

Preface

Nuclear technology is one of the main base-load electricity-generating sources available in the world today, producing around 11.2% of the global power production. According to the International Atomic Energy Agency (IAEA), the use of nuclear energy for electricity generation is expected to grow around the world, particularly in Asia and the Pacific Rim, as demand for electricity increases in that region as foreseen. It is also expected that the types of nuclear power reactors to be used in the future in several countries will not be as large as today, more than 1,000 MW of capacity, opening the possibility to the introduction of small modular reactors (SMRs) with a maximum capacity of 300 Me, which could be built in factories and transported to the different sites, by truck, train, or ship.

The book has seven chapters. Chapter 1 “General Overview” has been prepared to give the reader a general overview of the current situation and the future of the nuclear industry, particularly the current situation and of the development of the SMRs of different types. In 2016, a total of 31 countries was operating 447 nuclear power reactors with an installed capacity of 389,051 MWe. At the end of 2015, the electricity generated by nuclear power plants reached 2,441.33 TWh.

After a detailed analysis of the relevant information elaborated by the IAEA-PRIS (2016), the World Nuclear Association (WNA 2016), and the World Association of Nuclear Operators (WANO 2016), among other relevant sources on the use of nuclear energy for electricity generation and the future of this energy source, the following can be stated: It is expected that the nuclear market could gradually recover from the decline it suffered from being included in the energy mix of different countries during the period 2006–2014, particularly after the Fukushima Daiichi nuclear accident occurred in March 2011. However, the level of its recovery will depend on the following elements:

- Level of fossil fuel reserves;
- Fossil fuel prices;
- Uranium fuel supply and the future of advanced fuel cycles;
- Energy security concerns;
- Environmental and climate change considerations;

- Nuclear safety concerns;
- Nuclear waste management;
- The availability of new design of nuclear power reactors;
- The cost of new nuclear power reactors now under development (Generation III, III+, IV, and SMRs);
- Public opinion acceptance;
- Nuclear proliferation risks management.

Undoubtedly, the use of nuclear energy for electricity generation is not a cheap alternative or/and an easy option free of risks for many countries. It is a fact that many countries do not have the necessary conditions to use, in an economic and safe manner, nuclear energy for electricity generation at least during the coming decades. From the technological point of view, the use of nuclear energy for electricity generation could be very complicated and costly for many countries, particularly for those with a low level of technological development or with limited financial resources to be invested in the nuclear energy sector.

There is an agreement within the nuclear industry that nuclear power plants represent a long-term investment with deferred pay-outs. Moreover, the nuclear industry is very capital-intensive. This means that a high upfront capital investment is needed to set up the project (between 10–15 years) and a long payback period is needed to recover the capital expenditure. The longer is this period, the higher is the probability that, the scenario conditions may evolve in a different, unfavourable way, as compared to the forecasts.

A capital-intensive investment requires the full exploitation of its operating capability and an income stream as stable as possible. On a long-term horizon, a low volatility in a variable trend might translate into a widespread range of realisations of the variable value. This condition is common to every capital-intensive industry. Nevertheless, some risk factors are specific or particularly sensitive to the nuclear industry: Typically, the public acceptance, the political support in the long-term energy strategy, and the activity of safety and regulatory agencies. For these reasons, nuclear investment is usually perceived as the riskier investment option among the different available power generation technologies.

In addition, some of the countries that are now considering nuclear power as a potential option in the future, lack well-prepared and trained professionals, technicians, and highly-qualified workers, and have a relatively small electrical grid, elements that could limit the use of this type of energy for electricity generation in the future. In comparison to coal-fired and natural gas-fired-power plants, it is true that for many countries nuclear power plants could be more expensive to build, although less expensive to operate.

After the Fukushima Daiichi nuclear accident, all countries with major nuclear programmes revised their long-term energy plans and have developed stringent safety measures so that they can continue with their nuclear power development in the future. Despite the introduction of additional stringent safety measures in almost all nuclear power reactors currently in operation in the world, it is expected that the installation of new units in several countries in the future will continue its growth trajectory, but

perhaps at a slower pace. In some countries, all nuclear power plants currently in operation will be phased out during the coming decades, excluding with this action the inclusion of nuclear energy for electricity generation in their future energy mix.

The future growth of nuclear power will be driven by large-scale capacity additions in the Asia and the Pacific market. Out of 495 new projects, 316 are planned to be constructed in the Asia and the Pacific region (63.8% of the total). In addition, in 2014, a total of 47 units were under construction in that region (70% of the total units under construction) and 142 units were planned for 2030. Asians' investment in nuclear projects could reach US\$781 billion during the period up to 2030.

On the other hand, it is important to be aware that nuclear power capacity is expected to rise steadily worldwide, but at a slower path than initially planned. This increase is needed to satisfy an increase in the demand of energy in several countries, particularly in China, India, Russia, Brazil, Argentina, South Africa, UK, Hungary, the Czech Republic, and in some newcomers like the UAE, Turkey, Belarus, Poland, Vietnam, Jordan, and Bangladesh, to reduce the greenhouse emissions, and the negative impact on the environment as a result of the use of fossil fuels for electricity generation.

In 2016, there were 60 nuclear power reactors under construction in 15 countries according to IAEA sources (IAEA-PRIS 2016). Although most of the planned nuclear power reactors were in the Asia and the Pacific region (China 20 units; India five units; Korea three units; Japan two units; and Pakistan three units), it is important to highlight that Russia has also plans for the construction of seven new nuclear power reactors during the coming years. In addition to the setting up of new nuclear power reactors in the countries mentioned above, large amount of capacity will be generated through plant upgrades in many others.

Based on what has been said before, it is expected that nuclear power capacity will reach 520.6 GWe in 2025, and that nuclear power generation will reach 3,698 TWh by the same year; this means an increase of 56.8% with respect to 2014.

Chapter 2 “Advanced Nuclear Technologies and Its Future Possibilities”, written by Eng. Alejandro Seijas López, will provide the reader with the latest information about the different types of nuclear power reactors, particularly SMRs types currently under development or planned in several countries.

There are six different types of nuclear power reactors now operating in 31 countries. These are the following:

- Pressurised Water Reactors (PWR);
- Boiling Water Reactors (BWR);
- Fast-Neutron Breeder Reactors (FBR);
- Pressurised Heavy Water Reactors (PHWR);
- Gas-Cooled Reactors (AGE and Magnox);
- Light Water Graphite Reactor (RBMK and EGP).

Advanced nuclear technologies are expected to drive the future of the nuclear power market. They offer exciting potential for growth in the nuclear industry and exportable technologies that will address energy security, feedstock security, and

emissions concerns. For this reason, the nuclear power sector is expected to benefit soon from the following new nuclear technologies:

- Generation IV nuclear power reactors;
- European pressurised reactors (EPRs);
- Small modular reactors (SMRs).

A description of the economic and industrial potential features of SMRs is included in this chapter. SMRs would be less than one-third the size of current nuclear power reactors, and with a capacity less than 300 MWe. They have compact designs and could be made in factories and transported to sites by truck, rail, or ship. In other words, SMRs are designed based on the modularisation of their components, which means the structures, systems and components are shop-fabricated, then shipped and assembled on site, with the purpose of reducing considerably the construction time of this type of units, one of the main limitations that the use of nuclear energy for electricity generation has today in several countries. For this reason, SMRs would be ready to ‘plug and play’ upon arrival. If commercially successful, SMRs would significantly expand the options for nuclear power and its applications. Their small size makes them suitable to small electric grids so they are a good option for locations that cannot accommodate large-scale nuclear power reactors. The modular construction process would make SMRs more affordable by reducing capital costs and construction times. Their size would also increase flexibility for utilities since they could add units as demand changes, or use them for on-site replacement of aging fossil fuel power plants.

If nuclear energy is expected to continue to be part of the energy mix in several countries in all regions in the future, then a new type of nuclear power reactors, less costly and safer, should be developed and commercialised in the future. The SMRs is seen, according to the opinion of different experts, the appropriate answer to this concern.

Chapter 3 “The Current Situation and Perspective of the Small Modular Reactors Market in North and South America, Including the Caribbean Region” is composed with the aim of giving the reader a general overview of the current situation and perspective in the use of SMRs for electricity generation and other purposes in several countries in that region. Some of these countries, like Canada, U.S., Mexico, Brazil and Argentina, are using now a nuclear power programme for electricity generation, while some others are thinking to introduce nuclear energy in their energy mix in the future, such as Chile.

The use of nuclear energy for electricity generation started to be used in the U.S. since 1957, with the connection to the grid of two nuclear power reactors, GE Vallecitos and Shippingport. Since 1957, a total of 171 nuclear power reactors were built in the whole region, most them in the U.S. The Three Miles Island (1979) and Chernobyl (1986) nuclear accidents stop all new construction of nuclear power reactors in the U.S. until today, as well as in Canada, where the last unit was connected to the grid in 1993. However, the construction of new units continued in Argentina, where the last unit was connected to the grid in 2014, and in Brazil

where the last unit was connected to the grid in 2000. These two countries continued the construction of new units in 2016, one in Argentina and another in Brazil. The new nuclear power reactors under construction in the region are mostly large units (more than 1,000 MW), except for one SMR in Argentina the so-called “CAREM-25” with a capacity of 25 MW.

However, the situation in the U.S. has changed in the last years due to the support of the U.S. government to the development of SMRs as well as to the construction of new large units. For this reason, in the FY 2012 Administration budget, a new programme for the development and use of SMRs for electricity generation was approved. This would involve obtaining design certification for two light-water SMRs on a cost-share basis with the nuclear industry, with the purpose of accelerating the commercial deployment of this type of reactor in the country in the coming years. The NRC also requested US\$11 million for pre-application work on SMR licensing with two developers leading to filing the design certification applications, and some initial review for one such application.

More advanced designs such as metal- or gas-cooled SMRs could get some funds from DoE’s separate Reactor Concepts Research Development and Demonstration programme, US\$30 million of which is envisaged for SMR concepts.

In spite of what has been said in previous paragraphs, the U.S. market perspective for SMRs are not yet strong enough to be considered by the U.S. and by foreign nuclear and investment companies as a good business investment opportunity. For this reason, SMRs must find a viable marketplace in domestic markets, if this type of reactors would play an important role in the country future energy mix.

In Canada, there is only one type of nuclear power reactor operating for electricity generation, the so-called “CANDU reactor”, which is a PHWR reactor type. Undoubtedly, nuclear power is an important energy source in Ontario’s industrial heartland and supplies over half the province’s electricity (in 2015 around 60% of the total electricity generated in the province). There are currently no nuclear power plants operating in Western Canada: The British Columbia government has prohibited the use of nuclear energy for electricity generation and uranium mining.

Over the border, Alberta’s government is considering proposals to use nuclear energy to help extract oil from the tar sands. However, it is unlikely a nuclear power plant in the tar sands could come online before the decade is out. Potential SMR supply markets in Canada include remote off-grid applications, where prices associated to diesel-fired power plants are high due to challenging access, as well as higher consumption markets in more densely populated areas. Older nuclear power plants remain a key power generation source in the south-east provinces of Ontario and New Brunswick.

In the rest of the Latin American and the Caribbean countries, only Argentina is building an SMR (CAREM-25) and this situation will not change in the coming years.

Chapter 4 “The Current Situation and Perspective of the Small Modular Reactors Market in the European Region” is written with the purpose of giving the reader a general overview of the current situation and the perspective of the nuclear sector in the European region. The region can be divided in five groups of states. The first

group is composed by those countries that are using nuclear energy for electricity generation and has plans for the expansion in the use of this specific energy source in the future, such as France, the Czech Republic, Russia, Romania, the UK, Hungary, Finland, Slovakia, Slovenia, among others. The second group is composed by those countries that are now using nuclear energy for electricity generation, but has no plans for an increase in the use of this type of energy source in the coming decades, such as Spain, the Netherlands, Belgium, among others. The third group is composed of countries that are now using nuclear energy for electricity generation, but will shut down all nuclear power plants during the coming years such as Germany, Switzerland, among others. The fourth group is composed of countries that are not using nuclear energy for electricity generation, but have plans for the introduction of nuclear energy in their energy mix in the future, such as Poland and Lithuania, among others. The fifth group is composed of countries that are not using now nuclear energy for electricity generation and have no plans for the introduction of this type of energy source in their energy mix in the future, such as Austria, Denmark, Norway, Portugal, Italy, among others.

Today, there are 184 nuclear power reactors operating in the European region generating a total of 162,135 MWe and 16 units under construction with a total capacity of 14,810 MW.

Undoubtedly, the cost of the construction of a nuclear power plant is one of the key problems facing a revival of nuclear power at world level, particularly in the European region. Up to now, the sorts of nuclear power reactors used for generating electricity have tended toward the gigantic with units reaching gigawatt levels of output. With plants that large, small wonder that the cost of construction combined with obtaining permits, securing insurance and meeting legal challenges from environmentalist groups can push the cost of a conventional nuclear power plant toward as much as US\$9 billion in some cases. It also means very long build times of 10–15 years. This is not helped by the fact that big nuclear power plants are custom-designed from scratch in multi-billion dollar exercises, because even if the same type of reactor is used in the construction of a nuclear power plant, the structure is not always the same. With so much time and resources involved, an unforeseen change in regulations or discovery of something like a geological fault under the reactor site can make this a case of putting a lot of very expensive eggs in a very insecure basket.

However, and despite the rejection of several European countries to the use of nuclear energy for electricity generation, there are sound economic and technical reasons for some other European countries to diversify nuclear generation by building many SMRs instead of building a small number of large nuclear power plants. It is a fact that in several European countries, nuclear-powered electricity generation should be a key component of every country's energy portfolio to reduce their dependence on oil and coal for this purpose and of the CO₂ emission. In addition, with declining fossil fuel production and reserves in Europe, the continent is increasingly dependent on imported coal and gas and so subject to volatile market prices and the ever-present threat of politically motivated disruption of supply by producers or even countries hosting pipelines.

According to Waddington (2014), it is expected that by the year 2035, Russia, UK, Finland, Lithuania, and Slovenia will increase the nuclear power capacity by installing different types of SMRs. Russia and UK are expected to be the two European countries with the highest number of SMRs installed.

Chapter 5 “The Current Situation and Perspective of the Small Modular Reactors Market in the Asia and the Pacific Region” has been written with the aim of giving the reader a general overview of the current situation and perspective of the use of SMRs for electricity generation in Asia and the Pacific Rim, the region with the current biggest nuclear power programme in the world. According to WNA, in contrast to North America and most of Western Europe, where growth in electricity-generating capacity and particularly nuclear power levelled out for many years, a number of countries in East and South Asia are planning and building new nuclear power reactors to meet their future increasing demands for electricity.

During the period 2014–2025, it is expected to add, in some countries of the region, a nuclear generating capacity of 1,400 GWe, over 120 GWe per year. This is about 46% of the world’s new capacity in that period—under construction and planned (current world capacity is about 6,200 GWe, of which 380 GWe is nuclear). Much of this growth will be in China, India, and Korea. The nuclear share of these three countries until 2020 is expected to be considerable, especially if environmental constraints limit fossil fuel expansion.

However, according to Organization for Economic Co-operation and Development/International Energy Agency (OECD/IEA) sources, nuclear power has a limited role in Southeast Asia during the coming decades. This reflects the complexities of developing a nuclear power programme in some of the countries in that region and the slow progress to date of most countries that have included a nuclear power programme in their long-term plans. Vietnam is the most active country and is currently undertaking site preparation, workforce training and the creation of a legal framework. Moreover, Vietnam has signed a co-operative agreement (that includes financing) with Russia to build its first nuclear power plant, and with Japan for its second nuclear power plant, with the aim of entering the energy mix of the country before 2025. Thailand includes nuclear power in its Power Development Plan from 2026, but these plans could face public opposition. However, it is expected that Thailand could start producing electricity from nuclear power plants before 2030.

Without doubt, Asia and the Pacific is the region of the world with the largest nuclear power programme to be implemented in the coming decades. The countries with the largest nuclear power programme are China (36 units), the Republic of Korea (25 units), and India (22 units). Japan has also a large nuclear power programme, but almost all units have been shut down after the Fukushima Daiichi nuclear accident in 2011 and all new construction has been suspended. China has the largest nuclear power programme under construction in the world (20 units).

Chapter 6 “Benefits of Small Modular Reactors” has been composed by the Nuclear Physics masters student, Mustapha Boubcher (Canada). The purpose of this chapter is to give reader a comprehensive view of all benefits associated with the use of SMRs for electricity generation.

Many countries are moving swiftly to develop and commercialise SMRs as they offer an assortment of benefits that make them attractive to utilities and investors. They have the potential to solve challenges faced by large nuclear power reactors, such as cost overruns and construction delays risks, safety, and proliferation concerns. SMRs are designed to be safer than large nuclear power reactors and offer serious cost advantages over the larger units. SMRs are well-suited for locations with small grid and remote areas and could be affordable for many countries with limited investment capability. SMRs offer also a greater flexibility for utilities for incremental capacity increase, which could potentially increase the attractiveness of SMRs to investors.

The chapter includes several key benefits that SMRs can offer.

Chapter 7 “The Future of Small Modular Reactors” is written with the aim of giving the reader a summary of the future of SMRs. The small size and the modular structure of the SMRs make them suitable to small electric grids. For this reason, they are a good option for locations that cannot accommodate large-scale nuclear power plants. The modular construction process associated to SMRs would make them more affordable by reducing capital costs and construction times. Their modular structure would also increase flexibility for utilities since they could add units as demand changes. This type of nuclear power reactors can be used for on-site replacement of aging fossil fuel plants.

According to the IAEA Technical Review Panel Report (2012), the main priorities in the field of research and development of a group of SMRs are the following:

1. Priority research and development for Gas-cooled fast reactors;
2. Priority research and development for Lead-bismuth eutectic-cooled reactors (LBE);
3. Priority research and development for Sodium-cooled reactors.

Vienna, Austria

Jorge Morales Pedraza

Small Modular Reactors for Electricity Generation
An Economic and Technologically Sound Alternative
Morales Pedraza, J.
2017, XIX, 267 p. 40 illus., 39 illus. in color., Hardcover
ISBN: 978-3-319-52215-9