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Role of Small Modular Reactors in the Future of Nuclear Power

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ABSTRACT

There is a large international activity concerning Small Modular Reactors (SMRs) these days. Installed power of a single SMR is typically defined to be less than 300 MWe and many SMR units may be combined together to match the power of a modern NPP (order of 1000 MWe). SMRs are designed for modular manufacturing in factory production and transportation as modular units to a location for installation. The paper gives a brief survey of SMR technologies and activities of international organizations, as well as activities of the Slovenian Nuclear Safety Administration (SNSA).

1 INTRODUCTION

In recent years, the concept of Small Modular Reactors gained popularity. The SMR have lower power (up to 300 MWe) in comparison to NPPs, however, several SMR units may be combined together to match the power of a regular NPP (1000-1600 MWe). The SMR are called modular because they are designed for modular manufacturing in factory production and transportation as modular units to a location for installation. Serial production in a factory can improve quality of manufactured systems, lower the cost of single reactor unit, shorten the time of construction and make SMRs economically feasible. Therefore economy of scale is swapped for economy of mass production. Comparison of construction costs between SMRs and large NPPs is presented in Fig. 1.

2 WHERE CAN SMALL MODULAR REACTORS BE USED?

Energy production and use are responsible for around three quarters of global carbon dioxide emissions, of which the electricity and heat plants account for about 40% [1]. SMRs can play an important role in reduction of carbon dioxide emissions and especially in sectors which are considered to be technologically of financially difficult to decarbonize (hard-to-abate). OECD/NEA report [2] gave a list of hard-to-abate sectors where SMRs can be used:

- Replacement of coal-fired power stations for on-grid power: SMRs with installed power 200-300 MWe are capable to replace coal power plants for on-grid power. A virtue of

SMRs is that they have better capacity factor than coal-fired power stations. SMRs can use existing balance of replaced plants (supporting components and auxiliary systems of a power plant needed to deliver the energy). Plans about replacement of coal-fired power stations are getting momentum. A Memorandum of Cooperation concerning construction of SMRs in Slovakia has been signed in June 2023 by Slovakian Ministry of Economy and its partners in the energy sector. On that occasion it was said [3] that SMRs were not intended to replace Slovakian existing nuclear sources, but to replace coal-fired power plants.

- Replacement of fossil fuel for cogeneration: Some SMR designs are suitable for combined production of electricity and heat while some designs are specialised only for heat production. The heat can be used for district heating as well as in industries like chemical plants, oil refineries, paper mills and desalination of sea water. Due to the smaller footprint of the SMRs, they can be used at locations which are not suitable for large nuclear power plants.
- Diesel replacement for off-grid usage: SMRs can replace diesel generators at isolated locations. An example of such usage is mining at locations which are not grid connected.
- Production of hydrogen: SMR designs which operate at high temperatures are suitable for thermochemical production of hydrogen from water.
- Merchant shipping: There is a large experience with using nuclear energy for propulsion of submarines, aircraft carriers and icebreakers. These days, some SMRs are being designed for propulsion of merchant ships.

To improve SMR project competitiveness [4], the SMRs are supported by economies of series production, which rely on four key costs drivers: design simplification, standardisation and modularisation, while maximising factory fabrication and minimising on-site construction (Figure 1). By such approach the construction costs of SMRs become comparable to the construction costs for a large reactor.

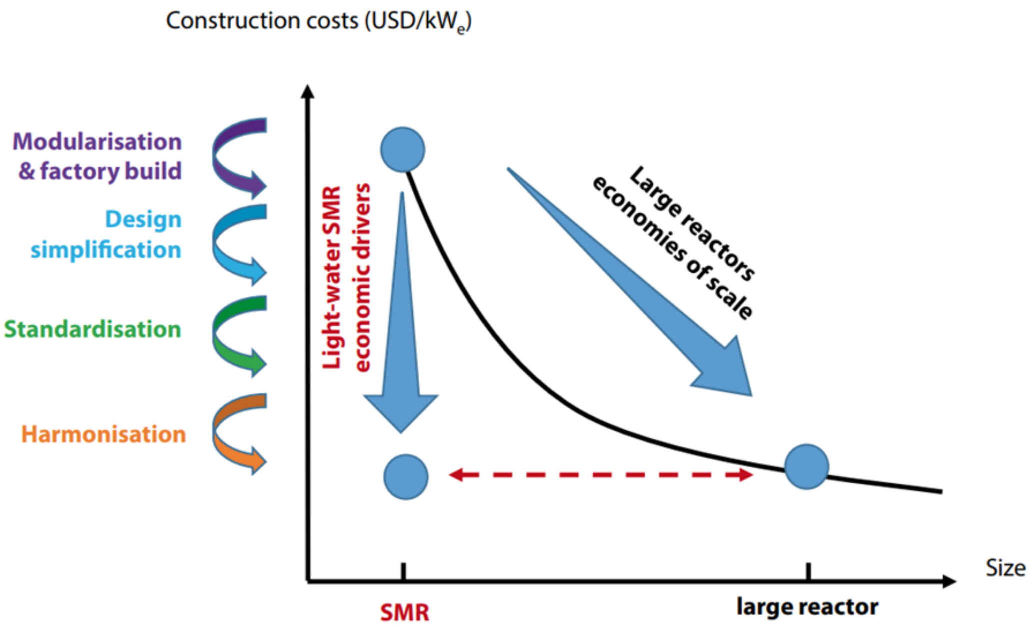

Figure 1: Economic competitiveness of SMRs in comparison to large NPPs [4].

3 SMR TECHNOLOGY

SMR technology is considered in recent publications [2, 5, 6, 7]. Reduced power of SMRs opens more space for the use of passive safety systems what implies that such designs do not need active interventions or backup power to safely shut down. Passive safety and small inventory can lead to emergency planning zones which are reduced in size. As a consequence of high passive safety, design, operation and maintenance can become more economical. More than seventy SMR designs that are currently being developed are presented in [5]. They can be grouped in classes according to their technology:

- Water cooled SMRs (Land Based) – SMRs in this class use water (light or heavy) as coolant and neutron moderator. Otherwise, designs comprise integral-PWRs, compact-PWRs, loop-PWRs, BWRs, CANDU-type designs, and pool type reactors. They are planned to be used for baseload electricity production, production of process heat, mining (oil sands), district heating, desalination and radioisotopes production.

- Water cooled SMRs (Marine Based) – Designs in this class are light water pressurized reactors, either of integral design or with loop. They are planned to be used on ships for power and heat supply to remote coastal areas and offshore oil platforms, as well as for desalination. The world first two operating SMRs are situated on powership Akademik Lomonosov which is docked in the Russia's Arctic port town Pevek. The reactors are KLT-40S type. They can produce 70 MWe along with 60 MW of thermal power for district heating. Delivery of thermal power can be increased to 170 MW in which case delivered electrical power is 30 MWe. The plant Akademik Lomonosov was fully commissioned in 2020.

- High temperature gas cooled SMRs – SMRs in this class use graphite for moderator and helium for coolant. Temperature of the outlet heat is about 750 °C what enables efficient electricity production. They can also be used for thermochemical production of hydrogen, process heat production, steelmaking and desalination. The Chinese High-Temperature gas-cooled Reactor Pebble-bed Module (HTR-PM) consists of two reactors (each of 250 MWt) that drive a single 210 MWe steam turbine. The HTR-PM uses helium as coolant and graphite moderator. It was reported [8] that the HTR-PM reached full power in 2022.

- Fast neutron spectrum SMRs - These SMRs use fast neutrons to sustain chain reaction and therefore do not need moderator. From the other side, larger fuel enrichment is required. Liquid metal (lead, sodium, lead-bismuth alloy) or helium is used for cooling. SMRs from this class are planned to be used for power production at remote sites, hydrogen production, desalination, process heat production, desalination and propulsion of merchant ships.

- Molten salts SMRs – This class of SMRs uses molten salt as coolant and fuel what enhances safety. Other advantages are low coolant pressure, high operating temperature and cheaper fuel. They can be used for electricity production, desalination, hydrogen production, etc.

- Micro modular reactors – Reactors from this class use various technological solutions. Their main feature is small size and electrical power about 10 MWe or smaller.

Countries which develop SMRs and corresponding designs are presented in Fig. 2.

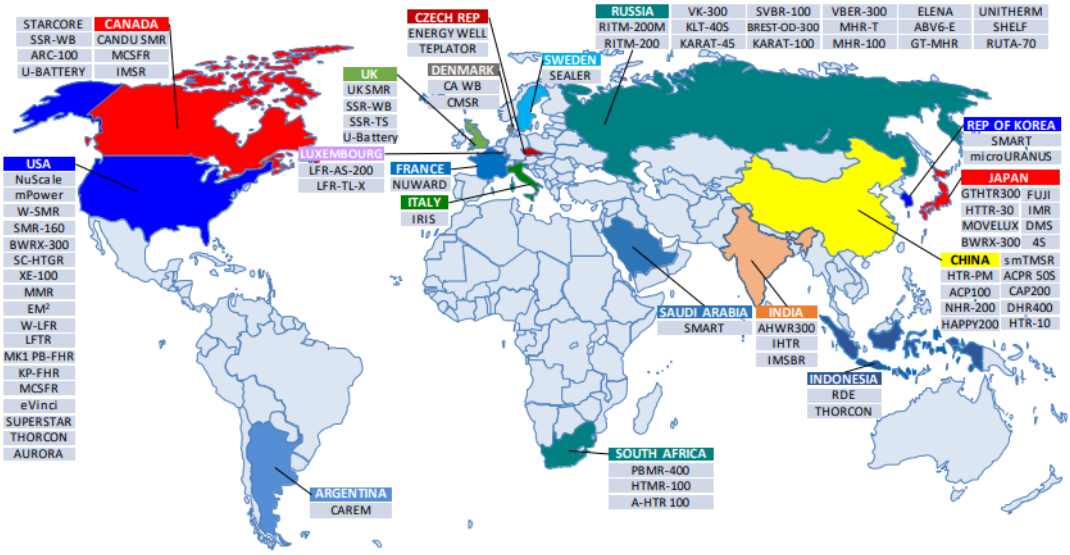

Figure 2: Countries which develop SMRs and corresponding designs [5].

4 HOW TO CONSIDER DIFFERENCES OF SMR IN DESIGNING AND LICENSING PROCESS

As a rule, licensing process of a nuclear power plant (NPP) is a complex and strenuous process which includes many steps [9]. Licensing can be quicker and cheaper if an efficient co-operation of several regulators can be achieved. It was announced [10] that France's Nuward SMR design will be the case study for an early joint regulatory review led by the French nuclear safety regulator (ASN) with the participation of the Czech (SUJB) and Finnish (STUK) nuclear regulators. Similarly, the Canadian (CNSC) and the United States of America (USNRC) regulator agreed [11] to work in co-operation on regulatory and safety issues in the licensing review of the BWRX-300 SMR design.

The International Atomic Energy Agency (IAEA) started a Nuclear Harmonization and Standardization Initiative in 2022 with a goal to develop a joint approach of different regulators, designers, vendors and operators for the use of SMR technology. The NHSI shall harmonize licencing requirements, safety standards for design and the technology assessment. This is challenging because the licensing legislation, such as requirements on design, safety and staffing is focused on large reactors in some countries and can be too much of a burden for smaller installations. The NHSI work proceeds in two tracks: Regulatory track where regulatory bodies are gathered and Industrial track for operators, designers, etc. The Regulatory track is divided in three Working Groups (WGs):

- WG1 is focusing on developing framework of sharing information concerning SMR technology among regulators. Some information used in regulator's work might be classified what poses problems in the case of sharing. Such problems have already been encountered in other international cooperations. In order to solve ambiguities the WG1 wants more participants with legal expertise.
- WG2 is focusing on multinational pre-licensing process of SMR designs. The idea of pre-licensing process is identification of potential problems in some design by regulatory bodies in an early phase of design development and therefore decreasing the need for design changes during national licensing process. Work on topics covered in the pre-licensing phase should not be duplicated in the national licensing process.

- WG3 works on two processes: leverage other regulators' reviews, collaboration of regulators during ongoing national regulatory reviews of SMR designs. WG3 takes into account experience of other regulators' collaborations (e.g. ASN-SUJB-STUK [10], USNRC-CNSC [11])

The work of the Industrial track has been organized into four Topical Groups:

- TG1 is focusing on harmonization of high-level user requirements that a SMR design has to comply with. The requirements will be listed in a document which will be useful for designers.
- TG2 is focusing to develop platform allowing high level comparison of national standards and codes concerning SMR technology. The topics encompass quality and management requirements, equipment qualification, suitability assessment for industrial grade components; engineering and design related codes and standards, non-nuclear codes and standards having leading to design differences, etc.
- TG3 is focusing to create global cooperation that will perform experimental testing and validation for design and safety analysis computer codes which are relevant for SMR technology. A new network named "NEXSHARE - Network for Experiments and Code Validation" will hold relevant publications, information about experimental facilities, and provide an opportunity for sharing and initiate collaborations.
- TG4 is focusing to support infrastructure development for recipient countries. This could significantly shorten plant development timeline.

WGs and TGs will write a number of documents by the end of 2024.

The IAEA has already published a number of Tecdocs and other publications concerning SMRs. Workshops are also regularly organized.

5 OECD-NEA ACTIVITIES

The Nuclear Energy Agency (NEA) of the Organization for Economic Co-operation and Development (OECD) included SMRs in its strategic plan [12] for period 2023-2028. The NEA's strategy is focused on three topics: Technologies, Enabling conditions, Applications and markets.

- Technologies - the NEA and partners will establish a foundation for reliable safety and technology assessments of SMR and Generation IV reactor technology,
- Enabling conditions - Governments and international organisations have a role to create the suitable conditions for deployment of SMRs and Generation IV reactor technology. The conditions include policies, regulatory readiness, legal aspects, human resources, reliable fuel supply chains, etc.
- Applications and markets – It is expected that SMRs will be used for various purposes having different requirements concerning power and temperature ranges, timelines, etc. The NEA foresees to play a central role in connecting with prospective end users and customers to understand their future requirements, evaluate overall market potential, and facilitate sector coupling.

The NEA implements the SMR strategy through work of its Standing Technical Committees and Technical Secretariat for NEA-serviced bodies (Generation IV International Forum, International Framework for Nuclear Energy Cooperation). In this way an Expert Group on Small Modular Reactors (EGSMR) was formed. The EGSMR develops a scientific basis which supports safety demonstration of SMRs and sets priorities for safety research to be done by NEA member countries. Furthermore, the NEA published two volumes of dashboard [3, 5] where progress of SMR designs was given in six kea areas: licensing, siting, financing, supply chain, engagement and fuel.

6 ACTIVITIES OF OTHER INTERNATIONAL ORGANIZATIONS

European Commission recognizes importance of SMRs for energy future of Europe. A Declaration on 'EU Small Modular Reactors (SMRs) 2030: Research & Innovation, Education & Training' was signed by Commissioner for Innovation, Research, Culture, Education and Youth and large EU nuclear stakeholders: nucleareurope, Sustainable Nuclear Energy Technology Platform (SNETP), European Nuclear Society (ENS) and European Nuclear Education Network (ENEN) [13]. The Declaration states that in order to ensure EU leadership and strategic independence for SMRs, there is a need to support the best regulatory and institutional standards (cf. licensing, controls, inspection), to improve human resource management, to make nuclear careers more attractive, to optimise the use of nuclear research infrastructures and to stimulate the emergence of EU SMR design. SMRs are seen as an opportunity to further improve nuclear safety (through SMRs' inherent safety features) and increase the stability of the grid. Signing parties committed to continue to lead research, innovation, education and training for the safety of European SMRs in support to the EU pre-partnership on SMRs.

The European Utility Requirements (EUR) is an association of companies with experience or interest for electricity production in nuclear plants in Europe. The EUR updates its report "The EUR Document" which gives a comprehensive set of requirements concerning safety, performance and competitiveness aspects of nuclear power plants. In 2021 the EUR published a report "EUR Keys Positions" giving requirements for light-water cooled SMRs. The next revision of The EUR Document (Revision F) will have requirements applicable to all light water reactors (large and SMRs).

The Western European Nuclear Regulators Association (WENRA) formed a subgroup dedicated to SMRs. The subgroup considered applicability of the WENRA Safety Objectives for new NPPs [14] to SMRs. The Safety Objectives are upper level principles that should be applicable to all types of reactors. It was confirmed [15] that the Safety Objectives are applicable also to SMR designs.

7 SITUATION IN SLOVENIA AND CONCLUSIONS

The SNSA is active within the IAEA NHSI where it is collaborating in the working group 3 of the NHSI. At this moment there is no formal initiative in Slovenia for installation of a SMR in a near future but it can change. As a sign of growing interest for SMRs in Slovenia, let us note that representatives of the GEN Energija which operates the only Slovenian NPP, attended the last plenary meeting of the NHSI. It was recently reported that the GEN Energija is forming a team of engineers that will focus on progress in SMRs. It would be possible to licence a SMR using existing Slovenian legislation. Graded approach could be used for licencing nuclear reactor if it would be shown that environment and people would not be endangered by severe consequences in case of an accident in SMR. The SNSA is not developing specific legislation focused on SMRs. The SNSA prepares to follow standards that will be set by some international organization (WENRA, IAEA, etc) and will take into account regulatory experiences of other European countries (i.e. France, Finland, Czech Republic, etc.). The SNSA actively follows advances concerning SMR regulation and in this way raises its readiness to provide timely licensing of possible SMR projects in Slovenia.

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