] (SVBR-100, New Hyperion Power Module). Alternatively, continuous cooling of the outer surface of the reactor vessel by air flow is being provided (PASCAR). Especially when the reactor vessel is in water, any crack in the primary boundary with coolant leak is known to be self-cured by the solidified lead-bismuth.

All of the lead-bismuth cooled SMRs considered are pool type reactors with no intermediate heat transport system. The steam generators are located high above the core to boost natural circulation and to prevent steam bubbles from getting into the core. Should a steam generator tube rupture occur, the flow path is optimised so as to allow the get bubbles released to a gas volume above the coolant free level in the top part of the reactor vessel before the coolant is directed toward the core via a downcomer.

Of the designs presented, a higher powered SVBR-100 uses forced circulation of the primary coolant in normal operation mode, others design concepts use natural circulation in all operating modes.

As all of the lead-bismuth cooled SMRs addressed are fast reactors with hard neutron spectrum, the reactivity swing due to fuel burn-up is essentially smaller compared to LWRs. This difference is due to a higher breeding ratio in the reactor core of a fast reactor. In one of the design modifications of the SVBR-100 it could be brought down to the values below one effective delayed neutron fraction, practically eliminating an option of prompt criticality accidents due to the inadvertent ejection of a control rod. Otherwise, the mechanical control rods are used in all of the designs for the reactivity control in reactor operation.

Reactor shutdown is accomplished by the diverse mechanical systems with control rods and absorber balls. In most cases the shutdown systems are passive, driven by gravity or by the force of springs. In the New Hyperion Power Module one of the shutdown systems is active. Also in the New Hyperion Power Module, the control rods are isolated from the lead-bismuth coolant to prevent surfacing in an upward coolant flow.

In normal shutdown, the normal operation heat removal systems are available to remove decay heat in all of the designs. Passive decay heat removal systems are provided to remove heat in accidents. In the SVBR-100, there are two such systems plus a passive heat removal path via convection and boiling of water in a pool surrounding the guard vessel. In a smaller sized PASCAR, the removal of decay heat is provided exclusively by the cooling system of the reactor guard vessel.

As all of the lead-bismuth cooled SMRs considered have a pressurised steam-water power circuit (secondary circuit), the steam line isolation systems are provided for the case of a steam generator tube rupture.

No information is provided regarding aircraft crash designs, but an underground location of the reactor is mentioned for the New Hyperion Power Module.

Seismic design for 0.3 g PGA with the 3D seismically isolated buildings is indicated for the PASCAR. The CDF and LERF are 10^{-7} and 10^{-8} per year, correspondingly.

[10] There is no water in the pool when a shut down lead-bismuth cooled reactor is being heated to prevent freezing of the coolant at 125°C.

8.8 Summary of SMR safety designs

8.8.1 Design for internal events

An assessment performed in the previous sections indicates that the designers of advanced SMRs target to implement safety design options with the maximum use of the inherent and passive safety features (also referred to as "by design" safety features) possible for a given technology line and for a given size of the plant.

As noted in the recent IAEA publication [8.5],

> An enveloping design strategy for the SMR designs … is to eliminate or de-rate as many accident initiators and/or to prevent or de-rate as many accident consequences as possible, by design, and then to deal with the remaining accidents/consequences using plausible combinations of the active and passive safety systems and consequence prevention measures. This strategy is also targeted for Generation IV energy systems and, to a certain extent it is implemented in some near-term light water reactor designs of larger capacity, such as the VVER-1000, the AP1000, and the ESBWR.

On their own, the "by design" safety features used in SMRs are in most cases not size dependent and could be applied in the reactors of larger capacity. However, SMRs offer broader possibilities to incorporate such features with a higher efficacy. As noted in [8.5], smaller reactor size contributes to a more effective implementation of the inherent and passive safety design features because of:

- "Larger surface-to-volume ratio, which facilitates easier decay heat removal, especially with a single-phase coolant.
- Reduced core power density, facilitating easy use of many passive safety features and systems.
- Lower potential hazard that generically results from lower source term owing to a lower fuel inventory, a lower non-nuclear energy stored in the reactor, and lower integral decay heat rate."

In some cases the incorporation of passive safety features limits the reactor output, as in the HTGR case.

Otherwise, all of the presented SMR designs aim to meet the current national regulations and generally meet the international safety norms, such as formulated in the IAEA Safety Standard NS-R-1 [8.7], regarding implementation of the defence-in-depth strategy and provision of the redundant and diverse active and passive safety systems. Specifically, the IAEA report [8.5] makes a note of the approach "…applied in several water cooled, gas cooled and liquid metal cooled SMRs…" that is "…to have all safety systems passive and safety grade. In this, it is assumed that certain non safety grade active systems/components of normal reactor operation are capable of making a (auxiliary) contribution to the execution of safety functions in accidents."

The core damage frequencies (CDFs) indicated by the designers of advanced SMRs are within the range from 10^{-5} to 10^{-8} per annum, i.e., are comparable to, or lower than the ones indicated for the state-of-the-art large capacity water cooled reactors [8.3, 8.10]. The upper boundary (10^{-5}) mainly results from the risks associated with a non-conventional deployment (e.g., floating power plants). The indicated large early release frequencies (LERFs) are typically one order of magnitude less than the CDFs.

8.8.2 Design for external events

The available information on the safety design features of SMRs for plant protection against the impacts of natural and human induced external events is generally sparser compared to that on the internal events [8.2, 8.3, 8.4 and 8.5]. One of the reasons may be the early design stages of many of the advanced SMRs.

Where indicated, seismic design of the considered SMRs meets the recommendations of the IAEA Safety Guide [8.8]. The indicated magnitudes of safe shutdown earthquake vary significantly even among the designs belonging to the same technology lines. The values are between 0.2 g and 0.7 g PGA (3.5-4.4 on the Japanese JMA scale). These values generally match or surpass the values incorporated in the designs of currently deployed large water cooled reactors [8.3]. However, one should keep in mind that the seismic design of SMRs might be re-analysed following the Fukushima Dai-ichi accident.

All of the analysed SMRs incorporate containments and in many cases these are double containments. Some of the designs in the PWR, HTGR, sodium cooled and lead-bismuth cooled technology lines assume underground or half-embedded underground location of the reactor buildings, which are all measures that would protect the plants against an aircraft crash. However, the design basis aircraft crash is quantified for only a few designs, including the Russian marine derivative reactors. On a number of occasions aircraft crash is said to be excluded from the design consideration to be dealt with by purely administrative measures.

Few details are available on external events other than the earthquake and aircraft crash. For the plants embedded underground no explanation is provided on how such embedment would affect plant vulnerability to natural floods.

Russian floating NPPs take into account a number of the external events peculiar to their on-water location. None of the land-based designs indicate an allowance for the effects of climate change, despite the IAEA guidance on this [8.9].

The IAEA publication [8.3] suggests that "…external events should be considered at the early stages of the reactor design. If external event considerations are added at later stages, they may lead to major modifications or even unacceptable safety levels." For the considered designs only in a few cases the designers clearly indicate that both, internal and external events have been considered when determining the CDFs and the LERFs (Russian marine derivative reactors, CAREM, IRIS, VK-300 and AHWR).

Regarding the combinations of internal and external events, the data provided for a limited number of SMRs in reference [8.3] indicates such combinations are included in the design basis of the CAREM, the VBER-300 and the IRIS.

According to reference [8.3], "…the contribution of external events to plant risk estimates is seen to be higher (in percentage) for evolutionary and innovative reactors since the internal event risks have been substantially reduced through better system design, avoidance of identified accident sequences, etc.". The presented data for the Russian KLT-40S, where the CDF for internal events at the beginning of operation is 10^{-7}, while the overall CDF is 10^{-5}, may serve as an illustration of this statement, see Table A2.1(a) in Appendix 2.

A certain synergy in coping with the internal and the external events is provided by broad incorporation of the inherent and passive safety features in the advanced SMR designs. According to reference [8.3], the NPP features contributing to protection against both, internal and external events, could be:

- “Capability to limit reactor power through inherent neutronic characteristics in the event of any failure of normal shutdown systems, and/or provision of a passive shutdown system not requiring any trip signal, power source, or operator action to effect a shutdown of the reactor if the safety critical plant parameters tend to exceed the design limits.

- Availability of a sufficiently large heat sink within the containment to indefinitely (or for a long grace period) remove core heat corresponding to the above-mentioned event.

- Availability of very reliable passive heat transfer mechanisms for the transfer of core heat to this heat sink…”

Many of the advanced SMR designs presented in this report incorporate the safety design features matching the provisions of the previous paragraphs.

8.8.3 Passive versus active safety systems

The information provided in Tables A.2.1-A2.6 of Appendix 2 indicates that passive safety systems are the preferred choice of the designers of many advanced SMRs. In a number of designs belonging to the technology lines of PWRs, advanced heavy water reactors, HTGRs, and sodium cooled and lead-bismuth cooled fast reactors the preferred strategy is to have all of the redundant and diverse safety systems passive and safety grade, while keeping the necessary normal operation active systems non-safety grade. In this, it is assumed that normal operation systems would on many occasions retain their performance in accidents and could, therefore, be used as a backup for dedicated safety systems. However, there is no unique strategy even within each selected technology line, and many designers still prefer to use plausible combinations of redundant and diverse active and passive systems. The latter choice might be facilitated by the considerations of plant economy as many active systems are well developed and require less materials and reactor building space to be implemented. The rule of thumb here is to have each of the independent safety systems, no matter whether active or passive, capable of a 100% performance of the required system function.

On their own, the passive safety systems implemented in advanced SMRs are not size specific and can be realised in the designs of large capacity as well.

It should be mentioned that since mid-1990s there are growing concerns about the reliability of passive safety systems implemented in advanced reactor designs. Appendix 1 of reference [8.5] lists the following reasons for these concerns:

- “Reliability of passive safety systems may not be understood so well as that of active safety systems.

- There may be a potential for undesired interaction of active and passive safety systems.

- It may be more difficult to “turn off” an activated passive safety system, if so desired, after it has been passively actuated…”

Several methodologies targeted at quantification of the reliability of a passive safety system performance are being developed worldwide, with the two distinct approaches represented by the European Union’s RMPS [8.12] and the Indian APSRA [8.13]. A brief summary of these approaches is provided in the appendix I of reference [8.5]. In addition to this, since 2009 the IAEA has been conducting a coordinated research project to develop a common analysis-and-test based method for the assessment of passive safety system performance in advanced reactors [8.14].

Currently, all of the above mentioned methodologies are at a preliminary development stage and in none of the cases has a nuclear regulatory assessment being made. However, all of the methodologies are being effectively used for the optimisation of passive safety system design and the preliminary results show that passive safety systems could be made equally reliable or even more reliable compared to the active ones.

Notwithstanding what was said above, there are examples of successful licensing of NPP projects with the reactors incorporating passive safety systems (the AP1000 in the United States and China; the KLT-40S in the Russian Federation, the VVER-1000 in the Russian Federation, China, India, and Iran). The validation of passive systems for all of these designs followed a well established approach including performance of the separate effect tests, development and validation of the codes, and performance of the integral tests [8.15].

8.8.4 Safety design and the economics

Although the changes in the safety requirements following the Fukushima-Daiichi accident are still not available, the possible generic implications of a safety design option on the SMR economics (summarised in chapter 4 of reference [8.5]) could be the following:

- On the one hand, broader reliance on the inherent and passive safety features helps achieve the design simplicity "resulting from a reduction of the number of systems and components, and simplicity of plant operation and maintenance, resulting from a reduced number of the systems and components requiring maintenance - both factors contribute to a reduction in plant costs".

- On the other hand, such factors as the lower core power density and the larger specific volume of the primary coolant (and, correspondingly, the larger volume and mass of the reactor vessel per unit the produced energy), often indicated as safety design features in Tables A2.1-A2.6 of Appendix 2, result in an increase of the specific overnight capital cost of the plant.

Additionally, one should not forget about the intrinsic economic disadvantage of SMRs related to the economy of scale.

In a few cases, such as the CCR, the IRIS, the NuScale, or the Russian marine derivative designs, the containment designs of a nuclear steam supply system appear compact, which could to some extent break the economy of scale law. For example, in the CCR (see Table A1.4 in Appendix 1 and Table A2.3 in Appendix 2) the use of a compact containment is expected to allow reducing the volume of the reactor buildings proportionally to the reactor power, as compared to the currently operated large advanced boiling water reactors (ABWRs). However, the CCR is still at a conceptual design stage and any conclusions about its economics are, therefore, very preliminary.

Many of the advanced SMR designs provide for the reduction of off-site emergency planning requirements (see the last row in Tables A2.1-A2.6 of Appendix 2). According to the designers, such a reduction may be possible due to high levels of safety provided by the design and could help attain certain economic benefits. An issue of the emergency planning zone reduction is discussed in more detail in Section 9.3.

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9. Licensing Issues

9.1 Licensing status and compliance with the current regulations

The licensing of SMRs will be affected by the Fukushima accident in the same way as for large reactors. Table 9.1 summarises the licensing status of SMRs addressed in the present report (as in 2010).

SMRs available for deployment, which are the CANDU-6, the PHWR-220, the QP-300, the CNNP-600, and the KLT-40S, have passed licensing procedures which is a confirmation of their compliance with the national regulations at the time of their licensing. The CANDU-6 and the QP-300 have been deployed in countries other than the country of origin, which means they have also been licensed in those countries, see Table 9.1.

The EC-6, which is an evolutionary upgrade of the operated CANDU-6, is said to have no regulatory issues and could be licensed as soon as particular deployment projects are defined.

Table 9.1. Summary of SMR licensing status (end of 2010)*

SMR	Country where the design was licensed (Licensing date for the latest unit built)	Country where licensing is in progress	Country where licensing pre-application is in progress	Comment
CANDU-6	Canada (~1982), China (~1998), Romania (~2002), Republic of Korea (~1994)	n/a	n/a	n/a
PHWR-220	India (~2005)	n/a	n/a	n/a
QP-300	China (~1984), Pakistan (~2004)	n/a	n/a	n/a
CNP-600	China (~2004)	n/a	n/a	n/a
KLT-40S	Russian Federation (~2006)	n/a	n/a	n/a
CAREM-25		Argentina	n/a	n/a
SMART		Republic of Korea	n/a	n/a
HTR-PM		China	n/a	n/a
IRIS, mPower, NuScale			United States	n/a
4S			United States	n/a
New Hyperion Power Module			United States	n/a
PBMR previous design			United States**	Originally planned deployment abandoned
AHWR			India	n/a

* This table has been compiled using the same sources as Table 4.7 in Section 4.3.

** Early in 2010, the financial collapse of the vendor, PBMR Pty. (South Africa), resulted in the abandonment of the original deployment plan; however, the licensing pre-application was still indicated on the US NRC web-site (as of the end of 2010) , see reference [7.1].

The NHR-200, which has an operating prototype, the NH-5, is expected to pose no licensing issues in China and will be licensed as soon as particular deployment projects are fixed.

The previous design version of the ABV has been licensed in the Russian Federation, although never built. Its future progress depends on certain design modifications, which would require an additional, although not huge licensing effort.

Different from other designs, for which licensing pre-applications were made in the countries of origin, the designers of the 4S (Japan) submitted a pre-application to the US NRC, see Table 9.1.

No licensing related actions have so far been undertaken for the CAREM-300, IMR, VBER-300, CCR, GTHTR300, SVBR-100 and PASCAR.

All of the advanced SMRs considered in the present report have been designed or are being designed in compliance with the current national regulations. Whether such compliance will be achieved will become clear after the completion of the licensing process. Possible issues that might be faced by certain groups of designs in the licensing process are summarised in the following section.

Another important set of regulatory requirements concern the ability of SMRs to resist nuclear proliferation. All advanced light water PWR SMRs use conventional LEU fuel and most of the PWR SMR designs use the *same* fuel as large PWRs. However, particular attention should be paid to the non-proliferation potential of some heavy-water or liquid-metal cooled designs, especially if they are intended to be deployed in politically unstable areas. The IAEA has an on-going activity on the options of incorporation of intrinsic proliferation resistance features in NPPs with innovative SMRs, and the report is expected to be published soon.

9.2 Possible regulatory issues and delays in licensing

This section identifies, on a generic level, some of the regulatory issues that might be faced by advanced SMRs in some countries. To make the consideration fair, no reference is made to any specific design or country.

9.2.1 General issues

With the increased number of planned and ongoing NPP construction projects worldwide, a delay in licensing of any non-conventional, advanced SMRs may result from the regulatory staff being busy dealing with the applications for NPPs with conventional large-sized water cooled reactors. A governmental programme to support licensing of selected advanced SMRs could help overcome the corresponding delays.

9.2.2 Water cooled SMRs

Some advanced water cooled SMR designs incorporate novel technical features and components targeting a reduced design and operation and maintenance complexity. Some of these technical features and components, e.g., in-vessel steam generators or compact containment designs, may challenge the practices of periodical in-service inspections established for the current generation of water cooled reactors. The designers are likely to be requested to provide explicit justifications of the reduced periodicity and scope of the inspections and maintenance with respect to such novel components/features. Licensing may proceed more smoothly in those countries which have experience of the implementation of such novel features in the reactors for non-civil applications, e.g., marine propulsion reactors.

9.2.3 Non water- cooled SMRs

Non water cooled SMRs may face licensing challenges in those countries where national regulations are not technology neutral, based on rules and firmly rooted in the established water cooled reactor practice. Countries with certain experience in particular technologies of non water cooled reactors will have an advantage.

Some national regulatory authorities may face a deficit of the qualified staff with expertise in the areas relevant to the design and technology of non water cooled reactors. Staffing problems may arise even in countries that have mastered such technologies in the past but discontinued their development long ago.

Modifying national regulations to a technology neutral approach provides a natural solution to this issue. Some countries, e.g., the Russian Federation and the United Kingdom, have national regulations that are already technology neutral. Specifically, in addition to PWRs (VVER) the Russian Federation has an operating sodium cooled fast reactor (and is building another one) and a number of operating light water cooled graphite moderated reactors of the RBMK type. The United Kingdom has an operating PWR but still operates 19 older design gas cooled reactors and had operated a sodium cooled fast reactor in the past. The experience of these countries could be useful to others. Recently, the IAEA has started a number of activities to interpret the documents of its Safety Standards series for application to the non water cooled reactors.

9.2.4 Reliability of passive safety systems

In Argentina, India, China, the Russian Federation, and the United States there is an established practice of design qualification and licensing for reactors incorporating passive safety systems. The design qualification includes performance of the separate effect tests, development and validation of the codes, and performance of the integral validation tests [9.3]. This practice is likely to be continued within the present decade. The regulatory trend is toward stricter requirements for such a qualification. For example, the regulatory authority in the Russian Federation (Rostekhnadzor) already requires the codes to be validated for beyond design basis conditions.

New developments, such as the RMPS [9.4] and the APSRA [9.5] methodologies, touched upon in Section 8.8.3, are unlikely to change the main conclusions from the established practice. Gradually evolving toward a maturity level acceptable to the regulators, they are expected to improve the quality of passive safety system design and streamline the current qualification practices in a more time-saving and cost effective way [9.6, 9.7].

9.2.5 Long-lived reactor cores and operation without on-site refuelling

Some of the SMR designs addressed in this report provide for a long-life reactor core operation in a “no on-site refuelling mode”. The targeted refuelling interval for such SMRs is between 5 and 30 calendar years. Although the fuel burn-up in all these designs is quite moderate and does not exceed the typical values for a conventionally refuelled design of the same technology line, the continuous long-time core operation may result in ageing and fatigue of some safety related structures and components. In view of this it would be necessary to justify that the original safety case is retained throughout the whole long period of continuous plant operation. The regulatory norms providing for such a justification may be not readily available in national regulations. Countries having relevant experience with marine propulsion reactors will have an advantage. Otherwise, a “license-by-test” approach highlighted in Section 9.4 could be helpful.

9.2.6 Reduced staffing requirements

Simplified operation and maintenance requirements are targeted by the designers of many advanced SMRs [9.2 and 9.4]. Reduced requirements to operation and maintenance are generically translated into reduced staffing requirements, and such requirements may challenge the corresponding national regulatory norms, specifically, if the latter are defined on a capacity-independent basis. For example, in some national regulations the requirements to have security staffing are independent of plant capacity, which is likely to pose a challenge to small NPPs designed for distributed deployment to serve the needs of small local communities in isolated areas. The corresponding revision or amendment of the regulatory norms will be required in such cases, and the updates need to be initiated in due time not to slow down the overall licensing process.

The issue of reduced off-site emergency planning requirements is addressed in more detail in the following section.

9.3 Reduced emergency planning requirements

The off-site emergency planning measures provide a necessary protection at Level 5 of the defence-in depth “Mitigation of radiological consequences of significant releases of radioactive materials” [9.8, 9.9] and generally include the designation of a zone (or several zones) around the plant with certain restrictions on residence and activities, as well as planning of the evacuation and relocation and other measures for the emergency cases. Rated necessary from the viewpoint of protection of the population and environment from radiological consequences of beyond design basis accidents, the off-site emergency planning generally narrows the siting possibilities for NPPs and may add certain economic burdens on a new NPP project [9.6].

For SMRs, location in closer proximity to the users is rated important for the following reasons [9.10, 9.11, 9.12 and 9.13]:

- Some of the niche markets targeted by SMRs offer no space for a large off-site emergency planning zone.
- Many advanced SMRs provide for non-electrical applications, such as district heating or desalinated water production, that benefit economically from plant location in the proximity to the users.
- Some advanced SMRs (e.g., HTGRs) foresee the collocation of chemical or other process heat application plants on the site.
- SMRs do not benefit from the economy of scale and, therefore, reduction of the costs associated with the off-site emergency planning is viewed as one of the factors to combat the negative economic impacts of a smaller plant size.

The basis for justifying the reduced off-site emergency planning for SMRs is provided by a smaller source term offered by some of the SMR designs, rather than by low CDFs and LERFs which are often matched by state-of-the-art NPPs with large water cooled reactors [9.14]. Smaller source terms for advanced SMRs may result from [9.6, 9.14]:

- smaller fissile inventory;
- smaller stored non-nuclear energy (pressure, temperature, chemical energy);
- the provision of a higher margin to fuel failure and the elimination of certain initiating events by design.

Some SMR designers examine options to reduce the emergency planning zone radius for their plants, as indicated by the summary data given in Table 9.2.

Off-site emergency planning has legal and institutional aspects varying from country to country.

In all countries with an ongoing nuclear power programme there are some more or less strictly prescribed values of the emergency planning zone radius for nuclear power plants. For example, in the United States the radius is 16 km around the plant, in Japan - 10 km, in France - 5 km, in the Russian Federation - 3 km (but with a 30 km monitoring zone) [9.6], all for NPPs of essentially the same type and independent on the number of units on the site.

Table 9.2. Designers' evaluation of the emergency planning zone radius (based on Appendix 2)

Evaluated emergency planning zone radius	SMR designs
No off-site emergency planning	VK-300, AHWR, GT-MHR, 4S
Simplified or abandoned off-site emergency planning	CAREM-25, mPower, NuScale, CCR (subject to proving of the in-vessel retention), HTR-PM, New Hyperion Power Module
400 m	PBMR (previous design)
1 km (no evacuation of population is required at any distance from the plant)	KLT-40S, VBER-300, ABV
2 km	IRIS (subject to future risk-informed regulations)
Nothing is specified	SMART, IMR, NHR-200, GTHTR300, SVBR-100, PASCAR

In some countries, e.g., the Russian Federation, there are provisions for the redefinition of the off-site emergency planning zone radius on a plant specific basis. For example, the smaller radius for a floating NPP with the two KLT-40S reactors (see in Table 9.2) has been justified using such provisions as adopted in the Russian Federation. The justification was based on a deterministic analysis with the supplementary probabilistic analysis to determine the CDF and LERF.

In other countries, e.g., the United States, the regulations could be more prescriptive. In such circumstances the progress in justifying the reduced off-site emergency planning is associated with the introduction of risk-informed safety regulations which would allow account to be taken of smaller source terms offered by some SMRs on a more realistic basis [9.6]. Reference [9.6] provides an example of the risk-informed methodology that might be used for the justification of a reduced emergency planning zone radius.

More details about the current maturity status of the risk-informed approaches are provided in the following section.

9.4 New regulatory approaches

This section provides a short summary of the emerging regulatory approaches and highlights the potential benefits to advanced SMRs that could result from the future implementation of these approaches.

9.4.1 License-by-test approach

Chapter 4 of reference [9.14] explains "license-by-test" approach as follows:

> A reactor prototype could be built and subjected to a pre-agreed set of anticipated transient without scram (ATWS) and other accident initiators. By demonstrating safety based on passive response, on the prototype, the licensing authority might be able to certify the design, permitting the manufacture of many tens (or hundreds) of replicate plants to the set of prints and design specifications used for the prototype. In order to assure that aging effects do not degrade the passive safety features of deployed plants, the licensing authority could prescribe the performance of periodic in-situ tests on the plant to confirm continued presence of reactivity feedbacks in the required range and of passive decay heat removal continuously operating at the required rate.

Application of such approach may be useful for licensing of the small reactors with long operation cycle, for which:

- it would be difficult to obtain the immediate licence for a long (15-30 years) operation cycle;

- mass production of standardised reactor modules is foreseen.

An example of the regulatory framework for the license-by-test approach is provided by the US NRC regulation 10 CFR Part 52 "Early site permits; standard design certifications; and combined licenses for nuclear power plants" [9.15]. Part B of this document refers to "…acceptable testing of an appropriately sited, full-size prototype of the design over a sufficient range of normal operating conditions, transient conditions, and specified accident sequences, including equilibrium core conditions…". So far, there have been no applications proposing license-by-test under 10 CFR Part 52. However, very similar approach has been used in licensing of the non-commercial Experimental Breeder Reactor - II (EBR-II) built and operated in the Argonne National Laboratory (ANL, United States) in the 70-90s [9.16].

9.4.2 Risk-informed approach

As it was mentioned in Section 9.3, the current deterministic approach can be used to justify the reduced off-site emergency planning requirements for advanced reactors, including SMRs, in countries where the provisions for such a justification exist. However, the deterministic justification is likely to be conservative as the assumptions typically used in it are conservative.

A risk-informed approach defines the acceptance criteria based on a "probability - consequences" curve derived from the Level 3 probabilistic safety analysis (PSA), which makes it possible to take into account the smaller source terms offered by some advanced SMRs [9.14, 9.17]. Risk-informed regulations are being developed in several countries, including the United States and the Republic of Korea, and risk-informed safety standards are being developed by the IAEA [9.17]. At least one country, Argentina, already has a risk-informed approach incorporated in its national regulations for NPP licensing, see annex III in reference [9.14].

In 2007, the IAEA has published the IAEA-TECDOC-1570 *Proposal of a Technology- Neutral Safety Approach for New Reactor Designs* [9.17]. This publication suggests "…a methodology/process to develop a new framework for development of the safety approach based on quantitative safety goals[1], fundamental safety functions, and generalised defence-in-depth, which includes probabilistic considerations…" However, publication [9.17] is not an IAEA Safety Standard.

In the United States, the US NRC considers developing a set of performance based, risk-informed, and technology-neutral requirements for licensing of the power reactors, to be included in

[1] *i.e.*, a probability - consequences curve correlated with each level of the defence in depth.

the NRC regulations as a new 10 CFR Part 53 that could be used as an alternative to the existing requirements 10 CFR Part 50 [9.15]. The 10 CFR Part 53 would provide a set of risk-informed requirements for both light water and non light water reactor designs [9.14]. A risk-informed regulation implementation plan (RIRIP) was adopted by the US NRC in 2006 [9.18], but the overall progress toward 10 CFR Part 53 is rather slow, and this part of the regulations is currently indicated as 'reserved' on the US NRC Web-site [9.19].

Once established, risk-informed national regulations could help the designers of advanced SMRs justify the reduced off-site emergency planning requirements for their designs. To achieve this, a method to quantify the reliability of passive safety systems would need to be established, as discussed in Section 9.3.

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10. Summary and Conclusions

The present NEA study is a synthesis report on the development status and deployment potential of SMRs. It brings together the information provided in a variety of recent publications in this field, and presents the characterisation of SMRs already available for deployment and those that are expected to become available in the next 10-15 years.

Particular attention is paid to the economics of such reactors, and the various factors affecting their competitiveness are analysed and discussed. Vendors' data on the economics of different designs is compared with the independent quantitative estimates of the electricity generating costs, and the deployment potential of SMRs in a number of markets and geographic locations is assessed.

The study also highlights the safety features and licensing issues regarding such reactors, although the Fukushima Dai-ichi accident might have a significant impact on the design and licensing of SMRs.

For this study, a SMR definition supported by the International Atomic Energy Agency (IAEA) was used, according to which "*small reactors* are reactors with the equivalent[1] electric power less than 300 MW, *medium-sized reactors* are reactors with the equivalent electric power between 300 and 700 MW". However, the main focus is on small reactors.

10.1 Summary

SMR characterisation (general)

Regarding the SMR characterisation, the conclusions are as follows:

- On a fundamental level, nuclear power plants with SMRs are not different from those with large reactors. The reasons to consider SMRs separately are:
  - higher degree of innovation implemented in their designs; and
  - specific conditions and requirements of the target markets, which are often substantially different from those of the nuclear power plants (NPPs) with conventional large reactors.
- Recent publications on SMRs point to the following two general classes of SMR applications:
  - Niche applications in remote or isolated areas where large generating capacities are not needed, the electrical grids are poorly developed or inexistent, and where the non-electrical products (such as heat or desalinated water) are as a bare necessity as the electricity is.

[1] Taking into account non-electrical applications.

– Traditional deployment and direct competition with NPPs with large reactors. In this, it is noted that the upfront capital investment for one unit of a SMR is significantly smaller than for a large reactor. Thus there is flexibility in incremental capacity increase, resulting in smaller financial risks and making such reactors potentially attractive to investors.

Currently available SMRs

At the time of this report (2011) there were eight proven in operation SMR designs with a perspective of international deployment. These designs include the pressure tube heavy water reactors developed in Canada (CANDU-6, EC6) and India (PHWR-220, 540, 700) and the PWRs developed in China (QP-300 and CNP-600). All of these SMRs are land-based. A stand-alone input in this category is the first-of-a-kind (FOAK) barge-mounted plant with the two PWR-type KLT-40S reactors which is currently under construction in the Russian Federation. The plant is expected to start operation in 2013. The KLT-40S design is based on a 6 500 reactor-year experience in the design and operation of the marine propulsion reactors in the Russian federation.

The CANDU-6 and the QP-300 have been deployed internationally, and there are agreements to build more of these reactors in Romania and Pakistan, respectively. Other proven in operation SMRs are being considered for international deployment.

All deployments of the CANDU-6 since 1996, as well as all deployments of the PHWR-220 since 2000, are reported to have been accomplished on schedule (or even ahead of it) and without exceeding the budget.

In the Slovak Republic, a decision has been made to finalise the construction project of the two older design VVER-440 reactors by 2012-2013. The construction project originally started in 1985 but was stopped in 1991. No plans exist for any additional build of the reactors of this dated type.

Advanced SMR designs

Early in 2011, there were about two dozen SMR design development projects ongoing worldwide. About twelve advanced SMRs currently being developed have reached advanced design stages and could in principle be implemented as FOAK or prototype plants before 2020. In some cases, pre-licensing negotiations or a formal licensing process have been initiated.

The majority of these near-term advanced SMRs are of PWR type, but there is one indirect cycle high temperature gas cooled reactor (using superheated steam in the power circuit), one advanced heavy water reactor (AHWR, being developed in India), two lead-bismuth cooled fast reactors, and one sodium cooled fast reactor.

PWRs constitute the majority of advanced SMR designs currently developed in the world. All of them could be divided in two design families:

- self-pressurised PWRs with in-vessel steam generators;

- compact modular PWRs (which are all Russian designs, sometimes referred to as “marine derivative” designs).

The gross electric output varies between 15 and 350 MW. The near-term advanced SMR projects fitting into the first group are CAREM-25 (Argentina), SMART (Republic of Korea), IRIS[2] (United States), Westinghouse SMR (United States), mPower (United States), and NuScale (United States). The Russian marine-derivative designs are KLT-40S, ABV, and VBER-300.

The self-pressurised PWR with in-vessel steam generators, also known as the integral design PWR, differ from conventional PWRs in that they have no external pressurisers and steam generators, with steam space under the reactor vessel dome acting as a pressuriser and steam generators being located inside the reactor vessel. Some of these designs also use the in-vessel (internal) control rod drives.

The compact modular SMR appears to be similar to conventional PWRs. However, the modules hosting the reactor core and internals, the steam generators, the pressuriser, and the coolant pumps are compactly arranged, and linked by short pipes (nozzles) with leak restriction devices. The pipes are mostly connected to the hot branch, and all primary coolant systems are located within the primary pressure boundary, so that the primary coolant system is sometimes referred to as "leak-tight".

Barge-mounted advanced SMRs are all Russian designs. The KLT-40S and the ABV would be implemented first as barge-mounted twin-unit plants. The ABV is being considered for a land-based plant. The VBER-300 is land-based but could be configured to operate on a barge. All non-Russian SMRs are land-based plants.

There is only one near-term advanced SMR in the advanced heavy water reactor category. This is the Indian AHWR which is being design to operate on uranium-thorium or plutonium-thorium fuel. The AHWR is a pressure tube vertical type direct cycle plant with natural circulation of the coolant in all circuits and all operation modes. The primary coolant is boiling light water.

Among the near-term non water cooled advanced SMRs, the most advanced is the Chinese high-temperature gas cooled reactor HTR-PM which is an indirect cycle reactor employing the steam generators and a Rankine cycle with reheating for power conversion. The indirect cycle efficiency of the HTR-PM is remarkably high, 42%, due to steam reheating. The HTR-PM is intended to produce only electricity.

In addition to this, there are three non water cooled fast reactors in the advanced SMR category which target deployment in the near term. These designs include the sodium-cooled 4S (Japan) and the lead-bismuth cooled SVBR-100 (the Russian federation) and New Hyperion Power Module (United States). All of these designs operate at a nearly atmospheric primary pressure and employ in-vessel steam generators or primary heat exchangers. The 4S has an intermediate heat transport system. Regarding advanced SMRs - fast reactors it is noted that all of them incorporate a high degree of innovation related to long refuelling interval and, therefore, only the prototype plants could be expected by 2020.

Design status and possible timeframes for deployment

Regarding the design status and possible deployment timeframes of advanced SMRs, the following was concluded:

[2] Late in 2010 the Westinghouse Electric Company stopped the development of the IRIS project and announced it would go with an alternative integral design PWR of a 200 MWe class. No technical details of this new SMR were available as of January 2011.

- By the middle of 2010, several pressurised water reactor SMRs could be constructed (KLT-40S, ABV, CAREM-25, SMART), as well as an indirect cycle HTGR for electricity production (HTR-PM).

- At the end of 2010 or slightly after, more SMRs with pressurised water reactors could become available as FOAK plants (NuScale, mPower, Westinghouse SMR, VBER-300). In addition to this a FOAK of an advanced heavy water reactor (AHWR) could also become available. Should the experience in deployment and operation of the FOAK SMR be successful, commercial deployments of many units of these reactors could follow, starting from the first half of 2020.

- The prospects for nearer term fast spectrum SMRs (SVBR-100, 4S, New Hyperion Power Module) are less certain because of many novel features incorporated in their designs. Even if deployed by 2020, they would be prototype or demonstration plants that would need to be operated for a number of years (especially in view of the targeted long refuelling intervals) before a decision on commercialisation could be taken. It is unlikely that these SMRs could be commercialised before 2025.

- FOAK HTGRs for high temperature non-electrical applications might be deployed around 2025. Their deployment is likely to be conditioned by the progress in hydrogen (or an alternative advanced energy carrier) economy and will also be conditioned by the operation experience of the HTR-PM.

- The countries in which FOAK SMRs could be deployed within the next 10-15 years are Argentina, China, India, Kazakhstan, the Republic of Korea, the Russian Federation, and the United States.

Nuclear co-generation and non-electrical energy products

NPP operation in a co-generation mode (for example, with co-production of heat or desalinated water) is not a prerogative of SMRs. On a technical level it could be realised in NPPs with large reactors as well. It has not been done so far for NPPs with large reactors because their primary designation was to produce electricity.

Examples exist when NPPs with SMRs have been used or are being used for co-production of the non-electrical energy products. The main reasons why non-electrical applications are more often considered for SMRs are as follows:

- Some small reactors target the niche markets in “off-grid” remote or isolated areas where non-electrical energy products are as much a value as the electricity is.

- Many SMRs are considered as possible replacement for the currently operated combined heat and power plants (CHPs). In many countries the distribution networks serviced by CHPs are tailored to the equivalent plant capacity of 250-700 MWe. Therefore, the use of a NPP with SMRs as a replacement would allow making full use of these networks (that cannot accommodate a large plant).

In regards to hydrogen or other advanced energy carriers requiring high temperature heat to be produced, HTGRs are being considered for this purpose. They all fit into the SMR category.

A somewhat cautious attitude of SMR designers to the inclusion of non-electrical applications in the designs of their FOAK plants is noted, which reflects the fact that some recent market surveys have shown the electricity applications to be of prime demand worldwide for the nearest decade. With this in mind, some of the designers intend to carry on with fastest deployment of the 'electricity-only' versions of their SMRs, reserving the non-electrical applications for a more distant future.

Notwithstanding what is said above, district heating is included as a FOAK design feature in all of the Russian PWR SMR designs, with the production of desalinated water specified as an option. Water desalination is included as a FOAK design feature in the Indian AHWR and the Korean SMART concepts.

Load following operation and compatibility with electricity grids

Many of the SMRs are designed (or are being designed) for both baseload and load-following operation. However, where specified, the magnitude and rate of (daily) power variations and the number of power level switches for SMRs do not differ much from those of the state-of-the-art large reactors.

The SMRs derived from marine reactors may have better manoeuvring capabilities than large reactors, since the original propulsion reactors have been specifically designed to allow rapid power variations in a wide power range. However, the precise information on manoeuvring capabilities of such advanced SMRs is currently not available.

For some co-generation plants with SMRs (the NuScale) it is proposed to change the ratio of electricity and desalinated water production at a constant thermal output of the reactor, which is expected to enable load-following operation precisely matching hourly load changes during the day.

Regarding the compatibility with electricity grids, the general "rule of thumb" is that unit size of a power plant should not exceed 10% of the overall grid capacity[3]. This requirement could, perhaps, be relaxed by some appropriate smart grid designs, but this is still a subject of the research. By definition, the NPPs with SMRs can be more easily deployed within the existing grid capacity, if compared to large reactors or any other large sources of power.

Cost data for SMRs

It was found that some cost data are available for most of the SMRs addressed in this study. In most of the cases the designers' evaluations of costs correspond to the period after the year 2000. The designers' data on Levelised Unit Electricity Cost (LUEC) of SMRs was compared to the projected costs of generating electricity by nuclear power plants in relevant countries in 2010 [10.1].

The conclusions regarding the **designers' cost data** for SMRs are as follows:

- The generating cost (LUEC) for some very small (well under 100 MWe) nuclear power plants intended for distributed deployment exceeds the median case projection of the cost of generating electricity by nuclear power plants roughly by a factor of two.

- For all other SMRs the designers' evaluations of generating cost appear to be close to, or below the median case projection.

- On a country-by-country level, the designers' evaluations of generating costs are in many cases higher than the projected costs of generating electricity by large nuclear power plants in the countries where SMRs are designed.

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[3] From the condition that an unplanned NPP shutdown does not disrupt the stable grid operation.

The available cost data indicate that the designers of advanced SMRs generally intend to compete with larger nuclear power plants. The exceptions are very small (below 100 MWe) NPPs that are being designed for distributed deployment in remote off-grid locations where the electricity costs could be much higher compared to the areas with common electricity grids.

Small modular reactors

Recently the so-called “mini” or small and modular reactors have attracted a lot of attention. Since 2008, several small private companies have been created in the United States to support the design development, patenting, licensing and commercialisation of several new SMR concepts. The design concepts of such reactors were analysed in this study. The conclusions are as follows:

- The new small and modular (‘mini’) reactor concepts being developed in the United States fit well into the known technology lines for nuclear reactors. The new US small and modular reactors (NuScale, mPower, New Hyperion Power Module, and ARC-100) share many of their design attributes with other small reactor design concepts being developed in countries other than the United States. It is their repeated use of the three attributes, namely:

  – multi-module plant option;

  – option of flexible capacity addition/deletion; and

  – underground location of the reactor modules;

  that distinguishes most of the new US small and modular reactors from other small reactor concepts developed elsewhere in the world.

- The attributes of small and modular reactors, such as small upfront capital investments, short on-site construction time (with the accordingly reduced cost of financing), and flexibility in plant configuration and applications, could be attractive for private investors.

Factors affecting the competitiveness of SMRs

In order to analyse the economics of different SMR projects and their deployment potential, the factors affecting the competitiveness were analysed and estimated in this study. The analysis was focused on a comparative assessment of the impact of the various design and deployment factors on the economy of a NPP with SMRs and that of a NPP with a large rector. The main conclusions are as follows:

- It was found that SMR deployments foreseen in the new decade would mainly take place in regulated electricity markets. For such markets, the levelised unit electricity cost (LUEC) appears to be an appropriate figure of merit. The LUEC, measured in USD per MWh, corresponds to the cost assuming the certainty of production costs and the stability of electricity prices.

- At a very general level, SMRs could be divided into two major categories, the traditional land-based nuclear power plants and the transportable (e.g., barge-mounted) plants. The land-based SMRs could be assembled on-site (like large reactors) or fabricated and assembled in full at a factory. These realisations may have very different effect on the competitiveness of each particular project.

- One of the main factors negatively affecting the investment component of LUEC for all SMRs is the economy of scale. Depending on the power level of the plant, the specific (per kWe) capital costs of SMRs are expected to be tens to hundred of percent higher than for large reactors. However, the total overnight costs for SMRs are expected to be significantly lower than the costs of NPPs with large reactors. This could make them attractive for investors in liberalised energy markets and to the countries willing to develop their nuclear programme but having limited financial resources.

While the economy of scale increases the specific capital costs and, therefore, the investment component of the LUEC for SMRs, other economic factors may tend to improve it:

- **Construction duration.** According to the vendors' estimates the construction duration of SMRs could be significantly shorter compared to large reactors, especially in the case of factory-assembled reactors. This results in an important economy in the costs of financing, which is particularly important if the discount rate is high (the specific capital costs could be reduced by up to 20%).

- **First-of-a-kind factors and economy of subsequent units on the site/multi-module plants.** According to the reported experience, FOAK plants are 15-55% more expensive than the subsequent serial units. Building several reactors on the same site is usually cheaper than building a NPP with a single reactor. These factors are the same for large reactors and SMRs. However, if the overall capacity requirement for the site is limited by, say, 1-2 GWe, the effects of learning in construction and sharing of the infrastructure on the site will be stronger when building several plants. The reduction of the effective (per unit) capital cost of SMRs could be 10-25%.

- **Economy of subsequent factory fabricated units.** Different from large reactors, some SMRs could be fully factory manufactured and assembled, and then transported (in the assembled form) to the deployment site. Factory fabrication is also subject to learning which could contribute positively to a reduction in capitals costs of SMRs and of the investment component of the LUEC. The magnitude of the effects of learning in factory fabrication of SMRs is comparable to that of the effects for on-site built plants (up to 30-40% in capital cost reduction, on the total).

- **Design simplification.** In some advanced SMRs, significant design simplifications could be achieved through broader incorporation of size-specific inherent safety features that would not be possible for large reactors. If such simplifications are achieved, this would make a positive contribution to the competitiveness of SMRs. The vendors' values of the effect of design simplification in capital cost reduction for near-term pressurised water SMRs are not less than 15%.

- **Full factory fabrication of a barge-mounted plant.** According to the vendors' data, a full factory fabricated barge-mounted NPP could be 20% less expensive compared to a land-based NPP with SMRs of the same type. The corresponding improvement of the LUEC would be, however, limited by 10% because of increased operation and maintenance costs for a barge-mounted plant compared to the land-based.

The possible impact of all of the above mentioned factors and their combined action were assessed though a number of case studies presented in the report. The conclusions are as follows:

- Even if all of the above mentioned factors are taken into account, the investment component of the LUEC for a SMR would still be at least 10-40% higher than in the case of a NPP with a large reactor.

- Regarding the operation and maintenance (O&M) and fuel cycle components of the LUEC for advanced SMRs, the tentative conclusion is that their sum is likely to be close to the corresponding sum for a large reactor (of similar technology). This conclusion results from the observation that SMR vendors often indicate the O&M costs could be lower than in present day large reactors due to a stronger reliance of SMRs on the inherent and passive safety features, resulting in simpler design and operation. Regarding the fuel costs, SMRs generally offer lower degree of fuel utilisation compared to state-of-the art large reactors, mainly because of poorer neutron economy due to a smaller reactor core.

- Because of the discounting in the LUEC calculation, the impact of decommissioning costs (which are the expenditures to be made in 40-60 years after the start-up of commercial operation of a plant) on LUEC is very small for both SMRs and large reactors.

- NPP operation in a co-generation mode with co-production of heat or desalinated water can potentially lead to a significant additional revenue or credit expressed in a currency unit per MWh. For some SMR designs operating in a co-generation mode the values of the LUEC could be improved by about 20-30%.

SMRs in liberalised energy markets

Although the world electricity markets are still essentially regulated, the tendency is toward more liberalisation and, therefore, it is useful to examine the investment related performance of SMRs according to the figures of merit appropriate for such future market conditions. The assumption of a regulated price would not be accurate under liberalised electricity market conditions. In such markets the fixed costs, the total costs and the capital-at-risk may matter more than LUEC.

No quantitative examinations using these figures-of-merit have been performed in this study; however, the published results of the studies [10.2] performed by a research team of the Politecnico di Milano (Italy) in collaboration with the Westinghouse Electric Company (United States) have been analyzed. Those studies were focused on comparison of the incremental deployments of SMRs versus large reactors in terms of the cash flow profiles, NPV and IRR, and also included sensitivity analyses. The preliminary conclusions by the Politecnico di Milano are as follows:

- Incremental capacity increases with SMR reduce the front-end investment and the capital-at-risk compared to capacity increase with large reactors, but moves the cash inflow forward.

- SMRs may more easily attract investment.

- Projects with incremental capacity increase offer higher reversibility, ensuring that under some force majeure market consequences the project can be stopped with minimum financial losses resulting from failure in the deployment of a relatively cheap next small unit.

- The staggered build of SMRs enables a partial self-financing of the subsequent SMR projects (at the expense of the profits obtained from sales of electricity from the already built and commenced units). The more staggered the SMR build is, the broader are the options for self-financing. This feature of incremental capacity increase could be attractive to those utilities who wish to increase the installed capacity using mostly their own funds, with minimum reliance on external loans.

An assessment of the results obtained by the Politecnico di Milano is beyond the scope of this report, in which the LEUC has been selected as a figure-of-merit to analyse nearer-term deployments of advanced SMRs.

Independent estimates of LUEC for typical SMRs

Independent estimates of the cost of generating electricity (LUEC) on NPPs with SMRs of PWR type were performed using the scaling-law methodology and the numerical estimates of the various factors affecting the competitiveness of SMRs. The uncertainties related to the parameter of the scaling law were taken into account. The resulting LUEC estimates, appearing as ranges corresponding to the variation of the scaling law parameter, were compared to the designers' cost data. The conclusions regarding the comparison are as follows:

- The LUEC estimates are quite sensitive to the selection of the scaling law parameter, and to inclusion of the heat credit. If the heat credit is not taken into account (where it applies) the majority of the independent LUEC estimates are significantly higher compared to the designers' data on LUEC. If heat credit is taken into account, the majority of the independent LUEC estimates envelope the designers' data on the LUEC.

- Regardless of the fact that the specific investment costs (per kWe) for SMRs are in some cases found to be rather high, the total investments are relatively small for a small reactor. For single module SMR plants with the electric output below 125 MWe, the total investments are below USD 1 billion. Another interesting feature of SMRs is that they could be incrementally deployed in relatively short time frames, owing to a shorter construction period. Together with low per-unit costs, this has a strong potential in a significant reduction of the front-end investment and the capital-at-risk, if compared to capacity increase with large reactors.

Evaluation of SMR deployment potential

The independent LUEC estimates performed in this study were used to analyse the competitiveness of SMRs in electricity and combined electricity/heat markets of some countries. In this analysis the LUEC estimates for the various SMR plant configurations were compared to the projected costs of generating electricity or the electricity tariffs. The analysis has been performed separately for the generation of electricity and co-generation of electricity and heat in areas with large interconnected electricity grids ("on-grid" locations), and also for the isolated or remote locations with small, local electricity grids or with no grids at all ("off-grid" locations).

Traditional deployment

The general conclusions from the evaluation of the competitiveness of SMRs performed for the electricity markets (in "on-grid" applications) are similar to the general findings on nuclear power presented in the recent OECD study *Projected Costs of Electricity Generation, 2010 Edition*. However, there are some important SMR-specific conclusions that are summarised below:

- Within the assumptions of the evaluation performed, the nuclear option in general (NPPs with large reactors or with SMRs) is competitive with many other technologies (coal-fired plants, gas-fired plants, renewable plants of the some types) in Brazil[4], Japan, the Republic of Korea, the Russian Federation and the United States, but not in China.

- SMRs, including twin-unit and multi-module plants, generally have higher values of LUEC than NPPs with large reactors. However, like NPPs with large reactors, some SMRs are

[4] In Brazil, more that 70% of electricity is generated from the hydroelectric power plants offering very low cost electricity. Other sources of electricity, including nuclear power plants (with large reactors or SMR), have higher electricity generation costs.

expected to be competitive with several of the coal-fired, gas-fired and renewable plants of the various types, including those of small to medium-sized capacity (below 700 MWe).

A plant with SMRs could be a competitive replacement for decommissioned small and medium-sized fossil fuel plants, as well as an alternative to newly planned such plants, in the cases when certain siting restrictions exist (such as limited free capacity of the grid, limited spinning reserve, and/or limited supply of water for cooling towers of a power plant). SMRs (like nuclear in general) could be more competitive if carbon taxes are emplaced.

In other words, SMRs could be more competitive than many non-nuclear technologies for generating electricity in the cases when NPPs with large plants are, for whatever reason, unable to compete.

Deployment in remote and isolated areas

To analyse the deployment potential of SMRs in remote or isolated areas, the LUEC estimates were compared with the electricity tariffs for those areas (where it is very difficult to calculate the generating costs).

The evaluation performed in this section has identified several potential niche markets for SMRs, in particular remote areas with severe climatic conditions hosting mining, refinement enterprises or military bases, and the affiliated small settlements.

On a purely economic basis, isolated islands and small off-grid settlements in populated developing countries (e.g. Indonesia, India) could also become potential market.

It has been found that a variety of land-based and barge-mounted SMR plants with LUEC substantially higher compared to large reactors could still be competitive on these niche markets if they meet certain technical and infrastructure requirements, defined by the specific climate, siting and transportation conditions. In particular, co-generation with the production of heat or desalinated water appears to be a common requirement in many of the analysed niche markets. NPPs with large reactors do not fit in any of these specific markets; therefore, SMRs would compete only with the local non-nuclear energy options;

In the analysis performed for the “off-grid” locations, many cases were found when small barge-mounted NPPs with the Russian ABV and KLT-40S designs would be competitive.

Safety features of advanced SMRs

The study analyses the most recent publications on SMR safety, in a large part originating from the International Atomic Energy Agency (IAEA). However, one should keep in mind that the safety features of SMRs will be re-analysed following the Fukushima Dai-ichi accident in order to take into account the lessons learnt from it.

The main conclusions regarding advanced SMR safety are as follows:

- The designers of advanced SMRs aim to implement safety design options with the maximum use of the inherent and passive safety features (also referred to as “by design” safety features).

- On their own, the “by design” safety features used in SMR are in most cases not size-dependent and could be applied in the reactors of larger capacity. However, SMRs offer broader possibilities to incorporate such features with a higher efficacy.

- In the case of some technologies (like high temperature gas reactors) the incorporation of passive safety features limits the reactor capacity.

- All of the SMR design concepts addressed in this study aim to meet the international safety norms, such as formulated in the IAEA Safety Standard NS-R-1 "Safety of the Nuclear Power Plants: Design Requirements", regarding implementation of the defence-in-depth strategy and provision of the redundant and diverse active and passive safety systems.

- The available information on safety features of advanced SMRs for plant protection against the impacts of natural and human-induced external events is generally sparser compared to that on the internal events. A certain synergy in coping with the internal and external events is provided by broader incorporation of the inherent and passive safety features ("by design" safety features).

- The core damage frequencies (CDFs) indicated by the designers of advanced SMRs are comparable to, or even lower than the ones indicated for the state-of-the-art large water cooled reactors.

Licensing issues for advanced SMRs

The licensing of SMRs will be affected by the Fukushima accident in the same way as for large reactors. Regarding licensing status and regulatory issues relevant to SMRs, the analysis of recent publications leads to the following observations:

- All of the advanced SMRs addressed in the present study have been designed or are being designed in compliance with current national regulations.

- SMRs available for deployment, which are the CANDU-6, PHWR, QP-300, CNNP-600, and the KLT-40S, have already passed the licensing procedures in the countries of origin, which is a confirmation of their compliance with the national regulations. The CANDU-6 and the QP-300 have been deployed in countries other than the country of origin, which means they have also been licensed in those countries.

- Regarding advanced SMR designs, three of them are in a formal licensing process in Argentina (CAREM-25), China (HTR-PM) and the Republic of Korea (SMART), and several others are in pre-licensing negotiations in the United States (NuScale, mPower, Westinghouse SMR, New Hyperion Power Module) and India (AHWR).

Regulatory issues and delays regarding advanced SMR licensing may be observed due to the following main reasons:

- Some advanced water cooled SMR design concepts incorporate novel technical features and components targeting reduced design and operation and maintenance complexity which need to be justified by the designers and accepted by the regulators. Regulatory provisions for such an acceptance may be not readily available.

- Non-water-cooled SMR may face licensing challenges in those countries where national regulations are not technology neutral, firmly rooted in the established water-cooled reactor practice and regulation based. Absence of regulatory staff familiar with non water cooled reactor technologies may also pose a problem.

- Some of the advanced SMR design concepts provide for a long-life reactor core operation in a "no on-site refuelling mode". The regulatory norms providing for justification of safety in such operation modes may be not readily available in national regulations.

A governmental programme to support licensing of selected advanced SMRs could help overcome the delays due the above mentioned and other reasons.

10.2 Conclusion

A principal conclusion of this study is that SMRs have a significant potential to expand the peaceful applications of nuclear power by catering to the energy needs of those market segments that cannot be served by conventional NPPs with large reactors. Such segments could be:

- Niche applications in remote or isolated areas where large generating capacities are not needed, the electrical grids are poorly developed or absent, and where the non-electrical products (such as heat or desalinated water) are as important as the electricity;

- Replacement for the decommissioned small and medium-sized fossil fuel plants, as well as an alternative to newly planned such plants, in the cases when certain siting restrictions exist, such as limited free capacity of the grid, limited spinning reserve, and/or limited supply of water for cooling towers of a power plant;

- Replacement for those decommissioned fossil-fuelled combined heat and power plants, where the SMR power range seems to better fit the requirements of the currently existing heat distribution infrastructure;

- Power plants in liberalised energy markets or those owned by private investors or utilities for whom small upfront capital investments, short on-site construction time (with the accordingly reduced cost of financing), and flexibility in plant configuration and applications matter more than the levelised unit electricity cost.

It should be noted, however, that none of the smaller reactors has yet been licensed for these applications and there remain both development challenges to overcome and regulatory approvals to obtain before deployment, especially in light of the recent accident at Fukushima.

The present study has found no situations where NPPs with SMRs could compete with the NPPs with state-of-the-art large reactors, on LUEC basis. However, it also found that SMRs could be competitive with many non-nuclear technologies in the cases when NPPs with large reactors are, for whatever reason, unable to compete.

References

[10.1] IEA/NEA (2010), *Projected Costs of Generating Electricity*: *2010 Edition*, OECD, Paris, France

[10.2] Boarin S. and M. Ricotti (2009), "Cost and Profitability Analysis of Modular SMRs in Different Deployment Scenarios", Proceedings of the 17th International Conference on Nuclear Engineering (ICONE 17), Brussels, Belgium, Paper ICONE17-75741.

Appendix 1. Design Specifications for Advanced SMRs

Table. A1.1. Design specifications of SMRs available for deployment

	EC6	PHWR-220	KLT-40S	QP300	CNP-600
Thermal/electric output (gross), MW	2 084/735	862/220	2x150/2x35	998.6/325	1 936/ 644
Thermodynamic cycle type/efficiency	Indirect Rankine cycle/ 35.3%	Indirect Rankine cycle/ 35.3%	Indirect Ranking steam condensing cycle/ 23.3%	Indirect Rankine cycle/ 32.5%	Indirect Rankine cycle/ 33%
Primary coolant, circulation mode	Heavy water, Forced	Heavy water, Forced	Light water, Forced	Light water, Forced	Light water, Forced
Primary pressure, MPa	11.2	9.9	12.7	15.2	15.5
Core inlet/outlet temperatures, ^{o}C	260/ 310	249/293.4	280/ 316	288.5/315.5	292.8/ 327
Core diameter×height, mm	7 600×5 940 (4 953 fuel column)	4 510 ×5 005	1 155 x1 200	2 486×2 900	2 670×3 658
Fuel type/ initial enrichment (%)	UO_2, natural uranium/ 0.714%	UO_2, natural uranium/ 0.714%	UO_2 in inert matrix/ 13 and 15.7% ^{235}U	UO_2/ 3.4%	UO_2/ 3.6 %
Burn-up cycle duration, equivalent full power days	On-power refuelling	On-power refuelling	854	366	549
Average burn-up of discharged fuel, MWday/kg	7.5	6.7	45.5	30	>45
Mode of reactivity control in operation	- Light water zone control absorbers; - Mechanical control absorbers; - Adjusters (cylindrical absorbing rods); - Soluble poison addition and removal to the moderator.	- Absorber cods; - Booster rods; - Poison in the moderator.	-Mechanical control rods; -No liquid boron.	-Mechanical control rods; -Liquid boron.	-Mechanical control rods; -Liquid boron.
Reactor vessel diameter×height, mm	N/A, Pressure tube reactor	N/A, Pressure tube reactor	2 176×4 148	3 724x10 705	4 410×12 395
Secondary pressure, MPa	4.6	4.2	3.82	6.8	6.71
SG secondary side inlet/outlet temperatures, ^{o}C	187/ 260	170/ 250.7	170/ 290	216/ 267.5	230/282.94
Turbine type	Single shaft tandem compound turbine	Single turbine	Two condensing - extraction steam turbines, one per each reactor	Double flow high pressure turbine and two double flow low pressure turbines	Single turbine
I&C system	State-of-the-art digital systems	Digital and analog, based on Indian experience	Based on the state-of-the-art for PWR and marine reactors	Based on the French experience	Based on Chinese, French and Japanese experience
Reactor unit and balance of plant elevation, m	Above the ground level	Above the ground level	Barge-mounted reactors	Above the ground level	Above the ground level
Containment type and dimensions, m	-Post-tensioned reinforced concrete containment of pressure suppression type, single or double; -Single: 43.2×44; -Multi-unit containment option.	Full double wall shell, single dome 39.6×53	-Primary rectangular steel containment 12×7.92×12; -Secondary containment: rectangular steel system of compartments, 15 000 m3.	Cylindrical, reinforced concrete, 36×57	Dry , double wall, in steel/concrete, 38×63.38
Co-generation options	N/A	Electricity and potable water	-Electricity and heat -Electricity and potable water	N/A	Electricity and potable water was considered for future design modifications
Non-electrical application process type	N/A	Hybrid multi-stage flash desalination and reverse osmosis (demonstration project, Kalpakkam)	Hybrid low temperature - high temperature multi-effect distillation/ reverse osmosis for desalination plant	N/A	High temperature multi-effect distillation
Plant surface area, m^2	48 700 for twin-unit EC6 of 1 470 MWe	-Not specified -Depends on the number of plants on a site	Coast: 8 000 Water area: 15 000	Not specified	Not specified

Table A1.2(a). Design specifications of advanced SMRs - pressurised water reactors

	CAREM-25	SMART	IRIS	IMR
Thermal/ electric output (gross), MW	100/ 27	330/100	1 000/ 335	1 000/ 350
Thermodynamic cycle type/efficiency	Indirect Rankine cycle/ 27 %	Indirect Rankine cycle/ 30.3%	Indirect Rankine cycle/ 33.5%	Indirect Rankine cycle on superheated steam/ 35%
Primary coolant, circulation mode	Light water, Natural	Light water, Forced	Light water, Forced	Boling light water, Natural
Primary pressure, MPa	12.25	15	15.5	15.51
Core inlet/outlet temperatures, ^{o}C	284/ 326	295.7/ 323	292/ 330	330/ 345
Core diameter×height, mm	Not specified×1400	1 831.6×2 000	2 410×4 267	2 950×3 650
Fuel type/ initial enrichment (%)	UO_2, 3.5% ^{235}U	UO_2, 4.8% ^{235}U	UO_2, 4.95% ^{235}U	UO_2, low enrichment by ^{235}U
Burn-up cycle duration, eff. full power days	330	864	915-1464	793
Average burn-up of discharged fuel, MWday/kg	35	36.1	60-70	46
Mode of reactivity control in operation	-Mechanical control rods with internal drives; -No liquid boron.	-Mechanical control rods with external drives; -Liquid boron.	-Mechanical control rods with internal drives -Liquid boron	-Mechanical control rods with internal drives; -No liquid boron.
Reactor vessel diameter×height, mm	3 430×11 000	5 994×16 162	6 780×21 300	4 370 and 6 550/ 17 260
Secondary pressure, MPa	4.7	5.2	6.4	5.0
SG secondary side inlet/outlet temperatures, ^{o}C	200/ 290	200/ 298	224/ 317	220/296
Turbine type	Single-stage condensing turbine	Two tandem combined type turbines	Available standard equipment	1×TC2F48
I&C system	Combined digital and analog	State-of-the-art digital Man-Machine Interface System	State-of-the-art PWR system	Based on newest PWR systems
Reactor unit and balance of plant elevation, m	Above the ground level	Above the ground level	-Nuclear island partly embedded underground, -13 m reactor vessel bottom; -Turbine building located on the ground level.	-Nuclear island is embedded underground -1.3 m reactor vessel top; -Turbine building is on the ground level.
Containment type and dimensions, m	Pressure-suppression type single reinforced concrete containment with embedded liner; Reactor building as a second containment.	Single steel lined concrete cylindrical containment, 44×68.5	Compact spherical steel containment, diameter: 25	Single cylindrical containment Diameter×height: 14.8x22.8
Co-generation options	Electricity and potable water	-Electricity and potable water; -Electricity and heat.	Various co-generation options possible	Various co-generation options possible
Non-electrical application process type	Reverse osmosis	Multi-effect distillation with thermal vapour compressor	Not specified	Not specified
Plant surface area, m^2	Not specified	99 800	141 000 for two twin-units (1 340 MWe)	4 900

Table A1.2 (b). Design specifications of advanced SMRs - pressurised water reactors

	ABV	VBER-300	mPower	NuScale	NHR-200
Thermal/ electric output (gross), MW	2x38/2x8.5	917/ 325	400/ 125 per module	160/ 48 per module 1 920/ 576 standard 12-module plant	200
Thermodynamic cycle type/efficiency	Indirect Rankine steam condensing cycle/ 21%	Indirect Rankine steam condensing cycle/ 33%	Indirect Rankine cycle/ 31.3%	Indirect Rankine cycle on superheated steam/ 30%	Dedicated reactor for heat production
Primary coolant, circulation mode	Light water, Natural	Light water, Forced	Light water, Forced	Light water, Natural	Light water, Natural
Primary pressure, MPa	15.7	16.3	13.1	10.7	2.5
Core inlet/outlet temperatures, ^{o}C	248/ 327	292/327.5	297/321	247.9/ 288.9	140/210
Core diameter×height, mm	1 155×1 200	2 285×3 530	2 000×2 030	Not specified, reduced height core	2 300×1 900
Fuel type/ initial enrichment (%)	UO_2 in inert matrix/ 18.7% ^{235}U	UO_2/ 4.95% ^{235}U	UO_2/ 5% ^{235}U	UO_2, 3-4% ^{235}U	UO_2, 1.8, 2.4 and 3.0 % ^{235}U
Burn-up cycle duration, eff. full power days	4 383	732	1 644	732	1 098
Average burn-up of discharged fuel, MWday/kg	49	47	40	62	30
Mode of reactivity control in operation	-Mechanical control rods with external drives; -Liquid boron.	-Mechanical control rods with external drives; -Liquid boron.	-Mechanical control rods with internal drives; -No liquid boron.	-Mechanical control rods with external drives; -Liquid boron.	Mechanical control rods with external (between vessels) drives
Reactor vessel diameter×height, mm	2 135×4 479	3 810×8 675	3 600×22 000	2 740x13 716	5 000×13 620, Double steel vessel
Secondary pressure, MPa	3.14	6.37	5.7	Not specified	3.0
SG secondary side inlet/outlet temperatures, ^{o}C	106/290	220/ 305	163/300	Not specified	135/170 (tertiary circuit); 127 (steam at the outlet of steam generator, 330 t/h).
Turbine type	Two condensing - extraction steam turbines, one per each reactor	One condensing-extraction steam turbine with intermediate separation and steam superheating	-Not specified, each module has its own turbine generator; -Air cooled condenser.	Available standard 45 MW turbine for each module	N/A
I&C system	Based on the state-of-the-art for PWR and marine reactors	Based on the state-of-the-art for PWR and marine reactors	Based on the state-of-the-art for PWR and marine reactors	State-of-the art PWR digital systems; One operator controls 4 reactors.	State-of-the-art digital systems and man-machine interfaces
Reactor unit and balance of plant elevation, m	Barge-mounted reactors	-Barge-mounted or land-based single or twin-units; -Land-based units located above the ground.	-The reactor modules are located under-ground; -Turbine building is on the ground level.	-Underground containment, control room and spent fuel pool, -18 m reactor vessel bottom; -Turbine building is on the ground level.	Reactor building partly embedded under-ground, -9 m reactor vessel bottom
Containment type and dimensions, m	-Primary rectangular steel containment 5.1×4×7.5; -Secondary containment: rectangular steel system of compartments.	-Primary cylindrical steel containment 34×48.9; -Secondary cylindrical reinforced concrete containment, 37×55.	-Cylindrical containment with spherical dome; -Secondary containment is provided by underground reactor building structures.	-Deep vacuum compact containment for each module, 4.570x18.290; -All modules submerged in a water pool.	Steel guard vessel acting as a containment, 5.84x15.1
Co-generation options	-Electricity and heat; -Electricity and potable water	-Electricity and heat; -Electricity and desalinated water (option).	N/A	-Process steam or potable water; -Load follow operation with variable potable water production rate.	-Electricity as an option; -Heat for district heating or centralised air conditioning; -Potable water.
Non-electrical application process type	Not specified	Not specified	N/A	Reverse osmosis for seawater desalination	Potable water: high temperature or low temperature multi effect distillation
Plant surface area, m^2	Coast: 6 000; Water area: 10 000	300 000 for a twin-unit land-based plant	Not specified, 4-module plant	156 300 for a 12-module plant	8 900

Table A1.3. Design specifications of advanced SMRs - boiling water reactors

	VK-300	**CCR**
Thermal/ electric output (gross), MW	750/250	1 268/423
Thermodynamic cycle type/efficiency	Direct Rankine cycle/ 33.3%	Direct Rankine cycle/ 32%
Primary coolant, circulation mode	Boiling light water, Natural	Boiling light water, Natural
Primary pressure, MPa	6.86	7.2
Core inlet/outlet temperatures, °C	190/ 284.5	278/ 287
Core diameter×height, mm	3 160x2 420	4 050×2 200
Fuel type/ initial enrichment (%)	UO_2, 4 % ^{235}U	UO_2, less than 5 % ^{235}U
Burn-up cycle duration, eff. full power days	437	732
Average burn-up of discharged fuel, MWday/kg	41.4	48
Mode of reactivity control in operation	Mechanical control rods	Mechanical control rods
Reactor vessel diameter×height, mm	4 535x13 100	5 754×19 504
Secondary pressure, MPa	N/A	N/A
SG secondary side inlet/outlet temperatures, °C	N/A	N/A
Turbine type	Single unit direct cycle two stage turbine	Standard equipment, 1×TCDF-41
I&C system	Based on VK-50 and VVER experience	Similar to, but simplified from, ABWR
Reactor unit and balance of plant elevation, m	Above the ground level	Above the ground level
Containment type, diameter×height, m	Double cylindrical containment with spherical dome	-Compact spherical-cylindrical primary containment, diameter×height: 13x24.;1 -Spherical stressed concrete building as secondary containment, width×length×height: 30x41.5x47.
Co-generation options	-Electricity and heat -Electricity and potable water possible	Various co-generation options possible
Non-electrical application process type	Not applicable Not specified	Not specified
Plant surface area, m^2	Not specified	5 000 (minimum)

Table A1.4. Design specifications of advanced SMRs - boiling light water cooled heavy water moderated reactors

	AHWR
Thermal/ electric output (gross) MW	920/ 300
Thermodynamic cycle type/efficiency	Direct Rankine cycle on nearly dry saturated steam/ 33%
Primary coolant, circulation mode	Boiling light water, Natural
Primary pressure, MPa	7.0
Core inlet/outlet temperatures, ^{o}C	259/ 285
Core diameter×height, mm	7 400×3 500
Fuel type/ initial enrichment (%)	Heterogeneous fuel assemblies: PuO_2-ThO_2: 2.5 and 4% Pu (homogenised), UO_2-ThO_2: 4.21% ^{235}U (homogenised)
Burn-up cycle duration, eff. full power days	On-line refuelling; Residence time: 1 644
Average burn-up of discharged fuel, MWday/kg	24
Mode of reactivity control in operation	Mechanical control rods
Reactor vessel diameter×height, mm	N/A (Pressure tube reactor)
Secondary pressure, MPa	N/A
SG secondary side inlet/outlet temperatures, ^{o}C	N/A
Turbine type	Steam turbine (for steam quality 99.75%)
I&C system	Best practice from PHWR
Reactor unit and balance of plant elevation, m	Above the ground level
Containment type, diameter×height, m	Reinforced concrete passively cooled double containment, ~ 55×75 m
Co-generation options	Electricity and potable water using reject heat
Non-electrical application process type	Low temperature multi-effect distillation
Plant surface area, m^2	9 000

Table A1.5. Design specifications of advanced SMRs - high temperature gas cooled reactors

	HTR-PM	PBMR old design	GTHTR300	GT-MHR
Thermal/ electric output (gross), MW	250/ 105	400/ 165	600/ 274	600/ 287
Thermodynamic cycle type/efficiency	Indirect Rankine steam turbine cycle with reheating/ 42%	Direct gas turbine Brayton cycle/ >41%	Direct gas turbine Brayton cycle/ >45%	Direct gas turbine Brayton cycle/ 48%
Primary coolant, circulation mode	Helium, forced	Helium, Forced	Helium, Forced	Helium, Forced
Primary pressure, MPa	7	9	7	7.07
Core inlet/outlet temperatures, ^{o}C	250/ 750	488/ 900	587/ 850	491/ 850
Core diameter×height, mm	Annular core: 2 000 and 3 700×11 000	Annular core: 2 000 and 3 700×11 000	Annular prismatic (hexagonal blocks) core: 3 700 and 5 500×8 000	Annular prismatic (hexagonal blocks) core: 3 000 and 4 800×7 900
Fuel type/ initial enrichment (%)	TRISO based pebble fuel, UO_2/ 8.77%	TRISO based pebble fuel, UO_2/ 9.6%	TRISO based pin-in-block fuel, UO_2/ 14%	TRISO based pin-in-block fuel, UCO/ 19.7% in fissile particles and 0 in fertile particles
Burn-up cycle duration, eff. full power days	On-line refuelling Residence time: 706	On-line refuelling	730	460
Average burn-up of discharged fuel, MWday/kg	80	>90	120	117
Mode of reactivity control in operation	Mechanical control rods (inserted in reflector area)	Mechanical control rods (inserted in reflector area)	Mechanical control rods (inserted in reflector area)	Mechanical control rods (inserted in reflector area)
Reactor vessel dimensions, mm	~7 000×23 840	6 560×30 000	7 940×24 300	7 840×31 200
Secondary pressure, MPa	14.2	N/A	N/A	N/A
SG secondary side inlet/outlet temperatures, ^{o}C	235.3/ 535	N/A	N/A	N/A
Turbine type	Commercially available steam turbine	Three-shaft horizontal gas turbine with oil bearings and dry gas seals	Horizontal shaft gas turbine	Vertical shaft gas turbine
I&C system	Not specified	State-of-the-art digital systems	State-of-the-art digital systems	State-of-the-art digital systems
Reactor unit and balance of plant elevation, m	Above the ground level	Above the ground level	All units installed below the ground level	Reactor and safety related buildings located underground
Containment type and dimensions, m	Citadel of the reactor building providing for pressure relief route	Citadel of the reactor building providing for pressure relief route	Citadel of the reactor building providing for pressure relief route	Citadel of the reactor building providing for pressure relief route
Co-generation options	Electricity only	-Electricity and hydrogen -Other options possible	-Electricity and hydrogen -Other options possible	-Electricity and hydrogen -Other options possible
Non-electrical application process type	N/A	Sulfur-Iodine process	Sulfur-Iodine process	Sulfur-Iodine process
Plant surface area, m^2	Not specified	11 639 for a 8-module plant of 1 320 MWe	Not specified	Not specified Standard configuration: 4-module plant of 1 148 MWe

Table A1.6. Design specifications of advanced SMRs - sodium cooled fast reactors

	4S
Thermal/ electric output (gross), MW	30/ 10
Thermodynamic cycle type/efficiency	Intermediate heat transport system (Na), Indirect Rankine cycle on superheated steam/ 33%
Primary coolant, circulation mode	Na, Forced
Primary pressure, MPa	0.3
Core inlet/outlet temperatures, ^{o}C	310/355
Core diameter×height, mm	950×2 500
Fuel type/ initial enrichment (%)	U-10Zr/ 17 and 19% ^{235}U
Burn-up cycle duration, eff. full power days	10 958
Average burn-up of discharged fuel, MWday/kg	34
Mode of reactivity control in operation	-Pre-programmed upward movement of carbon based radial reflector; -Feedwater flow rate change in the power circuit.
Reactor vessel diameter×height, mm	3 550×24 050, plus guard vessel
Secondary pressure, MPa	Steam circuit: 10.5
SG secondary side inlet/outlet temperatures, ^{o}C	Not specified/ 453
Turbine type	Available standard 10 MW equipment
I&C system	All sensors located in the primary coolant system
Reactor unit and balance of plant elevation, m	Reactor and steam generators just below the surface level, turbine generator - just above the surface level
Containment type, diameter×height, m	Guard vessel plus top dome/3.65 (diameter)
Co-generation options	Electricity and potable water or hydrogen
Non-electrical application process type	-Two-stage reverse osmosis for potable water; -High temperature electrolysis for hydrogen.
Plant surface area, m^2	Not specified

Table A1.7. Design specifications of advanced SMRs - lead-bismuth cooled fast reactors

	SVBR-100	**PASCAR**	**New Hyperion Power Module**
Thermal/ electric output (gross), MW	280/ 101.5	100/ 37	70/ 25
Thermodynamic cycle type/efficiency	Indirect Rankine cycle on saturated steam / 36%	Indirect Rankine cycle on superheated steam / 37%	Indirect Rankine cycle on superheated steam/ 36%
Primary coolant, circulation mode	Pb-Bi, Forced	Pb-Bi, Natural	Pb-Bi, Forced
Primary pressure, MPa	1×10^{-2}	0.1	Not specified
Core inlet/outlet temperatures, ^{o}C	320/ 482	320/ 420	Not specified/ 500
Core diameter×height, mm	1 645×900	2 062.7×1 000	1 500×2 000
Fuel type/ initial enrichment (%)	UO_2, 16.1% ^{235}U	U-TRU-Zr/ TRU: 14.5 and 20.14%	UN, less that 20% ^{235}U
Burn-up cycle duration, eff. full power days	2 557-2 922	7 305	1 826-5 479 (3 653 on average)
Average burn-up of discharged fuel, MWday/kg	67	70	Not specified
Mode of reactivity control in operation	Mechanical control rods	Mechanical control rods	Mechanical control rods
Reactor vessel diameter×height, mm	4 530×6 920	3 846×9 663, plus guard vessel	Reactor vessel and guard vessel
Secondary pressure, MPa	9.5	Not specified	Not specified
SG secondary side inlet/outlet temperatures, ^{o}C	241/307	Not specified	Not specified
Turbine type	Available standard equipment	Available standard equipment	Available standard equipment
I&C system	Similar to Na cooled reactors, special coolant chemistry control	Redundant digital elements and reliable power supplies	Not specified
Reactor unit and balance of plant elevation, m	Not specified, depends on plant configuration	-Reactor building embedded underground; -Steam turbine building located on the ground level.	-Reactor building and steam generator embedded underground; -Steam turbine building located on the ground level.
Containment type, diameter×height, m	Depends on plant configuration, reinforced concrete for multi-module plants	Double underground containment (guard vessel provides one of the containments)	Double containment
Co-generation options	Electricity and heat or potable water or process steam	Various co-generation options possible	Various co-generation options possible
Non-electrical application process type	No details specified	No details specified	No details specified
Plant surface area, m^2	Not specified, depends on plant configuration	Not specified	Not specified

Appendix 2. Safety Design Features of Advanced SMRs

Table A2.1(a). Safety design features of advanced SMRs - pressurised water reactors

<table>
<tr><th></th><th>KLT-40S</th><th>CAREM-25</th><th>SMART</th><th>IRIS</th><th>IMR</th></tr>
<tr><td rowspan="4">Inherent and passive safety features</td><td colspan="5">-Negative reactivity coefficients over the whole cycle;
-Relatively large coolant inventory and high heat capacity of the primary circuit or nuclear installation as a whole;
-Level of natural circulation sufficient for passive decay heat removal from a shut down reactor;
-Steam generators with secondary (lower pressure) coolant inside tubes.</td></tr>
<tr><td rowspan="3">-Compact modular design with no long pipelines;
-Leak tight reactor coolant system;
-Leak restriction devices in primary pipelines;
-'Soft" pressuriser system*;
-No reactivity control by liquid boron;
-Design facilitating implementation of leak before break concept;
-Once-through steam generators.</td><td colspan="4">-Integral design of primary circuit with in-vessel location of steam generators and self-pressurisation;
-Relatively low core power density.</td></tr>
<tr><td colspan="3">-Steam generators designed for full primary pressure.</td><td rowspan="2">-In-vessel control rod drive mechanisms;
-Natural circulation of the primary coolant in all modes with boiling allowed in the upper part of the core;
-Reduction in the number of safety systems (elimination of emergency core cooling system and containment spray system).</td></tr>
<tr><td>-In-vessel hydraulic control rod drive mechanisms;
-Natural circulation heat removal in all operation modes;
-No reactivity control by liquid boron;
-Low linear heat rate of fuel elements in the event of core uncovery.</td><td>-Canned in-vessel coolant pumps;
-Relatively low core flow resistance;
-Modular once-through steam generators located relatively high above the core to enhance natural circulation flow;
-Xenon oscillation instability eliminated by design.</td><td>-In-vessel control rod drive mechanisms;
-Internal, fully immersed pumps;
-Very low leakage containment with minimised penetrations.</td></tr>
<tr><td>Reactor shutdown systems</td><td>-Control rod insertion driven by electric motor;
-Control rod insertion driven by gravity;
-Control rod insertion driven by springs.</td><td>-Control rod insertion driven by gravity;
-Gravity driven high pressure borated water injection.</td><td>-Control rod insertion upon de-energisation, driven by gravity;
-Redundant passive safety injection system (water with liquid boron).</td><td>-Non-safety-grade control rod system with internal control rod drives;
-Injection of borated water from the emergency boron tank at high pressure.</td><td>-Control rod insertion driven by gravity;
-Borated water injection system driven by pressure.</td></tr>
<tr><td rowspan="2">Decay heat removal and depressurisation systems</td><td colspan="5">-Normal operation active/ passive heat removal system.</td></tr>
<tr><td>-Redundant and diverse active and passive core cooling systems</td><td>-Redundant natural circulation driven passive residual heat removing system;
-Emergency injection system with borated water to prevent core uncovery;
-Safety relief valve.</td><td>-Redundant and diverse active and passive core cooling systems;
-Reactor overpressure protection system (with safety valves).</td><td>-Redundant passive emergency decay heat removal system;
Indirect core cooling via containment cooling;
-Long-term gravity make-up system;
-A small automatic depressurisation system from the pressuriser steam space;
Safety relief valve.</td><td>-Active residual heat removal system;
-Active steam generator cooling system;
-Passive reactor vessel decompression system.</td></tr>
</table>

	KLT-40S	CAREM-25	SMART	IRIS	IMR
Reactor vessel and containment cooling systems	-Passive containment cooling system; -Passive system of reactor vessel bottom cooling.	-Suppression pool type containment; -Suppression pool cooling and purification system; Injection of water into reactor cavity.	-Containment spray system; -Severe accident mitigation system for containment and reactor vessel cooling.	-Pressure suppression containment system; -Passive flooding of the reactor cavity following a small LOCA; -Diverse active means of containment cooling.	-Passive containment vessel water injection system; -Passive containment vessel flooding system.
Seismic design	-3 g PGA** for the equipment and systems; -7 on MSK scale for 10-2 year-1 frequency; -8 on MSK scale for 10-4 year-1 frequency.	-0.4 g PGA; -Compliance with the IAEA guides	0.3 g PGA (Safe Shutdown Earthquake)	0.5 g PGA	Similar to the state-of-the-art Japanese PWRs S1:180 Gal***, S2:308 Gal×1.8
Aircraft crash design	Helicopter crash landing and fall of an aircraft from high altitude considered in the design	Not considered (appropriate site selection and administrative measures)	Not specified	-Not considered (appropriate site selection and administrative measures); -Small spherical containment is half embedded underground.	Provided by compact containment and reactor building
Core damage frequency/ Large early release frequency, year^{-1}	10^{-5} (10^{-7} for internal events at the start-up of operation)/10^{-6}	<10^{-6}/5.2×10^{-8}	10^{-7}/10^{-8}	2×10^{-8}/ Not specified	0.6~2.9×10^{-7}/ Not specified
Emergency planning zone radius (evaluated)	1 km, evacuation of population is not required at any distance from the plant	Simplified or abandoned off-site emergency planning requirements	Not specified	About 2 km (site dependent)	Not specified
Special events considered in safety design	-Collision of a floating power unit (FPU) with other ships; -Sinking of the FPU; -FPU landing on a rocky ground, etc.	Nothing applies here	Nothing applies here	Nothing applies here	Nothing applies here
Compliance with the current regulations	Being designed or have been designed in compliance with the current national regulations				
	Nothing in particular specified here	Being designed in compliance with the current risk-informed national regulations	Nothing in particular specified here	Future risk-informed regulations would facilitate justifying reduced emergency planning requirements	Nothing in particular specified here

* “Soft” pressuriser system is characterised by small changes of the primary pressure under a primary coolant temperature increase. This quality, due to a large volume of gas in the pressurising system, results in an increased period of pressure increase up to the limit value under the total loss of heat removal from the primary circuit. ** PGA = Peak Ground Acceleration. *** Gal = Galileo unit = cm/sec^2; g = 980 Gal; S1 = Operating basis earthquake, S2 = Safe shutdown earthquake.

Table A2.1(b). Safety design features of advanced SMRs - pressurised water reactors

<table>
<tr><th></th><th>VBER-300</th><th>ABV</th><th>mPower</th><th>NuScale</th><th>NHR-200</th></tr>
<tr><td rowspan="4">Inherent and passive safety features</td><td colspan="5">-Negative reactivity coefficients over the whole cycle;
-Relatively large coolant inventory and high heat capacity of the primary circuit or nuclear installation as a whole;
-Level of natural circulation sufficient for passive decay heat removal from a shut down reactor;
-Relatively low core power density.</td></tr>
<tr><td rowspan="3">-Connecting the majority of primary circuit pipelines to "hot" sections of the circuit and arranging the nozzles on the reactor vessel above the core level;
-Short load-bearing nozzles between the main equipment units, without lengthy large-diameter primary pipelines;
-Small-diameter flow restrictors in the nozzles of primary circuit auxiliary systems;
-Canned main circulation pumps.</td><td colspan="4">-Integral design of primary circuit with in-vessel location of steam generators (heat exchangers).</td></tr>
<tr><td colspan="3">-Steam generators with secondary (lower pressure) coolant inside tubes.</td><td rowspan="2">-Self-pressurisation;
-Intermediate heat circuit with pressure higher than the primary pressure (to keep the heating grid free from radioactivity);
-Natural circulation of primary coolant in all operating modes;
-Dual pressure vessel with all penetrations located at the top;
-Control rod drives located in a gap between main and guard vessel;
-Low pressure and low temperature of the primary coolant.</td></tr>
<tr><td>-Natural circulation of the coolant in the primary circuit;
-Primary systems connected to the top part of the reactor vessel;
-Flow restrictors in the nozzles connecting the primary circuit systems with the reactor;
-Leak tight reactor coolant system;
-High thermal conductivity of the fuel composition;
-Gas pressuriser system that excludes failures of the electric heaters;
-Design facilitating implementation of leak before break concept.</td><td>-Self-pressurisation;
In-vessel control rod drives;
-Small diameter tall reactor vessel to prevent core uncovery;
-Each module has its own containment.</td><td>-Self-pressurisation;
-Natural circulation of the primary coolant in all operating modes;
-Each module has its own high pressure containment vacuumed during normal operation'
-Modules in their individual containments are fully submerged in a water pool.</td></tr>
<tr><td>Reactor shutdown systems</td><td>-Control rod insertion driven by electric motor;
-Control rod insertion driven by gravity;
-Gravity driven injection of borated water.</td><td>-Control rod insertion driven by electric motor;
-Control rod insertion driven by gravity;
-Control rod insertion driven by springs.</td><td>Mechanical control rods.</td><td>Mechanical control rods.</td><td>-Mechanical control rods with hydraulic drives;
-Liquid boron safety injection, driven by gravity.</td></tr>
<tr><td rowspan="2">Decay heat removal and depressurisation systems</td><td colspan="5">-Normal operation active/ passive heat removal system.</td></tr>
<tr><td>Redundant and diverse passive emergency heat removal systems and emergency core cooling systems</td><td>Redundant and diverse active and passive core cooling systems</td><td>-Passive (gravity drive) emergency core cooling system;
-Clean-up valve.</td><td>Each module includes redundant passive Decay Heat Removal System (DHRS) and shutdown accumulator</td><td>-Redundant passive residual heat removal system;
-Isolation valves to limit consequences of heat exchanger tube rupture.</td></tr>
<tr><td>Reactor vessel and containment cooling systems</td><td>-Passive reactor vessel cooling system;
-Emergency containment cooling system.</td><td>-Passive containment cooling system;
-Passive reactor vessel bottom cooling system.</td><td>Not specified</td><td>-Each module includes redundant passive Containment Heat Removal System (CHRS);
-Pool of water in a stainless steel lined concrete structure that is entirely below grade, with all reactor modules submerged into it</td><td>Passive containment cooling system.</td></tr>
</table>

	VBER-300	ABV	mPower	NuScale	NHR-200
Seismic design	-3g PGA for the equipment and systems; -7 on MSK scale for 10^{-2} $year^{-1}$ frequency; -0.2 PGA, 8 on MSK scale for 10^{-4} $year^{-1}$ frequency.	-3g PGA for the equipment and systems; -7 on MSK scale for 10^{-2} $year^{-1}$ frequency; -8 on MSK scale for 10^{-4} $year^{-1}$ frequency.	Not specified	0.7g PGA for Safe Shutdown Earthquake	Not specified
Aircraft crash design	Aircraft 20 tons, 200 m/s, 10^{-7}/year (Helicopter $1.5x10^{-7}$/year)	Helicopter crash landing and fall of an aircraft from high altitude considered in the design	Underground location of reactor modules in containments with secondary containment provided by structures of the underground reactor building	Underground containment, control room and spent fuel pool	Not specified
Core damage frequency/ Large early release frequency, $year^{-1}$	$10^{-6}/10^{-7}$	$10^{-6}/10^{-7}$	Not specified	10^{-8}/ Not specified	$10^{-8}/10^{-9}$
Emergency planning zone radius (evaluated)	1 km	1 km, evacuation of population is not required at any distance from the plant	Location in proximity to the users being envisaged	Simplified off-site emergency planning requirements being considered	Not specified
Special events considered in safety design	For a FPU with VBER-300: -Collision of a floating power unit (FPU) with other ships; -Sinking of the FPU; -FPU landing on a rocky ground, etc.	-Collision of a floating power unit (FPU) with other ships; -Sinking of the FPU; -FPU landing on a rocky ground, etc.	Nothing applies here	Nothing applies here	Nothing applies here
Compliance with the current regulations	Being designed or have been designed to comply with the current national regulations				

Table A2.2. Safety design features of advanced SMRs - boiling water reactors

	VK-300	CCR
Inherent and passive safety features	-Negative reactivity coefficients over the whole cycle; -Top-mounted control rod drives with vessel penetrations in the top part of the reactor vessel; -Large coolant inventory in the reactor vessel to assure the reactor core is not uncovered in LOCA; -Natural circulation of coolant in all operating modes; -In-vessel separator unit.	
	-Relatively low linear heat rate of fuel elements.	-High pressure compact pressure containment vessel preventing a large coolant inventory loss from the reactor vessel in case of a pipe break accident; -Low power density in the core; -Reduction in the number of safety systems (elimination of high pressure and low pressure core flooding systems).
Reactor shutdown systems	-Two independent systems with mechanical control rods; -Liquid boron shutdown system.	-Mechanical control rods; -Liquid boron injection.
Decay heat removal and depressurisation systems	-Active or passive normal operation heat removal systems	
	-Passive, gravity driven emergency core cooling system; -Passive residual heat removal system; -Overpressure protection and depressurisation system.	-Residual heat removal system; -Isolation condenser; -Flooder lines to return water to the reactor pressure vessel, driven by gravity; -Safety valve.
Reactor vessel and containment cooling systems	-Isolation condensers and pressure suppression system; -System of heat removal to the ultimate heat sink.	-Forced airflow over the outer surface of the pressure containment vessel steel wall (in normal operation); -Isolation condenser (in accidents).
Seismic design	7 on MSK scale	Similar to the state-of-the-art Japanese PWRs
Aircraft crash design	20t aircraft, double containment	-Dome-shaped containment building, or -Completely-buried building.
Core damage frequency/ Large early release frequency, year^{-1}	Not specified/ $2x10^{-8}$	$10^{-5}/10^{-6}$
Emergency planning zone radius (evaluated)	No need for off-site emergency measures	Reduced or eliminated off-site emergency planning (subject to proof of in-vessel retention capability)
Compliance with the current regulations	Being designed of have been designed in compliance with the current national regulations	

Table A2.3. Safety design features of advanced SMRs - boiling light water cooled heavy water moderated reactors

	AHWR
Inherent and passive safety features	-Slightly negative void coefficient of reactivity and negative temperature coefficient of reactivity; -Natural circulation heat removal in all operating modes; -Relatively low core power density; -Low excess reactivity owing to the type of fuel (in the case of Pu-Th based fuel) and on-line refuelling; -Large coolant inventory in the main coolant system; -Large inventory of water inside the containment, in the gravity driven water pool (GDWP); -Heavy water moderator as a heat sink.
Reactor shutdown systems	-Two independent and diverse shutdown systems, one based on mechanical control rods, and another employing injection of liquid poison into low pressure moderator; of 100% shutdown capacity each; -Additional passive shutdown device for the injection of a poison using steam pressure.
Decay heat removal and depressurisation systems	-Passive injection of cooling water, first from the accumulator and later from the overhead GDWP, directly into the fuel cluster through four independent parallel trains; -Passive decay heat removal system, which transfers decay heat to GDWP using natural convection.
Reactor vessel* and containment cooling systems	-Flooding of the reactor cavity following a LOCA; -Passive containment isolation system; -Passive containment cooling system; -Vapour suppression in GDWP.
Seismic design	Designed for high level and low probability seismic events
Aircraft crash design	Double reinforced concrete containment
Core damage frequency/ Large early release frequency, year^{-1}	10^{-6}/ $<10^{-7}$
Emergency planning zone radius (evaluated)	No off-site emergency planning
Compliance with the current regulations	Being designed in compliance with the current national regulations based on IAEA safety standards.

* AHWR is a pressure tube reactor having no reactor vessel; therefore, the inputs in this line correspond to the reactor cavity.

Table A2.4. Safety design features of advanced SMRs - high temperature gas cooled reactors

	HTR-PM	PBMR old design	GTHTR300	GT-MHR
Inherent and passive safety features	-Negative reactivity feedbacks on temperature and power increase; -Use of tri-isotropic (TRISO) coated particle based fuel reliable at high temperatures and fuel burn-ups; -Use of chemically inert helium coolant with neutral neutronic properties; -Relatively low core power density; -Large volume of graphite inside the reactor vessel, contributing to thermal inertia of the reactor core and heat transfer via radiation and conduction, securing the option of heat removal from the core in the absence of helium coolant; -Helium loss not leading to core damage and radioactivity release; -Relatively large surface area of the reactor pressure vessel; -No large diameter pipelines in the primary circuit; -Leak tight (primary) coolant system.			
	-Small excess reactivity owing to on-line refuelling;		Nothing specified here	
Reactor shutdown systems	Two diverse and independent passive shutdown systems, one based on gravity driven insertion of control rods and another one on gravity driven insertion of absorber pellets	-Electromechanical insertion of control rods; -Drop down of boron carbide pellets.	Two diverse and independent passive shutdown systems, one based on gravity driven insertion of control rods and another one on gravity driven insertion of absorber pellets	-Two diverse and independent passive shutdown systems, one based on gravity driven insertion of control rods and another one on gravity driven insertion of absorber balls; -One active electromechanical control rod system of normal operation, capable of reactor shutdown.
Decay heat removal and depressurisation systems	-Active normal operation cooling system with helium blower, compressor and turbine, or helium blower and steam generators (for normal shutdown); -Residual heat removal from the core based on natural processes of conduction, radiation and convection, ending up with heat removal from outside of the reactor vessel by passive reactor cavity cooling system; -Helium release allowed at early stages of an accident, provided by overpressure protection (helium release) system.			
	Secondary water discharge system for the case of steam generator tube rupture.	Nothing specified here		
Reactor vessel and containment cooling systems	Passive reactor cavity cooling system using water panels mounted on a concrete wall.	-Passive reactor cavity cooling system using water pipes; -Confinement pressure relief system.	-Redundant passive reactor cavity cooling system by air; -Forced shutdown cooling system.	Redundant passive reactor cavity cooling system by water
Seismic design	Not specified	0.4 g horizontal PGA	Not specified	0.2g horizontal PGA, 8 MSK
Aircraft crash design	Double citadel of the reactor building.	Aircraft crash, < 2.7 t	-Double citadel of the reactor building -All NPP buildings located underground	-Citadel of the reactor building -Reactor and safety related buildings located underground
Core damage frequency/ Large early release frequency, $year^{-1}$	Not specified	Not specified / $<10^{-6}$	Not specified/$<10^{-8}$	$<10^{-5}$/$<10^{-7}$
Emergency planning zone radius (evaluated)	Reduced or completely abandoned off-site emergency planning	400 m	Not specified	No off-site emergency measures required in any accident
Compliance with the current regulations	Being designed or have been designed in compliance with the current national regulations			

Table A2.5. Safety design features of advanced SMRs - sodium cooled fast reactors

	4S
Inherent and passive safety features	-Low pressure primary coolant system; -Intermediate heat transport system; -Large negative feedbacks from fast spectrum core and from effective radial expansion of the core; negative whole-core void worth; -Pool type design with intermediate heat exchangers located inside the main reactor vessel; -Metallic fuel with high thermal conductivity; -Large specific (per unit of power) inventory of the primary coolant and large thermal inertia of the coolant and the shielding structure, owing to a relatively low linear heat rate of fuel; -The reactor vessel enclosed in a guard vessel to prevent loss of the primary coolant; -Use of double piping, double tubes and double vessels for the secondary sodium, including heat transfer tubes of the steam generator. -Burn-up reactivity compensation by very slow pre-programmed upper movement of the graphite based reflector; -Effective mechanism of fuel carry-over from the core in the case of fuel element cladding failure.
Reactor shutdown systems	-Two independent systems of reactor shutdown, each capable of shutting down the reactor by: -A drop of several sectors of the reflector; or -Gravity-driven insertion of the ultimate shutdown rod. -Passive shutdown capability*.
Decay heat removal and depressurisation systems	Redundant and diverse passive auxiliary cooling systems (IRACS or PRACS)**, both using draught of environmental air as an ultimate heat sink
Reactor vessel and containment cooling systems	Redundant passive auxiliary cooling system (RVACS)***, both using draught of environmental air as an ultimate heat sink
Seismic design	-Reactor building isolated horizontally; -Tiny shaped reactor has higher characteristic frequency (protection against vertical shock).
Aircraft crash design	The reactor located in a concrete- covered silo below the ground level.
Core damage frequency/ Large early release frequency, year^{-1}	10^{-6}/ Not specified
Emergency planning zone radius (evaluated)	No off-site emergency planning
Compliance with the current regulations	Being designed in compliance with the current US regulations

* "Passive shutdown" capability is the capability to bring the reactor to a safe low power state with balanced heat production and passive heat removal, and with no failure to barriers preventing radioactivity release to the environment; all relying on the inherent and passive safety features only, and with practically indefinite grace period. ** IRACS = Intermediate reactor auxiliary cooling system, PRACS = Primary reactor auxiliary cooling system. *** RVACS = Reactor vessel auxiliary cooling system.

Table A2.6. Safety design features of advanced SMRs - lead-bismuth cooled fast reactors

<table>
<tr><th></th><th>SVBR-100</th><th>PASCAR</th><th>New Hyperion Power Module</th></tr>
<tr><td rowspan="3">Inherent and passive safety features</td><td colspan="3">-Low pressure primary coolant system;
-Chemical inertness of Pb-Bi in water and air;
-Negative (optimum) reactivity feedbacks;
-Pool type reactor with large heat capacity of the primary circuit ;
-High level of natural circulation sufficient to remove decay heat from the core;
-LOCA excluded by design (very high boiling temperature of Pb-Bi, reactor vessel and guard vessel, etc.).</td></tr>
<tr><td rowspan="2">-Very low reactivity margin for fuel burn-up achieved via high conversion of fissile materials;
-Guard vessel located in a water pool to secure self-curing of cracks;
-Primary coolant flow path eliminating an option of steam bubbles getting into the core.</td><td colspan="2">-Natural circulation of primary coolant in all operating modes;
-Passive shutdown capability.</td></tr>
<tr><td>-Low core power density;
-Passive guard vessel cooling by air flow.</td><td>-Multiple containment;
-Control rods/absorber balls isolated from Pb-Bi coolant;
-Solid phase oxygen control system used to control the oxygen level in the coolant (to prevent corrosion).</td></tr>
<tr><td>Reactor shutdown systems</td><td>-Control rods inserted to the core driven by gravity, upon de-energisation;
-Control rods inserted driven by force of springs;</td><td>-Passive insertion of control rods;
-Insertion of boron stainless steel balls, driven by gravity.</td><td>-Active system of mechanical control rods;
-Passive system with absorber balls inserted in dedicated cavity in central part of the core, driven by gravity.</td></tr>
<tr><td rowspan="2">Decay heat removal and depressurisation systems</td><td colspan="3">-Normal operation active/passive heat removal systems</td></tr>
<tr><td>-Two passive decay heat removal systems;
-Passive heat removal via convection and boiling of water surrounding the outer reactor vessel;
-Steam generator leak localising system.</td><td>-Decay heat removed passively by the reactor vessel auxiliary cooling system;
-Steam line isolation valves.</td><td>-Passive heat removal via convection and boiling of water surrounding the outer reactor vessel.</td></tr>
<tr><td>Reactor vessel and containment cooling systems</td><td>Passive heat removal via convection and boiling of water surrounding the outer reactor vessel.</td><td>Reactor vessel auxiliary coolant system by natural draught of air.</td><td>-Passive heat removal via convection and boiling of water surrounding the outer reactor vessel;
-Redundant and diverse active and passive cooling systems, including those for safe transportation of sealed reactor module back to the factory.</td></tr>
<tr><td>Seismic design</td><td>Water tank with reactor mono-block acting as a seismic resistant structure.</td><td>0.3g PGA, 3D seismically isolated building.</td><td>Not specified</td></tr>
<tr><td>Aircraft crash design</td><td>Not specified</td><td>Not specified</td><td>Underground location of reactor module</td></tr>
<tr><td>Core damage frequency/ Large early release frequency, year^{-1}</td><td>Not specified</td><td>$10^{-7}/10^{-8}$</td><td>Very low</td></tr>
<tr><td>Emergency planning zone radius (evaluated)</td><td>Not specified</td><td>Not specified</td><td>Location in close proximity to the users envisaged</td></tr>
<tr><td>Compliance with the current regulations</td><td colspan="3">Being designed in compliance with the current national regulations</td></tr>
</table>

Appendix 3. Additional Economic Tables

Table A3.1. Designers' cost data for water cooled SMRs*

SMR [Source]	Unit power MWth	Overnight capital cost USD 2009/kWe (year)	LUEC** USD cent/kWh (year)	Levelised heat cost USD/GCal (year)	Levelised desalinated water cost USD cent/m³ (year)
PWRs					
ABV N [4.2, 4.18]	38	9 100 (2009)	≤12 (2009)	≤45 (2009)	≤155 (2009)
CAREM-25 [4.1, 4.30]	116	3 148 (2004)	~3.8*** at 8% DR (2005)	n/a	73.8*** at 8% DR (2005)
KLT-40S [4.16]	150	3 500-4 000 (2006)	4.5-5 (2006)	20-22 (2006)	80-90 (2006)
NHR-200 [4.9, 4.25]	200	550 (1991)	n/a	-	65-85 (2008)
SMART [4.1, 4.19]	330	-	6 (2009)	n/a	70 (2009)
CAREM-125 [4.1]	375	1 700 (2004)	-	n/a	n/a
CAREM-300**** [4.1]	900	1 050 (2004)	-	n/a	n/a
VBER-300 twin-unit [4.1, 4.24]	917	2 800 barge 3 500 land (2009)	3.3 barge 3.5 land (2009)	18 (2009)	n/a
QP300 two units average [4.32]	1 000	2 769 Pakistan (2007-8)	-	n/a	n/a
IRIS N [4.1]	1 000	1 030-1 240 IC (2004)	3-4 (2004)	n/a	n/a
CNP-600 [4.33]	1 936	1 330 (2002)	-	n/a	n/a
BWRs					
VK-300 [4.1]	750	867 (2001)	1.0 (2001)	3.33 (2001)	n/a
CCR [4.31]	1 268	2 980-4 000 (2008)	4.97 (2010)	n/a	n/a
HWRs/AHWRs					
PHWR-220 [4.30, 4.34]	862	1 300-1 500 (2006)	3.7 (2006) 4.5 at 7% DR (2005)	n/a	94-95 at 7% DR (2005)
AHWR [4.1, 4.35]	920	1 070 F (2001)	2.5 single 2.33 four plants (2008)	n/a	-
CANDU-6 twin-unit [4.32, 4.36]	2 064	3 500 (2007-8)	2.96 Canada 2.67 China (2002)	n/a	n/a

Notes: * IC - investment cost, F - first-of-a-kind plant, N - n^{th}-of-a-kind plant, barge - barge-mounted plant, land - land-based plant. ** At a 5% discount rate by default. *** CAREM-D is a co-generation version of the CAREM-25. **** For CAREM-300, the sum of the operation and maintenance (O&M) and fuel cycle costs is 1.25 USD cents/kWh in 2004 USD or 1.41 USD cents/kWh in 2009 USD; for other water cooled SMR there is no reliable data on O&M and fuel cycle costs.

Table A3.2. Designers' cost data for non water cooled SMRs*

SMR [Source]	Unit power MWth	Overnight capital cost USD/kWe (year)	Operation and maintenance (O&M) cost, USD cents/kWh (year)	Fuel cost, USD cents/kWh (year)	LUEC USD cent/kWh (year)	Levelised heat cost USD/GCal (year)	Levelised desalinated water cost USD cent/m³ (year)	Levelised hydrogen cost USD/kg (year)
HTGRs								
HTR-PM [4.1, 4.17]	250	2 000 F <1 500 N (2009)	0.76 (2004)	1.09 (2004)	4.5 (2004)	n/a	n/a	n/a
PBMR (previous design) [4.1]	400	<1 500 N (2004)	0.9 O&M+Fuel (2004)	As large LWR	n/a	n/a	-	
GT-MHR [4.1]	600	1 460 F 1 000 N (2003)	0.3 (2003)	0.74 (2003)	3.1 (2003)	n/a	-	1.6 (2003)
GTHTR300 [4.1]	600	<200 000 Yen/kWe (2001)	-	-	<4 Yen/kWh (2001)	-	-	-
Sodium cooled fast reactors								
4S [4.2]	30	-	-	-	10.4-24.3 (2001)	n/a	-	-
Lead-bismuth cooled fast reactors								
PASCAR [4.37, 4.38]	100	-	-	-	10 N (2009)	n/a	n/a	n/a
SVBR-100 [4.2]	280	1 000 prototype (2000)	-	-	1.46 for 1 600 MWe plant (1999) 3.5 for 400 MWe plant (2002)	-	74 for 400 MWe plant (2002)	n/a

* IC - investment cost, F - first-of-a-kind plant, N - n[th]-of-a-kind plant, barge - barge-mounted plant, land - land-based plant.

Table A3.3. GDP deflation data (reference [4.39] for USD; reference [4.40] for Japanese Yen).

Year	Deflation factor (USD)	Year	Deflation factor (USD)	Year	Deflation factor (USD)	Year	Deflation factor (USD)
1991	1.47	2001	1.21	2004	1.13	2007	1.03
1999	1.27	2002	1.19	2005	1.10	2008	1.01
2000	1.24	2003	1.17	2006	1.06	2009	1.0

Year	Deflation factor (Japanese Yen)	Year	Deflation factor (Japanese Yen)	USD/Yen exchange rate (2009)
2001	1.094	2009	0.916	0.011

Table A3.4. OVC for the various plant configurations obtained by multiplication of the OVC for single SMR plants by relevant factors

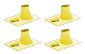
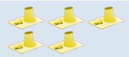
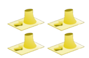
Plant configuration		OVC single-SMR plant *Table 7.1* *USD/kWe*	Twin-unit factor *(6.9)*	Factor for two twin-units *(6.10)*	Multi-module plant factor *Section 6.2.5*	Barge-mounted plant factor *(6.12)*	OVC for selected plant configuration USD/kWe
		Factor value:	0.87-0.93	0.81-0.9	0.83-0.85	0.8	
PWR-8 twin-unit barge-mounted		**27 600 ×**	24 000-25 700	-	-	19 200-20 600	**=19 200-20 600**
PWR-35 twin-unit barge-mounted		**13 300 ×**	11 600-12 400	-	-	9 270-9 910	**=9 270-9 910**
PWR-90(1) single module plant		**4 970 ×**	-	-	-	-	**=4 970**
PWR-90(2) single module plant		**5 070 ×**	-	-	-	-	**=5 070**
PWR-125(1) five or six module plant		**9 225 ×**	8 025-8 580	-	6 660-7 292	-	**=6 660-7 292**
PWR-302 twin-unit barge-mounted		**4 630 ×**	3 430-3 470	-	-	3 230-3 450	**=3 230-3 450**
PWR-302 twin-unit land-based		**4 630 ×**	-	3 750-4 170	-	-	**=3 750-4 170**
PWR-335 two twin-units		**5 690 ×**	-	4 610-5 120	-	-	**=4 610-5 120**

Table A3.5. Investment component of LUEC for the various SMR plant configurations

Plant configuration	Total electric output of the plant (net) MWe	Plant lifetime Years/ Availability	Investment cost at 5 % discount rate *Table 7.2* USD/kWe	Investment component of LUEC at 5% discount rate USD/MWh	Investment cost at 10% discount rate *Table 7.2* USD/kWe	Investment component of LUEC at 10% discount rate USD/MWh
PWR-8 twin-unit barge-mounted	15.8	50/80%	21 800-23 300	170-182	24 500-26 200	353-378
PWR-35 twin-unit barge-mounted	70	40/85%	10 500-11 200	82-88	11 800-12 700	163-174
PWR-90(1) single module plant	90	60/90%	5 490	37	6 040	77
PWR-90(2) single module plant	90	60/90%	5 600	38	6 150	78
PWR-125 five module plant	625-750	60/90%	7 350-8 046	47-51	8 085-8 851	94-102
PWR-302 twin-unit barge-mounted	604	60/92%	3 650-3 900	24-26	4 120-4 400	51-55
PWR-302 twin-unit land-based	604	60/92%	4 250-4 720	28-31	4 790-5 320	60-66
PWR-335 two twin-units	1 340	60/96%	5 086-5 651	30-34	5 595-6 216	61-67

Table A3.6. O&M and fuel components of LUEC for the various SMR plant configurations

Large reactor used a reference [7.1]	O&M +Fuel cost for large reactor, USD/MWh	Plant configuration		O&M + Fuel cost for SMR plant configuration, USD/MWh
VVER-1150	20.7 at 5 % discount rate 20.9 at 10% discount rate	PWR-8 twin-unit barge-mounted		31.1 at 5 % discount rate 31.4 at 10% discount rate
VVER-1150	20.7 at 5 % discount rate 20.9 at 10% discount rate	PWR-35 twin-unit barge-mounted		31.1 at 5 % discount rate 31.4 at 10% discount rate
APR-1400	16.9	PWR-90(1) single module plant		16.9
OPR-1000	18.3	PWR-90(2) single module plant		18.3
Advanced Gen. III+	22.2	PWR-125(1) five module plant		22.2
VVER-1150	20.7 at 5 % discount rate 20.9 at 10% discount rate	PWR-302 twin-unit barge-mounted		31.1 at 5 % discount rate 31.4 at 10% discount rate
VVER-1150	20.7 at 5 % discount rate 20.9 at 10% discount rate	PWR-302 twin-unit land-based		20.7 at 5 % discount rate 20.9 at 10% discount rate
Advanced Gen. III+	22.2	PWR-335 two twin-units		22.2