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Review Article

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A review of advanced Small Modular Reactors (SMRs) through a developed PIRT methodology

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H I G H L I G H T S

- Presenting a comprehensive comparison study between different types and applications of SMRs.
- Introducing a wide range of applications, novelties, and demands including high-tech space applications.
- Developing a new PIRT method to compare different types of SMRs through a graded approach coherently.
- Proposing a strategic roadmap considering short-term, mid-term, and long-term demands.

A B S T R A C T

Nowadays, a very particular type of nuclear reactors has become fascinating not only for most nuclear communities but also for the prominent energy suppliers to fix the global warming effects worldwide. They are Small Modular Reactors called SMRs. Usually, SMRs can are classified according to the seven different categories. They include PWRs (especially iPWRs), BWRs, PHWRs, GCR, LMFBR, MSR, and MMRs. Although many different plans have been proposed worldwide, only a few well-established or successive developing action plans are among many innovative conceptual designs. This paper briefly presents a comparison study reviewing the last advances and challenges. The proposed roadmap is strongly correlated and depends on the technology readiness and documentation, technology availability, safety and reliability, design, and construction feasibility for different countries. A new graded approach Phenomenological Identification Ranking Table (PIRT) has been developed and proposed to choose the most profitable and compatible action plan dependent on the situation. Finally, the best feasible designs are compared and proposed against the lack of First-of-A-Kind (FOAK). Furthermore, different options are proposed for different priorities and preferences based on the available nuclear infrastructures. Studies are very profitable to save money and time and develop a strategic action plan for newcomers and developing countries. On the other hand, some exceptional designs have extraordinary advantages for industrial countries and even more for the future of nuclear energy worldwide. Therefore, the proposed roadmap covers short-term, mid-term, and long-term strategies for developing countries and newcomers in the nuclear reactor industry.

K E Y W O R D S

SMR
iPWR
BWR
GCR
LMFR
MSR
MMR

H I S T O R Y

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1 Introduction

This paper discusses a particular type of nuclear power reactor called SMR. Fortunately, SMRs include different types of small and modular nuclear power reactors. Furthermore, some of them (IAEA, 2020a, 2021a, 2022, 2016b) could be a good prototype for the GEN IV reactors (Pioro and Rodriguez, 2023a; IAEA, 2016b).

Regarding another classification of nuclear power reactors, we also have Small (i.e., with the reactor thermal power less than 300 MWe), Medium (i.e., with the reactor thermal power less than 700 MWth), and Large nuclear power plants. The Small and Medium-sized Reactors were also called SMRs (IAEA, 1996, 1998, 2001b; IAEA., 2005; IAEA, 2011a, 2012c). They are also attractive for developing in regions with a smaller quantity demanded, the lack of suitable infrastructure, small-scale electricity generation, local electrical grid; and especially interesting

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for developing countries (Subki, 2020; IAEA, 1996, 1998, 2000, 2001b,a; IAEA., 2005; IAEA, 2006b, 2011b, 2012c). SMRs are also of particular interest for non-electrical applications such as seawater desalination, district heating, hydrogen production, and even high-temperature chemical and industrial processes such as oil refinement and steel forging (IAEA, 2012b, 2013b,c, 2016a, 2018a,c, 2017e).

Nowadays, advanced nuclear reactors especially SMRs are being much more interesting than before worldwide. Almost all such advanced innovative concepts and features (Hedayat, 2019a, 2020a; IAEA, 2016a, 2018b, 2019, 2020a, 2021a, 2022, 2017e,c; Ingersoll and Carelli, 2020; Westinghouse, 2020a; WNN, 2020; Zohuri, 2019) could be designed and built in the form of new Small Modular Reactors (SMRs) or Micro Modular Reactors (MMRs). In other words, nowadays, SMRs are usually interpreted as Small Modular Reactors for the future of nuclear energy in local and remote demands or even near towns (i.e., with reduced emergency planning zones). In contrast, large nuclear power plants are profitable for massive electrical power supplies of national electrical grid demands far from the big cities (i.e., a widespread emergency planning zone). Mostly, SMRs are to be able to be designed, constructed, relocated, installed, operated, and maintained within modular objects and operations (Bragg-Sitton et al., 2015; Hedayat, 2019a, 2020a; IAEA, 2018b, 2019, 2020a,b, 2021a, 2017e,c). Generally, SMRs reduce mass, objects, and active safety systems to compete with conventional large nuclear reactors. The most important benefits (Carelli et al., 2010; Bragg-Sitton et al., 2015; Hedayat, 2019a, 2020a; IAEA, 2019, 2020a,b, 2016b, 2017e,c; Ingersoll and Carelli, 2020; Li et al., 2020; Liu et al., 2020; NuScale, 2020; Westinghouse, 2020a; WNN, 2020; Zhang et al., 2020; Zohuri, 2019) could be listed as following: The economy of scale through compacted and integrated concepts and objects; Lower initial investment; Less required infrastructure and on-site manufacturing and building; Feasible and profitable Return of Investment (ROI) via modularization; Modular and more flexible operation and maintenance programs; Longer refueling cycles and removing soluble burnable poisons (some designs); Providing multi-utilization industrial applications via non-electrical heating loops; Reduced emergency zone planning and much simple site selection; The best prototypes for the GEN IV technologies; Regarding minor production of green gases (i.e., only by some secondary or supplementary systems), they could be classified as a type of clean technology; Regarding the sustainability of fissile production from fertile materials, especially by fast spectrum fast breeder reactors, they are still sustainable for the future of energy supplies; Compatible with other clean or renewable energies to make hybrid power plans; Promising smart grid development and local industrial towns; Providing strategic energy supplies for remote land-based, marine, and space applications, especially utilizing heat pipe cooled Micro Modular Reactors (MMRs); Furthermore, enhanced nuclear safety features through integrated systems, enhanced inherently safety features, passive safety systems, elimination of accident roots, modernized active safety systems, strengthened seismic design, and strengthened physical barriers of defense in depth.

There are also some major challenges or disadvantages (Carless et al., 2016; D'Auria et al., 1991; Deng et al., 2019; Erfaninia et al., 2016, 2017; Fernandez et al., 2017; Gharari et al., 2018, 2020, 2021; Hedayat, 2016b, 2017a, 2019a, 2020a; IAEA, 2006a, 2007a,c,d, 2011a, 2012a, 2018b, 2019, 2020a, 2021a, 2016b, 2017e,c; ICTP-IAEA, 2018, 2019; OECD et al., 2016; INRA-IAEA, 2014; Marcum and Brigantic, 2015; Mascari et al., 2012; Mignacca and Locatelli, 2020; Moghanaki and Hedayat, 2018; Pilehvar et al., 2020, 2018; Da Silva et al., 2011; Smithers et al., 1990) of this type of reactor that could be listed as following: The economy of large nuclear power plants for industrialized countries or base-load demanded of national electrical grid; Trusted and robust economy, market, and finances of clean or renewable energies, mainly hydro, solar, and wind power plants; Conventional complicated licensing requirements and rigid site selection rules for the conventional nuclear reactors; Radioactive hazards, political issues, green communities, and negative public trust against nuclear power plants, especially to be built near cities; Concerns about nuclear proliferation and nuclear security; Marketing and commercializing weakness of nuclear industry; A lot of non-matured conceptual designs; The lack of advanced but practical monitoring, alarm, automation, and supervision systems of Artificial Intelligence (AI) systems and incredibly advanced expert systems in nuclear reactors; Long-term aging problems and management, primarily due to radiation damage, require not only TRIGA and conventional Material Testing Reactors (MTRs) but also advanced high-flux and high-fluence research reactors at first to try and test new required long-lasting materials, instrumentations, and components; More material challenges due to high temperature and corrosion problems in practice; Required new neutronic and thermal-hydraulic data, codes, numerical methodologies, as well as extreme needs for multi-physics simulations; A very long time of the required Research Developments (R&Ds);The lack of knowledge and experience in new innovative designs; Required a broad range of sensitivity and uncertainty analysis in practice; Response of entirely passive safety systems based on the natural convection and inherently safety features against transients, especially unwanted and unknown transients; They do not belong to renewable energies; moreover, they could not still compete with other renewable energies such as hydro, wind, and solar in conventional applications; Regarding the countless hazards of the releases and fast and wide distribution of the hazardous radioactive materials and gases during severe nuclear accidents, almost all the relevant energy communities and societies have not considered and classified nuclear energy as a type of clean technology anymore; There are still many concerns about public health and environmental effects, even if such concerns reduce in practice beyond concepts in the future; Mitigation against unknown transients, Design Extension Conditions (DEC), and severe nuclear accidents, especially by lessons learned from three major severe accidents (i.e., Three-Mile-Island, Chornobyl, and Fukushima Daiichi Accidents) not only in general concepts and features but also in accurate simula-

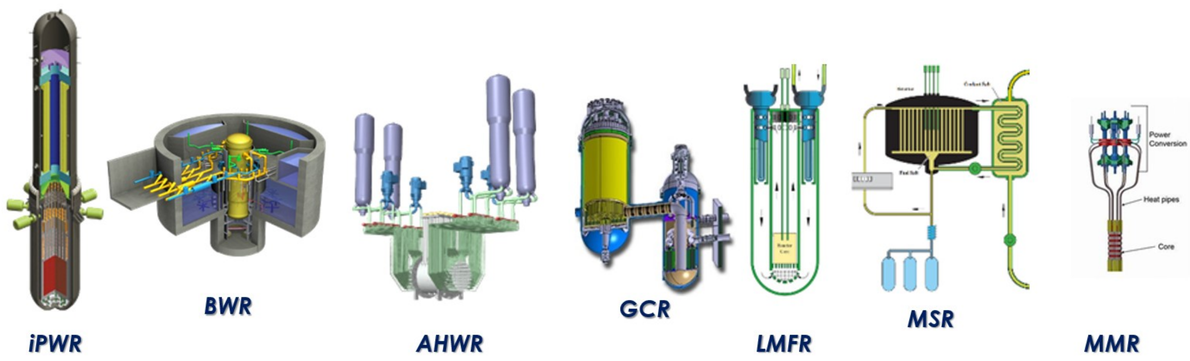

Figure 1: A graphical abstract of different SMRs.

tions, analyses, and practices; And most of all, the lack of First-of-A-Kind (FOAK) and even proven technology.

Therefore, nuclear experts and communities have encountered a complicated puzzle. There are many different types of SMRs. There are a lot of exciting points of view and advantages. Simultaneously, some crucial challenges, difficulties, lack of knowledge and experience, or even disadvantageous characteristics remain. First of all, it seems that the roadmap of the less developed or even developing countries should be different from the industrialized and developed countries. In other words, the proposed roadmap should distinguish between developing countries or countries with dependent nuclear industries; and developed or industrial countries with enough experience in nuclear technology independently. Furthermore, to reduce the risk of investments or rank the priorities, the main features of the roadmap should propose and distinguish between short-term approaches (i.e., less than five years), midterm approaches (i.e., less than ten years), and long-term approaches (i.e., between 10 and 20 years).

Briefly, the main goal of this paper is to solve this puzzle in a permanent way for the feature of nuclear energy worldwide. The proposed roadmap should be flexible, adaptable, and developmental to be updated and charismatic for different communities and societies. Therefore, the paper presents both advantages and disadvantages in detail for the seven different types of SMRs. They (Fig. 1) include Pressurized Water Reactors (PWRs), especially iPWRs, Boiling Water Reactors (BWRs), Pressurized Heavy Water Reactors (PHWRs), Gas Cooled Reactors (GCRs), Liquid Metal Fast Breeder Reactors (LMFBR), Molten Salt Reactors (MSR), and Micro Modular Reactors (MMRs).

In this paper, a particular Phenomenological Identification Ranking Table (PIRT) has been developed and proposed to make the strategy for SMR development and deployment, especially for developing countries. Simply because it is one of the most complicated forms of an industrial multi-objective decision making in practice (Censor, 1977; Gen and Cheng, 1999; Hedayat, 2020c; Hedayat et al., 2009; Konak et al., 2006), the developed PIRT methodology identifies and includes different decision objectives through a simplified table in mind for an expert panel in advance. Finally, the best items are also proposed for developing countries as a function of different goals and roadmaps. It is also worth mentioning that each part is enriched with many relevant references for further studies and investigations in-depth by dear readers.

2 The last status of SMR designs and projects: the pioneers

International studies and reports on Small and Medium-sized Reactors (IAEA, 1996, 1998, 2001b; IAEA., 2005; IAEA, 2006b, 2011b, 2012c) and especially on Small and Modular Reactors (IAEA, 2016a, 2018b, 2019, 2020b, 2021a, 2016b, 2017e,c) performed by International Atomic Energy Agency (IAEA) as well as the other good reviews and reference books in this field of study (Carelli et al., 2007, 2010; Bragg-Sitton et al., 2015; Hedayat, 2020a; Hidayatullah et al., 2015; Mignacca and Locatelli, 2020; NuScale, 2020; Pioro, 2016; Ramana and Ahmad, 2016; Rowinski et al., 2015; Söderholm et al., 2014; Vujić et al., 2012; WNN, 2021; Zohuri, 2019) confirm that a lot of conceptual designs and Research and Developments (R&Ds) in SMRs have been proposed for at least two decades. They are fascinating worldwide and especially in developed or newly industrialized countries. They exhibit an up-and-coming prospect, and even more, they could take an international effort to achieve a proven technology for the future of nuclear energy worldwide. Briefly and promisingly, they might be a compromise between absolutely clean renewably energies, high risky and less trusted nuclear energy (i.e., rather than renewable energies such as wind, solar, and hydro energies), and fossil fuels to survive both nuclear disasters and the other natural disasters because of the global warming effects in the future.

Although most of SMR designs belong to developed or industrialized countries, even developing countries or newcomers to the nuclear reactor industry also have some action plans. The USA, Russia, China, Japan, and Canada are pioneers in SMRs. Nevertheless, there are some other essential points of view as well.

First of all, even tiny developed countries in European Union (EU), such as Luxembourg, and developing countries without any operational nuclear power plants, such as

Saudi Arabia, have invested in SMRs. The second point of view is that there have been only a few matured detail designs among a lot of conceptual designs for a long time (Hedayat, 2019a, 2020a; IAEA., 2005; IAEA, 2011b, 2016a, 2017b, 2019, 2020b, 2021a, 2022, 2017c).

Briefly and frankly, although SMRs are very promising for the future of not only nuclear energy but also for the future of global energy suppliers, they could also be a precarious business at the moment if the lessons learned from other relevant studies and experiences are not taken into consideration.

The last point of view is that newcomers in the nuclear reactor industry need the support of developed or newly industrialized countries as well as the cooperation of the big, well-established, and well-experienced companies (IAEA, 2015, 2016a, 2020b; NEA et al., 2015) in the field of design, building, and manufacturing of nuclear reactors worldwide (IAEA, 2015). IAEA lists (IAEA, 2020b) at least 23, 21, 17, and 4 prominent companies and institutes in Asia, America (i.e., North America and Latin America), Europe (i.e., the United Kingdom, EU, and Russian Federation), and Africa continents, respectively.

In addition to all technical challenges and Technological Readiness Level (TRL) required for commercialization, it seems that there are still some challenges or at least some block boxes for designs; required balances between some active safety systems and entirely passive or fully integrated safety systems; new codes and standards; costly and time consuming RDs tasks; expert reviews; prolonged licensing processes; and even much more precise and accurate safety analysis in detail via complete simulations especially to investigate and mitigate against DECs (Erfaninia et al., 2016, 2017; Gharari et al., 2018; Pioro and Rodriguez, 2023a; Hedayat, 2017a, 2019a; Hidayatullah et al., 2015; IAEA, 2019, 2020b, 2021a, 2016b, 2017e,c; INRA-IAEA, 2014; Moghanaki and Hedayat, 2018; Pilehvar et al., 2020, 2018).

According to the last status of the SMR projects worldwide (IAEA, 2018b, 2019, 2020b, 2021a, 2022, 2017c) the following SMR designs could be proposed or nominated as forerunners and pioneers among a lot of SMR projects: KLT-40S (Russia); HTR-PM (China); CAREM25 (Argentina); ACP100 (China); BREST-OD-300 (Russia); NuScale (USA); RITM-200 (Russia); and SMART (South Korea).

Similarly, a review study (Hedayat, 2019a, 2020a) proposed the following is as the most outstanding and feasible concepts concerning the safety features, economic issues, innovative concepts, multi-purpose utilizations, and technological challenges: CAREM 25 (Argentina); SMART (South Korea); ACP100+ (China); MASLWR, NuScale (USA); and IRIS (USA-Italy).

3 The prospect of the economy and markets for SMRs

Studies confirm that there are only a few matured or semi-finalized pioneer projects among many proposed conceptual designs (Hedayat, 2020a; IAEA, 2015, 2016a, 2018b, 2019, 2020b, 2021a, 2022, 2017c). Moreover, the lack of transparent and profitable market, marketing, finance, and financing of the SMRs, in addition to nuclear safety and security concerns, political problems, nuclear proliferation concerns, and negative mind of the public against nuclear reactors, should be kept in mind and solve to compete against renewable energies.

It is also worth mentioning that the most crucial challenge of SMRs, especially for investors and newcomers from developing countries, is the lack of FOAK and proven technology, indeed (IAEA, 2019). On the other hand, although there are a few good examples of international financial assistants or corporations as well as domestic grants by national organizations in SMR technologies, one of the most critical challenges for vendors from developed countries is the shortage of investment for the future (i.e., for prolonged or lengthy projects rather than usual action plans because of the lack of knowledge and experiences in this new field of study). Moreover, there is generally a lack of trust in developing countries, especially newcomers, to invest and finance in an unclear and high-risk business (IAEA, 2019). Therefore, KLT-40S, HTR-PM, CAREM25, ACP100, NuScale, RITM-200, and SMART, might be the best solutions for newcomers from developing countries to invest.

Furthermore, some relevant vendors, such as NuScale, have recently proposed some good, clear, and profitable commercial plans for the future of the SMR market and development worldwide (Carelli et al., 2007, 2010; Bragg-Sitton et al., 2015; Hedayat, 2017a; IAEA, 2019; Ingersoll et al., 2014b,c; Ingersoll, 2009, 2015; Ingersoll et al., 2014a,d; Moghanaki and Hedayat, 2018; NuScale, 2020). Fortunately, the both reported cost and the proposed price are regarded as competitive with advanced large GEN III+ nuclear power plants (IAEA, 2019; NuScale, 2020) but via modular construction and operation of compacted and integral PWRs in advance (Bragg-Sitton et al., 2015; Hedayat, 2019a, 2020a; IAEA, 2019; NuScale, 2020).

In the following, advanced high-temperature cogeneration applications in high-temperature SMRs, especially high-temperature gas-cooled reactors such as HTR-PM, could be very profitable and have an exciting market (IAEA, 2016b, 2017e). However, there are still some safety requirements to be established for such hybrid thermal plans with a nuclear reactor in advance (IAEA, 2001b, 2012a,b, 2013c, 2017b,d, 2018c, 2019, 2016b, 2017e). In other words, regarding specific challenges and standard requirements for high-temperature industrial non-electrical applications (IAEA, 2013c, 2017b,d, 2018c, 2017e) of SMRs (i.e., it is still under development even by international organizations), a nuclear-based industrial town (IAEA, 2016b, 2017e) for high-temperature thermal processes especially by using high-temperature gas-cooled reactors like the HTR-PM might significantly impact on the global warming effects and reduce the relevant natural disasters. It is crucial because of the massive reduction of greenhouse gasses from high-temperature industries such as steel making and forging, petrochemical applications, and hydrogen production.

But what about the other possible long-term nuclear roadmaps or much more advanced technologies. MSR could be the best challenging example in this case of study. There is a long-standing and growing interest in MSR. Furthermore, the US Air Force proposed the first reported nuclear-based propulsion idea for air-force and space applications based on the MSR (ICTP-IAEA, 2018). Today, MSR is exciting for developed or newly industrialized countries, even some small countries from the EU or even some developing countries. In other words, there is some good potential for investment and proposed markets (Bragg-Sitton et al., 2015; T, 2016; Pioro and Rodriguez, 2023a; IAEA, 2018b, 2020b, 2021a; Ingersoll and Carelli, 2020; LeBlanc, 2010; MacPherson, 1985; Mignacca and Locatelli, 2020; Pioro, 2016; Rosenthal et al., 1970; WNN, 2021) regardless the lack of enough knowledge in practice and experiences for such innovative conceptual designs.

Significant risks and concerns include the lack of enough knowledge and experience for detailed designs; licensing; fewer physical barriers and defense in depth against the most spread fission products and actinides; problems in practice, corrosion and fatigue issues; aging management; practical applications and maintenance of highly radioactive components; and especially very serious hazards of very high-level nuclear wastes and molten fuel not only in fuel assemblies but also throughout whole the primary loop.

There are still some other challenges. Challenges mainly include the lack of the FOAK; there is not any declared successful near-term project; the short duration operation, retro design, and the lack of published experiences of the first pilot operation (i.e., called MSRE designed by Oak Ridge National Laboratory in the 1960s); absence of the commercialized projects; technological challenges of salt coolant, fuels, and relevant industries (i.e., primarily encountering with nuclear activation and radioactivity); much more complex problems as technological challenges of corrosions and high-temperature effects among very high radioactive environments in practice; and providing scheduled and profitable ROI and financial solutions for customers (Hedayat, 2019a, 2020a).

On the other hand, they are proposed to be utilized and used as nuclear waste burners, fissile breeders, online radioisotope production, and high-temperature nonelectrical applications. They could burn the remaining fissile materials in the other extracted fuels to have a more economical fuel cycle (Driscoll et al., 1990; Duderstadt and Hamilton, 1976; Hedayat, 2017a). They can transmute the minor actinides, extract the gaseous neutron poisons, control the reactivity more safely and without excess reactivity, and use a very different combination of fissile and fertile materials as nuclear fuels (i.e., different possible nuclear fuel cycles by using different isotopes of Th, U, and Pu). They could significantly reduce tasks and optimize nuclear waste management, especially to reduce the final disposed radioactivity level and the required waste management timeline. Some Design Basis Accidents (DBAs), especially Loss of Coolant Accident (LOCA) or Reactivity Induced Accident (RIA), might be less hazardous than similar accidents in conventional reactors. There are also some particular inherent safety features and passive safety systems that help to mitigate against DECs (Bragg-Sitton et al., 2015; IAEA, 2016a, 2018b, 2020b; ICTP-IAEA, 2018, 2019). Nevertheless, MSR will play a crucial role in the GEN-IV reactors and significantly enhance the advanced closed nuclear fuel cycle to be sustainable for the future (Pioro and Rodriguez, 2023a; Pioro, 2016).

Although such an expensive design process is a part of the long-term nuclear roadmap of some developed or newly industrialized countries (Pioro and Rodriguez, 2023a; IAEA, 2016a, 2018a, 2020b, 2021a; NEA et al., 2015), the market for MSR for developing counties needs to be more trusted, cleared, declared, scheduled, and competitive in practice.

Based on the evidence and mentioned challenges, the First-of-A-Kind (FOAK) of such an innovative SMR (i.e., MSR) is estimated to be very expensive and uneconomic than the other more conventional SMRs such as iPWRs. Moreover, the design maturity, the financial risks, new learning process, site selection, radioactive hazards, the technology of advanced high-temperature materials, corrosion problems, gaps in knowledge required a considerable amount of Research Development (RD) tasks to fill the gaps, analyze and mitigate the severe accidents, and establish new licensing and regulatory issues. They will form some parts of the required RDs of MSR projects in practice. The cost of an Nth-of-A-Kind (NOAK) MSR is expected to decrease even if they are built in different countries (Mignacca and Locatelli, 2020). They could only be considered long-term approaches and priorities, especially to replace the conventional reprocessing and nuclear waste management plans. They will be the future of industrial countries' advanced closed nuclear fuel cycles.

There are also some good examples (Mignacca and Locatelli, 2020) of the cost of electricity. However, it is hard to believe any reliable cost or even competitive price of the advanced Gen IV technology (i.e., such as MSR). Moreover, there is not any operational plant or even approved detailed designs yet (i.e., except a very old fashioned and low power pilot called MSRE constructed and tested at the Oak Ridge National Laboratory in the 1960s) (IAEA, 2019, 2020a,b, 2021a; ICTP-IAEA, 2018; Mignacca and Locatelli, 2020). In other words, there are only some limited conceptual designs (IAEA, 2020a, 2021a). Moreover, the cost of electricity is usually taken into account regardless of the high cost of plant decommissioning in practice (IAEA, 2016b) and the extra budget required to strengthen the design against any hazardous, radioactive releases or severe accidents (Gharari et al., 2018; ICTP-IAEA, 2018, 2019; INRA-IAEA, 2014), even though such high extra costs could be very influential in price and even change the first consideration. Therefore, it is very soon to predict the cost or price of such innovative designs (IAEA, 2016a, 2018b, 2020a,b; Williams et al., 2006; WNN, 2021). Finally, a straightforward question might remain in mind is that if such novel concepts (i.e., such as MSR) are very feasible to build, very cheap, very profitable, very safe, and cost-competitive with conventional nuclear power plants, where is any commercial MSR worldwide for a long time?.

It is necessary to supply much more sustainable nuclear energy through GEN IV reactors via a long-term roadmap. Moreover, some advanced types such as MSR would be incredibly profitable for developed countries with high-income economies and undoubtedly enough experience in nuclear reprocessing plants and salt-based industries. Much more details about the advantages and disadvantageous or challenges of different SMR types are discussed in sections 7 and 8, respectively. Finally, unlike the other clean technologies, there is no transparent market for SMRs worldwide, one of the most critical weaknesses of nuclear energy.

4 Multi-purpose or co-generation applications

It is worth mentioning that nuclear reactors are a costly industry, especially in comparison with renewable energies. The best way is to utilize multiple applications coherently and demands to enhance the ROI (Hedayat, 2016b, 2020b,c,a; ROI, 2014). There are two categories in this way. They could be classified as multipurpose irradiating applications for research reactors (i.e., and for some SMRs) and cogeneration or secondary thermal applications for non-electrical applications of nuclear power plants.

4.1 Multipurpose irradiating applications

Nuclear research reactors can be utilized for a lot of neutron irradiating applications such as (Hedayat, 2014a,b, 2016b,c, 2020b,c; IAEA, 1999, 2007a,c, 2011a): Radioisotope Production; Neutron Activation Analyses (NAA); Neutron Transmutation Doping (NTD); Neutron radiography; Medical therapy, especially Boron Neutron Capture Therapy (BNCT); Geochronology; Gemstone coloring; Radiation damage study of IC and structural materials under radiation; Material structure studies; Destructive and nondestructive fuel tests; Radioactive nuclear safety tests; and, A full-scale prototype of new reactor designs.

Research Reactors (RRs) could be classified as neutron sources, subcritical assemblies, or zero power reactors; low power RRs such as a Miniature Neutron Source Reactor (MNSR); conventional pool-type Material Testing Reactors called MTRs (i.e., including low power, medium power, and high power MTRs); advanced Multi-Purpose Research Reactors (MPRRs); and high flux RRs for advanced material and fuel tests that need high-fluence neutron irradiations in advance (Hedayat, 2014a,b, 2016b,c, 2020b,c; IAEA, 1999, 2007a,c, 2011a, 2016b).

The best economic and profitable method is designing and utilizing multi-purpose RRs for a single application and almost all possible irradiating applications together, coherently. Following documents present the minimum required conditions for conventional irradiating applications, typical neutron fluxes of RRs, and minimum required RR power for multipurpose applications in advance, respectively (Hedayat, 2016b, 2020b,c; IAEA, 1999, 2007a,c, 2011a). Furthermore, these RRs are usually open pool-type nuclear reactors with plate-type fuel assemblies at the bottom of the pool (IAEA, 2007a,c) as well as more conventional and usual MTRs (Hedayat, 2014b, 2016a,c, 2017b, 2019b; Hedayat et al., 2009, 2007; Guidebook, 1980; IAEA, 1992, 2007a). More modern designs also utilize a surrounding irradiating tank by using a good reflector material such as D2O as well as a passive surrounding secondary and emergency shutdown system, coherently at the same time (ANSTO, 2021; Hedayat, 2016b; IAEA, 2007a,c; INVAP, 2021).

RUTA-70 is the only multi-purpose (IAEA, 1999, 2007a,c, 2011a) SMR mentioned for irradiating applications. It is a water-cooled water-moderated integral pool-type reactor serving as a Nuclear Heating Plant (NHP) of 70 MW(t) thermal capacity for district heating, desalination, and radioisotopes production for medical and industrial purposes as well (IAEA, 2016a, 2018b, 2019, 2020b, 2021a, 2017c).

Although there has not been reported any other SMR design like RUTA-70 that utilized with such irradiating applications in advance and in parallel with other industrial applications, there are some other pool type SMRs such as DHR 400 (IAEA, 2016a, 2018b, 2019, 2020b, 2021a, 2017c) that has some potential capacities in which it might be modified and utilized by such multi-purpose irradiating applications in addition to proposed district-heating non-electrical application as well. DHR 400 is a 400 MWth open pool-type reactor designed by CNNC (china) proposed for only district heating. Moreover, although its basic design utilized district heating, the coupling with desalination and radioisotope productions is also proposed as its outstanding features (IAEA, 2016a, 2018b, 2019, 2020b, 2021a, 2017c). There is still one challenge for such SMR designs. Both RUTA-70 and DHR 400 are still a conceptual design against a lot of operational MTRs (Guidebook, 1980; IAEA, 1992, 2007a) or even multi-purpose research reactors (IAEA, 1999, 2007a,c, 2011a) worldwide.

It is also worth mentioning that conventional nuclear power plants take some specimens for material tests on the main structural components against radiation damage and other aging effects. Those specimens are usually kept inside the reactor pressure vessels during operations and extracted for material tests and studies.

In the next, regardless of such a sizeable pool-type design, at the moment and based on the current studies and technologies, there is remained only one option from all possible irradiating applications that could be feasible for SMRs. It would be the radioisotope production. There are a lot of industrial and medical radioisotopes that need different operating conditions (IAEA, 1999, 2007a,c, 2011a). Among all of them, we can only choose cases that require a long irradiating time for some thermal spectrum SMRs (i.e., such as iPWRs, BWRs, PHWRs, and especially PHWRs) or those radioisotopes that use fission targets for some of the online refueling designs (i.e., especially PHWRs) or on-line reprocessing plants (i.e., especially MSR).

A conventional type of PHWR (i.e., PHWR 220) produces the 60Co as one of the essential industrial radioisotopes (IAEA, 2016b, 2017e). However, conventional PHWRs (Bajaj and Gore, 2006; NPCIL, 2011), such as PHWR 220 (India), are usually classified as Small and Medium-Sized Reactors (IAEA, 2001b, 2012c), not Small

Modular Reactors. Nevertheless, some new enhanced designs, such as AHWRs (Sinha and Kakodkar, 2006), are classified as Small Modular Reactors (IAEA, 2020b, 2021a), and it seems that they can be utilized for Co-60 production as well. Furthermore, some designs of MSRs have proposed some potential for radioisotope productions via online processing of molten salt fuels (IAEA, 2016a, 2018b, 2016b).

4.2 Cogeneration or multi-applicable thermal processes

Mainly, industrial thermal applications have been proposed to be utilized and used as non-electrical applications for SMRs (Bragg-Sitton et al., 2015; Hedayat, 2019a, 2020a; IAEA, 2016a, 2018b, 2019, 2020b, 2021a, 2017e). Some of them are the following: On-line power production for the national electrical grid (i.e., the higher the temperature, the higher the thermodynamic efficiency); More robust and flexible load following of the electrical grid by new modular nuclear reactors; Remote and transportable power production for small domestic demands or off-grid applications; Brackish or even sea water desalination (i.e., low temperature); Restricted regional heating (i.e., low temperature); Ethanol concentration (i.e., low temperature); Petroleum refining (i.e., medium temperature); Oil shale and oil sand transportation and processing (i.e., medium temperature); Biomass hydrothermal gasification (i.e., high temperature); Steam reforming of natural gas (i.e., high temperature); Coal gasification (i.e., very high temperature); Liquid hydrogen production (i.e., medium up to very high temperature depending on the used technology); and Steel forging and making (i.e., very high temperature).

The thermal non-electrical application strongly correlated with the operating temperature range, while different types of SMRs can provide different working temperatures. The higher the operating temperature, the higher the thermodynamic efficiency. Moreover, some applications have more benefits. As a good example, coal gasification is suitable for producing carbon-free energy resources and reducing the released radioactive C-14 into the environment (IAEA, 2016b, 2017e).

Recently, Japanese industry leaders have also called for nuclear reactors to restart as soon as possible to meet the government's carbon neutrality goal effectively and economically. For more details, nuclear reactors should work again to enable cost-effective Japanese steel and achieve zero-carbon steel by 2050 (WNN, 2021). Therefore, nuclear reactors can play a crucial role in reducing greenhouse gases via different pathways.

However, this is not the whole story. The nuclear reactor dynamics (Duderstadt and Hamilton, 1976; El-Wakil, 1971; Lamarsh et al., 2001; Moghanaki and Hedayat, 2018; Pilehvar et al., 2020, 2018; Stacey, 2018) is susceptible to transients, huge transients or unknown transients due to failure or complete loss of the secondary thermal systems (Hedayat, 2019a, 2020a). Therefore, in addition to conventional industrial safety codes and standards, some rigid restrictions for secondary thermal utilizations are required for such a hybrid plant with a nuclear reactor, as well as accurate and well-established codes and standards (IAEA, 2012a,b, 2013c, 2017b,d, 2018c), massive safety analyses and safety reviews, and industrialized and proven technologies (Hedayat, 2019a, 2020c; Hidayatullah et al., 2015; IAEA, 2019, 2017e).

Briefly, water-cooled SMRs (i.e., PWRs, iPWRs, BWRs, PHWRs, and AHWRs) are suitable and compatible with low-temperature applications such as sea water desalination or district heating. At the same time, more high-temperature SMRs (i.e., LMFBR, MSR, GCR, and especially VHTGR) are suitable and compatible with high-temperature applications, incredibly economical thermo-chemical production of the liquid hydrogen.

Usually, a non-electrical application with electricity production called cogeneration is proposed for SMRs, especially for iPWRs. Nevertheless, there are still some different conceptual designs. For more detail, China introduced DHR 400 (i.e., a 400 MWth open pool-type reactor) for only district heating (IAEA, 2020b) despite a hybrid multi-applicable plan to be used for a nuclear-based industrial town by using a high-temperature gas-cooled reactor (i.e., HTR-PM) to supply required electricity and high-temperature thermal processes instead of conventional fossil fuels (IAEA, 2017e).

It is also worth mentioning that KLT-40S is not only the FOAK of SMRs but also is the first cogeneration floating power plant for producing both carbon-free electrical and non-electrical applications (i.e., seawater desalination or district heating).

5 Advanced innovative designs and high-tech applications

Studies and experiences indicate that space missions far from the earth, such as discoveries on Mars, need a more robust, reliable, and sustainable energy supply than solar panels. Furthermore, long-lasting space missions of discoveries and explorations on Mars may cause a thick layer of dust is forming on the solar panels. Daily and seasonal variations in addition to the martian atmosphere may also cause serious failures even in long-lasting frozen states. In addition to the mentioned difficulties, very long distances from the sun and unknown or unpredicted phenomena and structures during missions (i.e., that need more energy supply and time of operation) can reduce at least energy and project efficiency or even may cause underestimated missions and monthly delays (McFall-Johnsen, 2021).

Briefly, sometimes space systems (i.e., satellites, space crafts, rovers or vehicles, remote mining or discovery stations) might be close enough to the Sun or need less energy than 1-kilowatt electrical power in which solar panels or nuclear batteries (i.e., such as radioisotope thermoelectric power supplies) can provide sufficient power supplies for those space missions. As a good example, NASA's Mars 2020 Rover (i.e., Perseverance Rover) and the previous Curiosity Rover have utilized nuclear batteries usually called Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs). A nuclear battery uses the decay heat of Pu-238 and thermoelectric effects to supply 110 W electrical power and required heat to keep devices warm enough and prohibit it from the frozen state, especially during martian winter on Mars (Agle, 2019).

Therefore, deep space exploration missions, faster-traveling goals, more complex and long-lasting explorations or discoveries on other plants, aging problems of solar panels, and radiation damage of cosmic rays and particles in addition to the other requirements (i.e., such as special requirements for robust electromechanical operations that may need more than 1 kW electrical power) can change the future of primary deep space energy supplies from the solar panels or nuclear batteries to the nuclear fission reactors (Agle, 2019; Hall, 2018; Dunbar, 2021; McFall-Johnsen, 2021).

In this way, the USA's National Aeronautics and Space Administration (NASA) has proposed and tested a very innovative high-tech reactor design based on heat pipe technology called kilopower (Dunbar, 2021). Concerning advanced space missions (i.e., that may need more than 1 kW electrical power or encounter particular challenges such as very long distances from the sun), NASA designed and tested Kilopower. It is a novel MMR based on heat pipe cooling, passive safety features, a self-regulated control system, Sterling engines, radiation shields, and thermal radiators.

However, this is not all th might be listed as the first reported successful project and test for space propulsion applications of nuclear reactors. At least 36 nuclear reactor power systems have been launched into space. They mainly include SNAP-10A by USA or BUK and TOPAZ-I by the Soviet Union (Li et al., 2016). They are specially designed and applied for deep space propulsion and robust power supplies for satellite devices in advance (Dunbar, 2021; Li et al., 2016; Liu et al., 2020; Peakman et al., 2018; Zhang et al., 2020).

Usually, such a novel and specific small nuclear reactor needs to be utilized with extraordinary features or high-tech utilities (Agle, 2019; Hall, 2018; Dunbar, 2021; Li et al., 2016; Liu et al., 2020; Peakman et al., 2018; Zhang et al., 2020) to handle and run an extraordinary space mission in advance as follows: Adapted design and system operation to the space applications and environment especially they shall be independent of the gravity force; Tolerable and resilient against tough shocks, acceleration, supersonic, and vibrations; Including fewer moving parts especially omitting conventional moving control rods; Providing mini power supplies with the 1 to 10 kW electrical power as well as providing the required heat to keep devices warm enough during very low-temperatures or harsh weather conditions; Presenting a very compact but robust and resilient structure within an integrated design platform and operation; Utilizing a self-autonomous and self-regulating control system mainly based on the inherent safety features and passive safety performances; Utilizing a very reliable, sustainable, and high-temperature passive cooling systems such as heat pipes in advanced (i.e., including a very determined, reliable, and functional temperature dependency) such as sodium heat pipes as the primary coolant and He cooled integral Stirling engines (i.e., in which Stirling cycles can gain the highest thermodynamic efficiency for those low power designs); Using integral Stirling engines and optimized thermodynamic performances (i.e., to gain the highest thermodynamic efficiency, sustainability, and reliability); Sometimes, including combined and hybrid cycles of Stirling and Bryton cycles in addition to suitable and reliable heat transfer and energy conversion through heat pipes and gas-cooled systems in much more efficient, robust, and advanced designs; Using advanced fuel and core structures such as accident tolerant multi-layered fuel pins in parallel with sodium, potassium, or lithium-filled heat pipes through passive and self-regulation control systems; Using potential sustainable nuclear fuels of breeder designs of fast spectrum core structures or using High Enriched Uranium (HEU) or Pu-239 based fuels in parallel with suitable but compact thermal and radiation shields against core radiation and cosmic rays; Using resilient fuel materials such as ceramic-metallic fuels to prohibit unwanted erosions and cracking, in addition to performing required tests against harsh conditions and transients; Provide a very ultra-safe (i.e., especially for the criticality safety) and long-term operation without refueling and maintenance during its lifetime; Accident tolerant design, especially during space lunches whenever they might be fully submersed in dry or wet sand or flooded with seawater or freshwater during an accident; Resistant and keep safe against an extensive range of transients and accidents, especially possible start-up process and procedure from a frozen state, negative reactivity feedbacks during all possible scenarios, and preventing loss of cooling caused by heat pipe burnout or failures.

The small space-class nuclear reactors are essential to realize and study advanced MMRs in practice. In other words, they are not only able to provide far faster transit times to Mars or other deep-space destinations (Hall, 2018) but also they could be considered as the proven technology promisingly as well as proposed very novel conceptual designs (Dunbar, 2021; Li et al., 2016; Liu et al., 2020; Zhang et al., 2020) of advanced heat-pipe based MMRs. Perhaps, similar to the role of the marine-based nuclear reactors as proven technologies of light water-cooled SMRs (i.e., especially KLT-40S and RITM-200).

Today, prominent and prosperous nuclear companies like Westinghouse have started designing and developing land-based MMRs like eVinci for the very robust, flexible, and special remote missions on earth (IAEA, 2020b; Westinghouse, 2020a,b). MMRs are particularly compatible and suitable to supply reliable and sustainable electricity generation for remote, transportable, or local applications (i.e., minimal demands such as islands, big hospitals, hard to reach locations such as Sites on Arctic shore regions) as well as some good examples of space propulsion applications or remote power supplies for mining and explorations on the other Planets (i.e., satellites, deep space explorations, or mining and explorations on Mars). They will be the future of robust, sustainable, and resilient energy power supplies in advance.

Nevertheless, what is more about the future, and what would be the next step for the developing countries?

NASA proposed a special algorithm called Technological Readiness Level (TRL) to determine, develop, and validate the technology readiness levels before making the FOAK or commercialization through 9 steps for the first time. Nowadays, similar steps are taken into account by the TRL of the required advanced technologies for different industries. Westinghouse has also used a similar methodology to determine and develop the Manufacturing Readiness Level (MRL) for the novel heat pipe manufacturing for such an innovative MMR.

6 Nuclear safety review

The 1970s was the decade of the enormous growth of the Gen II commercial nuclear power plants worldwide (IAEA, 2015). However, unfortunately, the first nuclear severe accident happened on March 28, 1979, initiated by a Small Break Loss of Coolant Accident (SBLOCA) in a PWR. After that, nuclear safety rules were strengthened much more. Therefore, some new concepts such as nuclear reliability, availability, redundancy, and diversity of major active safety systems (IAEA, 2006a) are strictly enforced.

A few years later, Chernobyl happened on April 26, 1986, initiated by a type of RIA in an RBMK during an accident. Inherently safety features could change the accident progression to prohibit such a nuclear severe accident disaster if such safety features were implemented and kept completely. They mainly include negative reactivity coefficients during all transients modes, the priority of active safety systems, especially emergency shutdown systems, listing and running all of the necessary Operational Limits and Conditions (OLC) (IAEA, 2000, 2001b, 2007b), and implementing all of the required defense-in-depth concepts and physical barriers (IAEA, 2006a; ICTP-IAEA, 2019), especially a resilient reactor safety containment.

Therefore, regulatory bodies have enforced stringent nuclear safety rules for new reactor designs and constructions, particularly after severe nuclear accidents. Moreover, a new generation of nuclear reactors called Gen III was considered for new designs and constructions, especially utilizing the new passive safety systems against DBAs and DECs or even severe accident progression (ICTP-IAEA, 2019). AP 1000 of PWR type could be mentioned as the pioneer GEN III reactor worldwide enhanced by a lot of passive safety systems as well as its robust inherently safety features and active safety systems in practice (Bessette and di Marzo, 1999; Deng et al., 2019; Friend et al., 1998; Matzie, 2008; Wang et al., 2013). Nuclear reactors had been exciting and growing again (Pioro and Rodriguez, 2023a; IAEA., 2005; IAEA, 2015; NEA et al., 2015) until the third severe nuclear accident suddenly happened at Fukushima Daiichi on March 11, 2011. It was initiated by an underestimated natural disaster called Beyond Design Basis Accident (BDBA) or Design Extension Condition (DEC). A severe earthquake in the sea created a tsunami of 14 meters high, flooded the nuclear site, and caused a complete SBO in a series of ordinary BWRs and the sequence of events that caused the third nuclear severe accident.

After that, lessons learned from the Fukushima Daiichi accident indicated that although the frequency of the core meltdown or the release of harmful radioactive materials to the public after a severe accident might be very low if a severe accident occurs, radiological, nuclear hazards will be enormous for both human public health and even the economy and future of nuclear industries (ICTP-IAEA, 2019; INRA-IAEA, 2014). Therefore, some new safety trends have also been taken into account. They mainly include: Passive safety features shall be enhanced to encounter with even DECs as well as DBAs, mainly a complete SBO to prohibit a severe nuclear accident; Even DECs, especially for natural disasters, shall be considered and taken into safety analyses to be ready to control and manage any possible accident progression; Robust emergency planning and nuclear accident management, as well as continuous monitoring, shall be established both on-site and off-site, resiliently, remotely, and long-lastingly; Enhanced safety by design can remove some of the DBAs roots a, such as omitting Large Break Loss of Coolant Accident (LBLOCA) by omitting the conventional primary cooling loops; Concerning the conventional Probabilistic Safety Assessment (PSA), even probabilistic results, especially Large Early Release Frequency (LERF) and Core Damage Frequency (CDF) or should be decreased sufficiently rather than conventional reactors; Release of any harmful radioactive releases to the public should be impossible via strengthening defense-in-depth concepts and barriers, using accident tolerant fuel assemblies, improving safety systems, burying the reactor containment below the ground level, and implementing a very determined accident management strategy; The emergency safety systems not only should be resilient against DBA but also should be resilient against and manage a severe accident progression as well; In addition to performing much more complete, trustable, and reliable simulations, different types of experiments shall be performed to fulfill different requirements and validate the safety performances of the inherent safety features, active safety systems, and passive safety systems, especially against different possible combinations of failures; New enhanced nuclear-grade structures, systems, and tools to manage a severe accident, including very resilient, robust, flexible robotic and remote machines; extended and strengthened cooling pools for molten lava; passive hydrogen re-combiners; intelligent filtered venting systems; smart detection systems and stations; and very resilient resin to cover up distributed radioactive materials should be considered to handle and control an occurred severe accident as well.

Those new requirements proposed the advanced gen III+ reactors (IAEA, 2020a; ICTP-IAEA, August 20-24 2018, June 24-28, 2019) such as ESBWR, VVER-1200, APR 1400, CAP 1400 to be replaced with commercial sizeable nuclear power plants or near-term generation of Gen IV nuclear reactors such as CAREM-25, NuScale, or SMART, in practice (Bae et al., 2017; Choi et al., 2012; Chu et al., 2008; Chun et al., 2013; Chung et al., 2015a,b, 2016, 2012; Delmastro, 2002; Deng et al., 2019; Gharari et al., 2018; Hu et al., 2014; ICTP-IAEA, 2018, 2019; Ingersoll and Carelli, 2020; Kim et al., 2013, 2018; Li et al., 2016; Liao et al., 2016; Locatelli et al., 2013; Magan et al.,

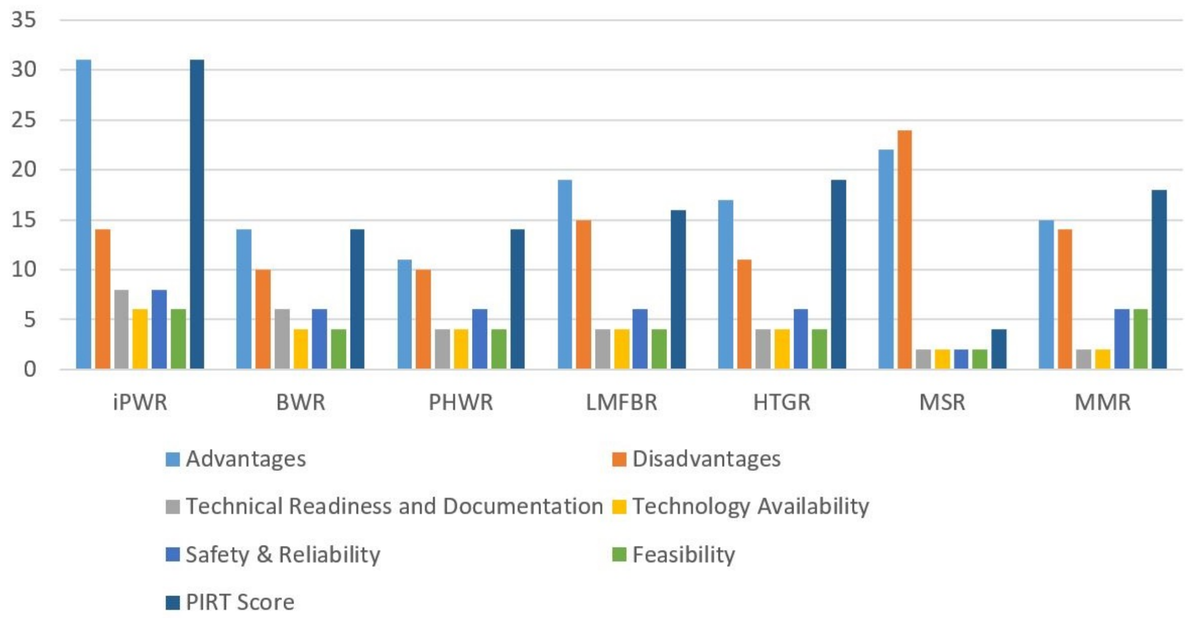

Figure 2: A comparison study between SMRs according to the developed PIRT methodology.

2011; Marcel et al., 2014; Mascari et al., 2012; Park et al., 2014; S., 2020a,b; Pilehvar et al., 2020, 2018; Pioro, 2016; Rohde et al., 2010; ROSATOM, 2019; Yun et al., 2017; Zohuri, 2019).

Next, such goals are also considered for very innovative Gen IV reactors (Pioro and Rodriguez, 2023a; IAEA, 2020a; ICTP-IAEA, 2018; Pioro, 2016; Tuček et al., 2013). Fortunately, SMRs also cover different Gen IV reactors and can be considered a prototype of the next Gen IV commercial reactors in the future. SMR designs are suitable to enhance nuclear safety features to be resilient against both DBAs and DECs, even severe accidents, especially by lessons learned from the Fukushima Daiichi accident. Some of those particular characteristics could be listed as follows: Enhanced passive safety features; Improved safety by design through the optimization of PSA and the elimination of the significant accident roots, particularly LBLOCA; Less dependency on active safety systems, particularly during relevant DBAs such as SBO and LOFA; Improved Inherently Safety Features; Improved defense-in-depth concepts and physical barriers; More safe and secure layout, structure, vessels, and containment; Strengthen against DECs even Severe Accidents; Contain less radio-active source terms per module; Higher availability, reliability, and flexibility regarding modular operations; Usually fully installed and buried underground in-depth resistant against DECs, especially natural disasters, terrorist attacks, and severe nuclear accidents; Usually more tolerable and resilient against seismic conditions; Smaller CDF; Smaller LERF; Smaller and more restricted EPZ (Emergency Planning Zone); Sometimes involving an off-site refueling or very long-term refueling to reduce the risk of nuclear proliferation concerns and radiation hazards; More compatible with optimizing nuclear core management and open fuel cycle in parallel, especially nuclear waste management, to reach a cleaner and more sustainable nuclear energy supply; therefore, they reduce the risk of reserving very long-term and highly radioactive materials via a compound open nuclear fuel cycle as well. There are a few action plans for constructing a few modern SMRs such as CAREM 25 or HTR-PM. It seems that there is still a long way to establish and validate all considered and proposed safety features and technology requirements in practice (Pioro and Rodriguez, 2023a; Hedayat, 2019a, 2020a; Hidayatullah et al., 2015; IAEA, 2018b, 2019, 2020b, 2021a; ICTP-IAEA, 2018; Liu and Fan, 2014; NuScale, 2020; Rowinski et al., 2015). Moreover, a review of nuclear safety analyses and technological challenges for SMRs should also be included and fulfill any possible DEC and even a good enough mitigation of a severe nuclear accident, especially for those modern designs initially proposed before the Fukushima Daiichi accident.

7 Developing and involving a PIRT methodology for decision making in SMRs

Todays, Phenomena Identification and Ranking Table (PIRT) becomes a very practical tool for decision making in the field of nuclear safety for expert panels in advance (Aksan, 2014; Deng et al., 2019; ICTP-IAEA, 2019; Kang et al., 2015; Krepper and Beyer, 2010; Trégourès, 2021). It is especially useful for: The gap analysis and find out a new strategy; To find out priorities of Research and Developments (R&Ds); or to made the best decision covering safety and economy issues.

Generally, this methodology has four main features and outlines. A conventional PIRT include: Phenomena Identification (i.e. the entire spectrum); Ranking "safety significance"; Ranking "degree of knowledge"; Panel Experts (i.e. shall cover up sufficient expertise and diversity).

In this paper, a developed PIRT methodology has been

Table 1: A typical PIRT table for SMRs filled by the author.

Parameters			Number of Advantageous	Number of Disadvantageous	Technology Readiness and Documentation	Technology Availability	Safety and Reliability	Feasibility of design and construction	PIRT Score
			NA	ND	TRD	TA	SR	F	
Weighting Factors			W_{NA}	W_{ND}	W_{TRD}	W_{TA}	W_{SR}	W_F	Eq. (1)
Default Values			1.0	-0.5	0.25	0.25	0.25	0.25	
Row	SMR Type	SMR Technology	Ranking through a Graded Approach						
			VL (Very Low:2) L (Low:4) M (Medium:6) H (High:8) VH (Very High:10)						
1	iPWR	NuScale	31	14	8	6	8	6	31
2	BWR	BWRX-300	14	10	6	4	6	4	14
3	PHWR	AHWR	11	10	4	4	6	4	14
4	LMFBR	4S	19	15	4	4	6	4	16
5	HTGR	HTR-PM	17	11	4	4	6	4	19
6	MSR	Moltex Energy SSR-W300	22	24	2	2	2	2	4
7	MMR	eVinci Westinghouse	15	14	2	2	6	6	18

proposed to develop strategic planning for SMR technology development and deployment, especially for developing countries or new comers (i.e. countries with less experience in the nuclear reactor industry). The following equation (Eq. (1)) is proposed to collect the net PIRT score:

$$\text{PIRT Score} = \text{Round}\Big(W_{NA}NA - W_{ND}ND + W_{TRD}TRD + W_{TA}TA + W_{SR}SR + W_F F\Big) \tag{1}$$

where NA is the Number of main Advantages, and W_{NA} is the relevant weight; ND is the Number of main Disadvantageous or challenges, and W_{ND} is the relevant weight; TRD is the Technology Readiness and Documentation, and W_{TRD} is the relevant weight; TA is the Technology Availability, and W_{TA} is the relevant weight; SR is the nuclear Safety and industrial Reliability, and W_{SR} is the relevant weight; and finally, F is the Feasibility of design and construction, and W_F is the relevant weight.

The next equation (Eq. (2)) is also taken into account the normalized factors:

$$\text{Normalized PIRT Score} = \text{Round}\Big(\frac{\text{PIRT Score} - \text{Min}(\text{PIRT Score})}{\text{Max}(\text{PIRT Score}) - \text{Min}(\text{PIRT Score})}\Big) \tag{2}$$

Furthermore, the following scoring pattern inspired of the Fuzzy-Logic concept (Zadeh, 1968, 1971) is proposed to rank each item in the ranking table via a graded approach: Very Low (VL): 2; Low (L) : 4; Medium (M): 6; High (H): 8; Very High (VH): 10.

Table 1 and Fig. 2 present a comparison study between SMRs according to the developed PIRT methodology by the author. It could be noted that the selected technologies for each reactor type is proposed by the author based on the studies. Undoubtedly, to develop a domestic strategic plan, an expert panel should score and evaluate the factors as well. Moreover, Table 2 presents a more simplified model of Table 1 dismissing the number of advantageous and number of disadvantageous for an expert panel.

8 Prospects for new projects timelines and progressions

In addition to the last states, outlook, and prospects of pioneers and forerunners of SMRs, a review of submitted designs and action plans to IAEA (IAEA., 2005; IAEA, 2006b, 2011b, 2012c, 2016a, 2018b, 2019, 2020b, 2021a, 2022, 2017c) show that based on the evidences and the last progressions, at least 10 years is required to complete a new design and enter the operating tests of an iPWR even for industrialized countries with enough experience and knowledge in this field of study.

More advanced or innovative designs especially GEN IV designs of HTGR or MSR might need 20 to 30 years for commercialization. But in the next, the NOAK deployments and developments will be significantly reduced in time and cost, or even they might be completely competitive with current conventional NPPs in the future. Studies (Bragg-Sitton et al., 2015; Hall, 2018; T, 2016; Pioro and Rodriguez, 2023b,a; Hedayat, 2020a; IAEA, 2001b; IAEA., 2005; IAEA, 2006b, 2012a,c, 2013a, 2015, 2016a, 2017a, 2018a, 2019, 2020b, 2021b, 2016b, 2017e,c; ICTP-IAEA, 2018; INRA-IAEA, 2014; Liu and Fan, 2014; Locatelli et al., 2013; Magan et al., 2011; Marcel et al., 2014; Rowinski et al., 2015; Testoni et al., 2021; Tuček et al., 2013; Velidi and Guven, 2020; Vujić et al., 2012; WNN, 2020; Zohuri, 2019, 2020) indicate that such a new design and construction project may include: Preliminary studies and initial pre-conceptual design (i.e. about 2 to 4 years); Feasibility study of design and construction including the development of the pre-conceptual phase, technology validation, and vendor contracts and qualification (2-4 years); Developing conceptual design (i.e. 1-2 years); Pre-review and Pre-licensing(i.e. at least 1 year usually in parallel); Funding and Basic Design (i.e. 1-2 years); RD for more ordinary plants especially developing required major tests loops and facilities (i.e. a few years usually in parallel); RD for more advanced technologies especially for the demonstration of key technologies and pilot plans (i.e. up to 10 years); Detailed Design (i.e. up to 5 years); Material and fuel tests (i.e. at least a few years sometimes in parallel); RD in parallel with detail design to support new developments and fill the gaps (i.e.

Table 2: Proposed a more simplified PIRT table for an expert panel.

Parameters		Technology Readiness and Documentation	Technology Availability	Safety and Reliability	Feasibility of design and construction	PIRT Score
		TRD	TA	SR	F	
Weighting Factors		W_{TRD}	W_{TA}	W_{SR}	W_F	PIRT Score = Round$\Big(W_{TRD}TRD$
Default Values		0.25	0.25	0.25	0.25	$+W_{TA}TA + W_{SR}SR + W_F F\Big)$
Row	SMR Type	Ranking through a Graded Approach				
		VL (Very Low:2) L (Low:4) M (Medium:6) H (High:8) VH (Very High:10)				
1	iPWR					
2	BWR					
3	PHWR					
4	LMFBR					
5	HTGR					
6	MSR					
7	MMR					

at least a few years sometimes in parallel); Licensing Process (i.e. at least a few years); Civil and Construction (i.e. 1 to 5 years); Commissioning includes initial conventional industrial tests, operational and hot tests, cold criticality, operational modes (i.e. 1 to 2 years); and, Commercialization (i.e. after building the FOAK).

Therefore, developing the current pioneer designs but undoubtedly those designs with sufficient and available safety analyses and technological readiness could accelerate the SMR development worldwide as one of the undeniable solutions to solve the global warming and climate change issues and reach carbon-free and sustainable energy resources, particularly for special conditions, locations, and applications.

9 Proposed roadmap and action plan for developing countries

Next, in this paper, we propose five different roadmaps for SMR developments and deployments especially for developing countries in general. They include:

- **Roadmap A** : fast modular development and deployment of SMRs based on the local grid capacity, or fast modular development of restricted region or with less dependency on the national power grid;
- **Roadmap B**: very fast modular development of coastline regions, islands, inshore, or offshore regions especially based on the fully turnkey contracts;
- **Roadmap C**: involving both electrical and non-electrical applications especially high-temperature demands to develop nuclear-based industrial cities, and developing near-term technologies of the Gen IV Reactors;
- **Roadmap D**: Very restricted or strategic remote applications.
- **Roadmap E**: Developing more advance Gen IV reactors, especially to optimize closed nuclear fuel cycle, and enhance the conventional nuclear waste management and reprocessing plants.

Table 3 presents the proposed the strategic plans for the SMR development and deployment based on the developed PIRT methodology by the author due to the proposed roadmaps. In other words, table 3 also presents the predicted possible winner designs proposed for developing countries or new commers. Undoubtedly, this strategic plan is developmental and can be updated and adapted with the last status of SMR technologies and national demands through a collective wisdom of an expert panel.

The last main feature of a strategic action plan is the estimated time lines for roadmaps. Three main classification is proposed for SMR development and deployment. They include:

- Short-term approach (i.e. less than five years),
- Mid-term approach (i.e. less than 10 years),
- Long-term approach (i.e. between 10 and 20 years).

Table 3 also predicted the required timelines based on the last status of the SMR projects. It could be also noted that the less developed countries or newcomers in the nuclear industry should strongly joint with primary developers to take benefits of SMRs in practice. Moreover, the projects timelines can reduce for developing countries or countries with dependent nuclear industries, and especially for the developed or industrial countries with enough experiences in nuclear technology, independently.

Regarding the last proposed roadmap for long-term SMR development in developing countries, it is worth mentioning that SMR is a developing technology and needs to be a proven technology. In other words, although Gen IV reactors are considered to be the future of nuclear energy, they are still under development and needs a broad range of RDs. Furthermore, concerning the treaty on the proliferation or misuses of nuclear materials, such advanced SMRs might be banned or extremely limited to be deployed in the developing countries.

10 Conclusions

This paper exclusively presents a comprehensive comparison study between different types and applications of SMRs. The paper also covers different classifications and generations. It includes iPWR, BWR, PHWR, LMFBR,

Table 3: Potential of the winner designs for developing countries based on the proposed PIRT methodology depend on the chosen roadmap.

Row	Roadmap	SMR Type	Technology Supplier	Country of Origin	Total PIRT SCORE	Normalized PIRT SCORE	Priority	Timelines
1	A	iPWR	NuScale	USA	31	1.0	Distributed Modular Deployment	Mid-term
2	A	iPWRs	CAREM-25	Argentina	31	1.0	Grid Connections/ Local Demands	Mid-term
3	A	iPWRs	ACP 100+	China	31	1.0	Grid Connections/ Local Demands	Mid-term
4	B	iPWRs (Floating P.P.)	KLT-40S RITM 200	Russia	31	1.0	Domestic Coastal Needs	Short-term
5	C	iPWRS	SMART	South Korea	31	1.0	Local Demands/ Sea Water Desalination	Mid-term
6	C	HTGR	HTR-PM	China	19	0.6	Grid Connections/ High-temperature Applications	Long-term
7	D	MMR	eVinci	USA	18	0.5	Strategic or Remote Applications	Short-term
8	E	MSR	Moltex Energy	UK and Canada	4	0.0	Developing GEN IV, Fuel Cycles, and Waste Management	Long-term

GCR, MSR, and MMR as well. Some special futuristic nuclear reactors are also introduced and discussed through their challenging issues.

Next, the last status of SMR designs and projects are noticed and discussed. The prospect of the economy and markets for SMRs are also presented and discussed as well. In the next part, both non-electrical irradiating applications and thermal co-generation applications are also introduced and discussed via relevant examples and references. Advanced high-tech applications of MMRs from deep-space exploration to remote siting applications on earth or even other plants are also introduced and discussed through advantages, applications, and technical challenges.

Then in the next section, nuclear safety is mentioned and discussed as the most important challenging subject to develop nuclear reactors worldwide. Main advantageous and disadvantageous are also noticed and reviewed in detail for all different types of SMRs. Moreover, each part of study is enriched with a lot of relevant references for further studies and investigations in-depth by dear readers.

Studies indicate that developing strategic plans for SMR development and deployment is a very complicated decision making in the current situation, especially for newcomers or even developing countries with good experiences in the nuclear industry. Therefore, a special PIRT methodology has been developed and proposed for decision making in this field of study. It mainly include: the number of main advantages; the Number of main disadvantageous or challenges; technology readiness and documentation; technology availability; nuclear safety and industrial reliability; and feasibility of design and construction. A filling form is also proposed for extended decision making through expert panels. A fuzzy scoring pattern is proposed to rank each item in the ranking table. The corresponding tables and figures also present the proposed results based on the authors consideration and minds on different cited references. They briefly present a comparison study between different types of SMRs according to the developed PIRT methodology and selected technology suppliers by the author. Undoubtedly, the proposed ranking table should be completed and inferred by the relevant expert panel for domestic or national demands and needs in advance.

Throughout the whole paper, it has been tried to propose the best options for the future of nuclear energy based on the classified short-term (i.e. less than 5 years), mid-term (i.e. between 5 to 10 years), and long-term (i.e. the next 20 years) strategies. In other words, the main features of the proposed and projected roadmap include a short-term approach (i.e. less than five years), midterm approach (i.e. less than 10 years), and long-term approach (i.e. between 10 and 20 years) especially for developing countries. Therefore, the prospects for the project timelines and progressions of new nuclear reactors are also reviewed and discussed briefly.

Finally, five different roadmaps and action plans are proposed for developing countries. They include : fast modular development and deployment of SMRs based on the local grid capacity, or fast modular development of restricted regions with less dependency on the national power grid; very fast modular development of coastline regions, islands, inshore, or offshore regions especially based on the fully turnkey contracts; involving both electrical and non-electrical applications especially high-temperature demands to develop nuclear-based industrial cities, and developing proven technologies of the Gen IV Reactors; developing very restricted or strategic remote applications; and finally, developing more advance or novel Gen IV reactors, especially to optimize closed nuclear fuel cycles and enhance the conventional nuclear waste management and reprocessing plants throughout a long-term vision.

Consequently, for short-term strategies, the fast way is to enhance the nuclear capacity utilizing the pioneers of water cooled floating power plants such as KLT-40S and RITM based on the turnkey contract on coastal regions.

For mid-term strategies, the best competitive solutions are pioneer land-based SMRs especially iPWRs with a higher TRL such as CAREM25, NuScale, SMART, and ACP100. It is worth mentioning that HTR-PM of GCR is especially competitive for developing grid connections with higher power capacity and demands as well.

For long-term strategies, some Gen IV technologies especially VHTR or MSR may also change the world in the future. Non-electrical applications such as district heating and high-temperature thermal applications such as hydrogen production (i.e. especially as the cleanest fuel ever known) or steel forging utilizing co-generation of advanced nuclear power plants may finally overcome the greenhouse warming effects. Particularly, MSRs should be considered for the long-term roadmap of the future of nuclear energy especially to be replaced with conventional closed fuel cycles and nuclear waste management in industrial countries with sufficient experience in nuclear fuel cycle reprocessing and knowledge of industrial salt-based utilities and suppliers.

Finally, research reactors especially MPRRs and MMRS are also necessary for the future of nuclear power plants as well as the other modern technologies from semiconductor industries to deep space explorations or even strategic remote demands on earth.

Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work.

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