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A review of advanced SMRs particularly iPWRs regarding safety features, economy issues, innovative concepts, and multi-purpose deployment

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HIGHLIGHTS

- Comprehensive unique introduction and supplementary concepts.
- Using and introducing valued international issues and documents.
- Discussing about safety, operating performances, and economy coherently.
- Introducing the most important SMRs via advantages and challenges.
- Developing and innovative programs about SMRs especially multi-applications.

ABSTRACT

Both of small and medium sized reactors and small modular reactors are called SMRs. They are reviewed and discussed in this paper, particularly integral Pressurized Water Reactors (iPWRs). Studies show that PWRs are the most interested, designed and constructed nuclear reactor type worldwide. Some innovative small modular PWRs like the MASLWR, NuScale, CAREM-25, SMART and ACP-100 have several outstanding characteristics to be promisingly recognized as near term options of the next generation of small modular PWRs. They have several inherently safety features and improved passive safety system. They require smaller infrastructure and capital costs. They can be also developed rapidly in different and independent modular unites even for remote area or outlands without required infrastructure or electrical grids. It should be noted that new modern economy strategies like the Return of Investment (ROI) issues may advice medium or large reactors rather than small units for developed and industrial countries while small modular plans can be much more interesting and accessible for new comers or even developing countries. Finally, multi-applicability is an appropriate solution to develop expensive nuclear power plants economically as well as multi-purpose research reactors (especially by means of small modular iPWRs).

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1 Introduction

Currently, small and medium sized power reactors are more interested worldwide. They are called SMR according to the IAEA classification (Kuznetsov, 2004; IAEA, 2006b, 2007, 2011b,a); Also a specific type of them, Small Modular Reactors, has been more selected and proceeded along new Research and Development (R&D) programs of industrial countries to be developed throughout the world simply and rapidly via their modular deployment. Similarly, they are called SMR (Carelli and Ingersoll, 2014). There are several documents and papers which could be useful for corresponding studies. Mainly, they can be mentioned and followed in detail by (Carelli et al., 2010; Carelli and Ingersoll, 2014; Erfaninia et al., 2016, 2017; Hedayat, 2017; Kuznetsov, 2004; IAEA, 2006b, 2007, 2011b,a, 2018, 2019; Modro et al., 2003; Ingersoll, 2009; Ingersoll et al., 2014; Reyes and Ingersoll, 2013; Reyes et al., 2007; Söderholm et al., 2014; Zhang et al., 2009; Zohuri, 2019) as well as reviews (Hidayatullah et al., 2015; Liu and Fan, 2014; Locatelli et al., 2014; Ramana et al., 2013; Rowinski et al., 2015).

Small and Medium sized power Reactors (SMRs) have been developed widely as different concepts and designs to be used in local, restricted, or portable area especially for developing countries (by industrial countries). A variety of designs and safety approaches targeted at a near and long term deployment. New concepts and designs also cover the

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expanded range of energy products (including petrochemical products such as gasoline and clean fuels like the hydrogen), potable water, also secondary heating applications of residential heat. SMRs have many common issues related to the provision of economic competitiveness, safety, and nuclear technologies. Innovative approaches are needed to resolve these issues, and finding a solution to balance design, construction, and maintenance costs and their revenues and benefits. As an example, inherently and passive safety features are much more concerned and involved in new advanced designs of SMRs like CAREM, MASLWR, NUSCALE, and IRIS. It could be noted that such new concept should be taken into account and tested carefully. As an example much more careful analyses of a complete self-pressurizer passive heat removal system by natural convection shows some un-stabilities (Marcel et al., 2013). Such operational problems (based on using passive safety futures) may be much more complicated or even resolved when additional piping lines of multi-purpose applications are added to the plants. On the other hand, some layouts such as the MASLWR (Modro et al., 2003) were introduced to be a multi-applicable small modular reactor. Such multi-purpose plants can be much more cost effective regarding Return of Investment (ROI) issues (ROI-Institute, 2014). Such characteristics could be complementary for competitive patterns with large sized PWRs regarding economy of scale. When a simple scaled down pattern may lose some benefits, some new type of lesser mass produced patterns (e.g. iPWRs) can be competitive with large reactors. In specific, an international consortium was firmed to overcome challenges for near term demands within the IRIS project (Petrovic et al., 2006). It was proposed as a modular integral PWR (iPWR) creating power of 335 MWe per each module.

In this paper, a concise introduction to all type of SMRs, corresponding economic policies and issues, safety, and some technological performances are presented and briefly discussed via corresponding references. Then small sized PWRs, with power less than 300 MWe, are introduced. It includes major differences between types, safety trends, some innovative technological trends, multi-applicable programs and capacities, current and developing technologies, some innovative designs and features, inherently safety features and passive safety systems, economy issues, and a brief feasibility study are reviewed and discussed. Finally, a general comparison between all types of small PWRs including near-terms and long-terms (innovative designs) are discussed, briefly.

It seems that such studies should be much more completed and traced worldwide to develop a reliable and sustainable nuclear road map (IAEA, 2015; Energy, 2014), and to change the negative public opinion, and also the negative effect on the nuclear reactor operations, designs, and constructions of nuclear power plants especially after Fukushima Daiichi accident (IAEA, 2015; Energy, 2014; INRA and IAEA, 2014). On the other hand, the high blue map of the global energy policy may enhance the developing capacities of nuclear power plants by 2050 as a powerful clean technology policy (to reduce green-house gas production and finally to restrict global warming effect). Anyway, new advanced innovative SMRs have some potential to be completely safe for public without any sensible radiation hazard risks even in a severe accident; especially those ones that an integral pressure vessel will be fully submerged underwater and reactor containment fully installed underground.

Studies indicate that PWRs are the most wanted case worldwide (IAEA, 2015); also iPWRs can overcome economy of scale and improve passive safety system; also, they may be a much more flexible items to be compatible with secondary heating application based on a natural core cooling system (via multiple internal heat exchanger). On the other hand, both of anticipated and even unknown transients should be checked out carefully. Studies (Carelli and Ingersoll, 2014; IAEA, 2015) show very influential positive effects on the current status of iPWRs in safety by design based on the lessons learnt from Fukushima Daiichi accident (INRA and IAEA, 2014). New codes and standards, also test loops should be developed. It could be inference that CAREM-25 and NuScale (a modified version of the MASLWR) can be chosen as the best option of the small modular iPWRs (regarding performed feasibility studies, their safety performances , and economy performances), while the IRIS could be the best choice of the medium sized modular iPWRs within a borderline of GEN-III+ and GEN-IV reactors. On the other hand, some designs like the SMART and ACP-100 may be also good solutions to develop economic multi-purpose small modular PWRs, too. It is also worth mentioning that there are still a lot of other designs (such as KLT-40S, RITHM-200, CNP-300, RUTA, etc) that might be studied and developed worldwide in a near future. Some of them are proposed as a practical platform for some special applications particularly marine-based applications (such as KLT-40S, and RITHM). Briefly, some designs are more innovative, futuristic, or likely to be chosen and considered for researches. Anyway, it seems that much more accurate simulations, experimental tests, and feasibility studies are required to reach trade-marked reactors in this category (multi-purpose small or medium sized modular iPWRs) worldwide (IAEA, 2015). Figures 1 and 2 show 3-D views of the pointed SMRs. For more information, please visit the IAEA Advanced Reactors Information System (website: https://aris.iaea.org/).

On the other hand, some countries used simple scaled down small nuclear reactors to study carefully about GEN-IV reactors (IAEA, 2016). Recently, researches (Garcia et al., 2016) proposed hybrid power plants based on the SMRs, other clean technologies (especially solar cells), and high capacitance storage batteries. They may be used (in a near future) to get much more flexible, economic, and safe load following, and to take high performance secondary heating applications especially water desalination and gasoline production; also, such plants may solve or at least reduce the difficulties of a flexible load following of nuclear power plants. Briefly, a flexible, robust, and safe action plan for non-electrical applications could be developed regarding advanced modular iPWRs based on modern economy issues and developing new required codes and standards. Modularity, hybrid operations (of

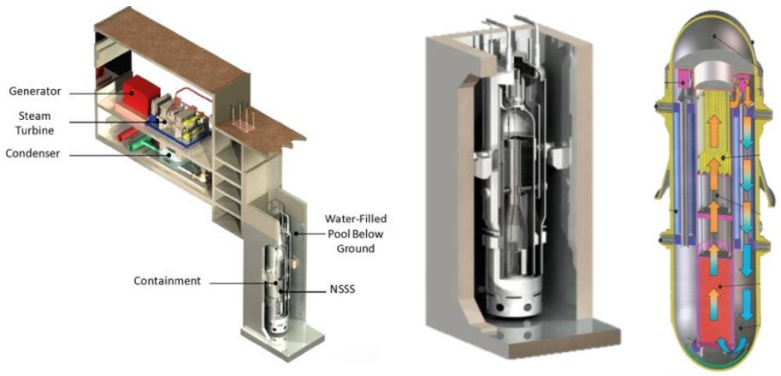

Figure 1: An independent module of the MASLWR (left), NuScale (centered), IRIS (right).

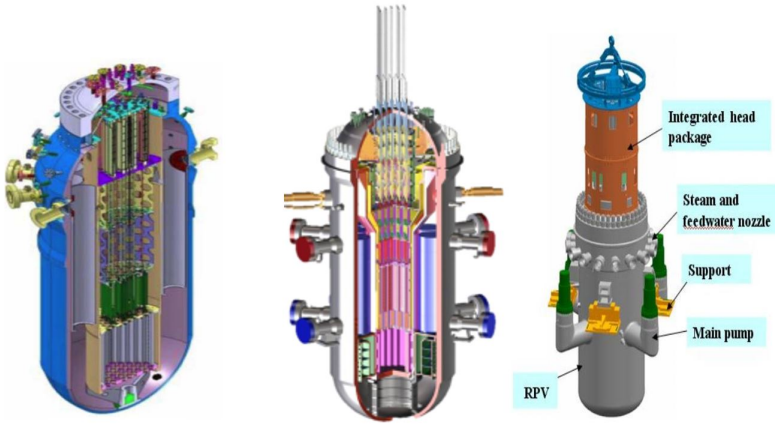

Figure 2: An independent module of the CAREM-25 (left), SMART (centered), and ACP100 (right).

SMRs and the other clean technologies), also providing a robust control of additional heating process can also improve the performance of the next generation of advanced nuclear reactors in a near future. Stability of natural core cooling and self-pressurized systems should be checked out and tested carefully against every possible anticipated transients and even un-known transients (Pilehvar et al., 2019; Moghanaki and Hedayat, 2018). New adapted best estimate tools (Hidayatullah et al., 2015; Rowinski et al., 2015), careful simulation and analyses of Computational Fluid Dynamics (CFD), and accurate coupling of neutronic and thermal-hydraulic calculations (Erfaninia et al., 2016, 2017) should be encouraged and improved in this way as well as developing new required codes and standards (Hidayatullah et al., 2015; Rowinski et al., 2015), real time test loops (Reyes et al., 2007) and full scope simulators.

2 Small and Medium Sized Reactors (SMRs)

Small and Medium sized Reactors (SMRs) are especially suitable for deployment in the developing countries with low electrical grid capacity and in countries with low electricity demand projections. SMRs are also the preferred option for non-electrical applications of nuclear energy such as desalination of seawater, district heating, hydrogen production and other process heat applications. In the past, the main trend in nuclear power reactor technology development showed an emphasis towards large reactors due to the economy of scale. The current status of the operational nuclear power plants worldwide confirms this global tendency and decision making (IAEA, 2015). A development of SMRs points into the opposite direction especially towards smaller outputs with an equivalent electrical power of less than 700 MWe according to the IAEA classification (Kuznetsov, 2004; IAEA, 2006b, 2007, 2011b,a).

Although registered constructed or planned nuclear power reactors worldwide to the IAEA reference data (IAEA, 2015) shows an international trend to the large PWRs, there are several practical and on-going (Carelli and Ingersoll, 2014; Liu and Fan, 2014; Locatelli et al., 2014; Rowinski et al., 2015) Research Development (R&D) programs toward the SMRs.

Several approaches (Carelli and Ingersoll, 2014) are being under development and consideration, including the increased use of passive safety features for reactivity control and reactor shut down systems, decay heat removal and core cooling systems, and reliance on the increased margin to fuel failure achieved via the use of advanced high-temperature fuel forms and structural materials. Some SMRs also offer the possibility of very long core lifetimes with burnable absorbers or high conversion ratio in the core. These reactors incorporate increased proliferation resistance and may offer a very attractive so-

lution for the implementation of adequate safeguards in a scenario of global deployment of nuclear power plants.

The activities on design and technology development for SMRs are ongoing in many countries; and there are still growing expectations of an increased support from the IAEA to interested member states in the definition of common technology and infrastructure development needs and in the coordination of selected international Research and Development (R&D) efforts for such reactors (Carelli and Ingersoll, 2014; Kuznetsov, 2004; IAEA, 2006a,b, 2007, 2011b,a).

2.1 Classification and current status of the SMRs

Regarding previous studies, about 50 concepts and designs of the innovative SMRs could be under development in more than 15 IAEA member states. SMRs are under development for all principle reactor lines, i.e., water cooled, liquid metal cooled, gas cooled, and molten salt cooled reactors, as well as for some non-conventional patterns (Kuznetsov, 2004; IAEA, 2006a,b, 2007, 2011b,a).

It seems that there are some problems to get a final license from national regulatory bodies especially for new advanced types (Ramana et al., 2013). Certainly, The Fukushima Daiichi accident had a very strong effect on the nuclear safety issues and licensing process. Anyway, new studies show promising developments in some advanced iPWRs like the CAREM-25 and the NuScale (Carelli and Ingersoll, 2014; Hidayatullah et al., 2015).

Currently, there are more than 45 SMR designs under development, only a few of them have received design certification, some of them are under construction as prototype plants, and others are under various stages of design development (Hidayatullah et al., 2015); maybe a complicate re-design process (INRA and IAEA, 2015) is required or there are some major problems about emergency zone planning especially after Fukushima Daiichi accident (INRA and IAEA, 2014).

Also, a literature review of the technology showed the gaps in commercializing and marketing of this technology. Currently, only a few designs are commercially developed, and others remain only as concepts (especially Generation IV designs). In other words, substantial research and development efforts are required (Rowinski et al., 2015).

It is noted that although SMR is an emerging energy technology that can meet the demand of safety, efficiency and sustainability; there is still a long way (at least about 10 years) to take a complete technological readiness of new SMRs. There are also some conceptual designs of industrial involvement (beside academic and experimental supports) which imply a potential of near-term commercialization (Liu and Fan, 2014). The WSMR, CAREM-25 and NuScale can be admired as outstanding near-term models. It could be noted that some international effort besides the knowledge and technology management of high experienced companies may overcome such problems and speed up the required technology readiness for advanced SMRs in an unique international pattern like IRIS. Similar potential can be catch up with smaller reactors like MASLWR regarding a complete passive primary cooling system without any primary pumps.

There are much more figures and description in detail about SMRs according to the four main categories including light-water cooled, heavy-water cooled, fast liquid-metal cooled, and gas-cooled SMRs (Carelli and Ingersoll, 2014; IAEA, 2011b; Subki, 2012). There are also some more examples about the other types of SMRs (Rowinski et al., 2015).

Usually, current operating SMRs have been developed based on the GEN II or partially GEN III PWRs for naval applications or PHWRs for power generation around the world. Water cooled SMRs could be the most suitable candidate for a near-term deployment (of generation IV reactors). On the other hand, high temperature gas cooled reactors can provide the most beneficent thermodynamic efficiency of electrical power generation and even some of non-electrical applications (specially high-efficient economic production of hydrogen fuel as a complete clean fuel for the next generation of private and public transportation). It could be noted that there are some special (appropriate) choices and roadmaps in coordinated with developing Very High Temperature Gas cooled Reactors (VHTGR) regarding GEN IV reactors for industrial countries (Howarth, 2008).

2.2 Major Arguments

According to the classification adopted by the IAEA, small reactor is a reactor with the equivalent electric power less than 300 MW, medium sized reactor is a reactor with the equivalent electric power between 300 and 700 MW (Kuznetsov, 2004; IAEA, 2006a,b, 2007, 2011b,a). A development of Small and Medium sized Reactors (SMRs) is supported by the following major arguments:

- The principal drivers behind the projected large increase in global energy needs are population growth and economic development in todays developing countries, which often have insufficient infrastructure and small electricity grids; The reactor fitting into a SMR range may be a good choice to meet the demand of such countries;
- Many less developed or even developing countries have limited investment capability; In this situation, SMRs may become the only affordable nuclear power option for such countries;
- In industrialized countries, the electricity market deregulation is calling for a flexibility of power generation and applications that smaller reactors may offer. In particular, the SMRs of modular design provide for an incremental capacity increase, which makes it possible to spread the investments in time and to reduce the associated financial risk;
- SMRs can be particular interest for both near-term, e.g. seawater desalination, and advanced future non-electrical applications, such as hydrogen production, coal liquefaction, and other process heat applications;

- New technologies cant be deployed at once to a large scale. Learning from a small prototype plant may be necessary to reach the final goal of their wide-scale deployment;
- There are several coal mines worldwide which should be replaced with other clean technologies; SMRs could be a good choice regarding small amount of required infrastructures;
- The modularity is much more adapted with new economy issues like the V model of Return of Investment (ROI) (ROI-Institute, 2014) especially in order to take an effective, modular action plane during schedules and action plans of the reactor construction and maintenance tasks;
- And, it seems that design and operation of the Integrated Pressurized Water Reactor (iPWR) type of SMRs especially those ones providing a multi-applicable programs like the MASLWR (Modro et al., 2003) to be completely well-matched with new modern Integrated Management System (IMS) supposed to be used for nuclear industry (IAEA, 2013) as well as compatibility with modern economy issues (Modro et al., 2003; Söderholm et al., 2014).

2.3 Multi-applicable SMRs

There are several applications for new generation of nuclear reactors as: power generation, sea water desalination and potable water production, Hydrogen production (as a completely clean fuel producing water after combustion), local heating system, required high temperature heating application including industrial and chemical process. There are several pointed applications to be included in reactor design (Carelli and Ingersoll, 2014; Kuznetsov, 2004; IAEA, 2006a,b, 2007, 2011b,a; Modro et al., 2003). Table 1 illustrates a variety of SMR applications and cogeneration options via some more examples (Kuznetsov, 2004; IAEA, 2006a,b, 2007, 2011b,a).

For some designs, such as HTR-PM, various cogeneration options will be probably added at further stages of their design development. Many patterns provide appropriate objects and options for a flexibility of different applications or cogeneration options. Such cases can be mentioned as the PWR type small reactors from Russia especially for floating applications like ice-breakers, and the MASLWR or lead-bismuth cooled reactors from the USA; also, the remarkable examples of a multiple cogeneration option are provided by the PBMR-400. Here, the approach is to produce electricity, hydrogen and potable water within a single balance of plant. Finally, many designers make a provision for the purposeful use of the rejected heat, which is viewed as an important factor contributing to the competitiveness of their SMRs. In addition, MASLWR (Modro et al., 2003) could be mentioned as one of the most successful project to bring new passive safety feature of the core cooling system and integration of pressurization in an integral vessel. It was introduced as a Multi-Applicable Small Light Water Reactor; and finally it was well-tested based on a real time test loop at Oregan university; it was redesigned as the NuScale reactor and finally submitted to US-NRC for final approval (Ingersoll et al., 2014; Reyes et al., 2007; Reyes and Ingersoll, 2013). It could be noted that an integrated fuel management system can be modified and developed to support specific requirements for module-based load following via small standby modules (Hedayat, 2017). Then, the electrical power production of nuclear reactors could be more flexible and robust to support load following requirements of the overall grid requirement even by means of developing a new type of smart grids (Zhang et al., 2013) for automatic reactor operations.

3 Small sized and modular PWRs

According to the IAEA classification small sized nuclear reactor has been defined with the output electric power less than 300 MW (Kuznetsov, 2004; IAEA, 2006a,b, 2007, 2011b,a). Nowadays, nuclear communities and industries have been very interested in small sized reactors especially in design and construction of small modular PWRs as integrated and independent units for restricted or portable zones. Decision making for selecting the reactor type and power is a complicated problem and depends on specific conditions of each country or even state. Usually small PWRs are more suitable for new comers or even developing countries. It should be noted that, PWRs are the most interested and constructed reactor type in the world (Kuznetsov, 2004); similarly, it is noted that, the majority of the near-term deployment advanced SMRs is the integral Pressurized Water Reactors (iPWR) (Hidayatullah et al., 2015).

3.1 Major Differences between Small sized PWRs

The majority of innovative SMR designs are light water cooled reactors (specially PWRs). They can be mainly classified as following:

- Integral type of PWRs called iPWRs targeted at near term deployment (Hidayatullah et al., 2015; IAEA, 2006a,b, 2007, 2011b,a; Subki, 2012): All reactors in this group provide design solutions to exclude the possibility of certain accidents, e.g. large break LOCA, LOFA, SBO, or control rod ejection. They also incorporate cost-effective design optimization to overcome the economy of scale. CAREM-25 and NuScale could be nominated as the most practical innovative iPWRs targeted at near term deployment of the next generation of nuclear reactors.
- Modular integral or loop type PWRs for barge-mounted NPPs (Bilbao and Subki, 2010; Hyperion-Power, 2010; Kuznetsov, 2004; IAEA, 2006a,b, 2007, 2011b,a; Söderholm et al., 2014; Subki, 2012): These reactors, coming mostly from the Russian Federation, are factory fabricated and fuelled, and provide for design standardization and mass production to increase their competitiveness. They make a full use

Table 1: Summary of SMR applications.

Application	SMR design
Electricity generation	IRIS, CAREM, SVBR-75/100, AHWR, HTR-PM PBMR-400, VBER, SCOR, FBNR, HTR-F
Potable water production	AHWR, SSTAR, HTR-F, FBNR
District heating	ABV-3, RUTA-70, PFPWR50, FBNR
Hydrogen production	PBMR-400, STAR-H2, VHTR (Generation-IV), CHTR, HTR-F
Process heat applications	VHTR (Generation-IV), HTR-F, CHTR
Hydrogen and potable water production	STAR-H2
Use of the rejected heat, e.g. for seawater desalination or district heating	PBMR-400, AHWR, STAR family,ELENA, UNITHERM, ABV-3, ABV-6, KLT-40S, SVBR-75/100, VBER, RIT, MARS, HTR-F, FBNR
Co-generation of electricity with:	
- Potable water production	SMART, IRIS, CAREM-125, PBMR-400, STARLM, ABV-3, ABV-6, KLT-40S, SVBR-75/100, VBER, RIT, MARS, NIKA-70, SPINNOR, VSPINNOR, HTR-F
- District heating	SAKHA-92, ELENA, ABV-3, ABV-6, KLT-40S, SVBR-75/100, VBER, RIT, MARS, VKR-MT, UNITHERM, IRIS
- Hydrogen production	PBMR-400, HTR-F
- Other process heat applications	MARS, FBNR

of the multi-year operation experience of the reactors, and incorporate many inherent safety features and passive safety systems (Reyes et al., 2007).

- Small battery-type reactors for heat and electricity supply to isolated settlements in remote areas (Hyperion-Power, 2010; Kuznetsov, 2004; IAEA, 2006a,b, 2007, 2011b,a): These designs from Russia provide a very small core power density, which makes them possible to rely on reactivity self-regulation and passive shut down during a very long period of unattended operation.

- Several concepts of water cooled SMRs with coated particle or pebble bed HTGR type fuel (Bilbao and Subki, 2010; Hyperion-Power, 2010; Kuznetsov, 2004; IAEA, 2006a,b, 2007, 2011b,a; Söderholm et al., 2014; Subki, 2012): Being capable to confine fission products perfectly at very high temperatures, such fuels are targeted to avoid heat exchange crisis, to reduce heat energy stored in the core, and to eliminate significant radioactivity releases in Beyond Design Basis Accidents (BDBAs). The suggested modes of fuel use a wide variation from coated particles in a graphite matrix within conventional zirconium alloy claddings to a pebble bed of coated particles directly cooled by lateral coolant flow, to a movable bed of spherical fuel elements (the fixed bed concept). Furthering of these concepts will require certain RD on fuel design and qualification for the conditions of water cooled reactors (Hussain and Xinrong, 2010).

Following sections introduce much more examples about innovative SMRs. Other challenges can be also mentioned as follows:

Licensing requirements and site selection: All designers of the innovative water cooled SMRs would attempt to reduce or eliminate the off-site emergency planning requirements in licensing (Bilbao and Subki, 2010; Hyperion-Power, 2010; Kuznetsov, 2004; IAEA, 2006a,b, 2007, 2011b,a; Reyes et al., 2007). It is noted that, in countries like the United States, vendors and potential customers, such as utilities, are unlikely to proceed with commercializing SMRs without some licensing requirements such as providing a long-range of prohibited urban area without population as well as usual large nuclear reactors. On the other hand, these changes raise the concern that advanced safety features that some SMR designs might be able to demonstrate could be offset by a simultaneous relaxation of licensing requirements, e.g., by siting SMRs closer to urban areas (Ramana et al., 2013). At a same time, it seems that new generation tends to be constructed on low-developed or remote areas, and may be completely underground in some patterns where there isnt need to off-site emergency planning or introducing restricted areas as usual nuclear power plants (Carelli and Ingersoll, 2014; Hyperion-Power, 2010; Kuznetsov, 2004; IAEA, 2006a,b, 2007, 2011b,a).

Refueling programs: Some innovative SMRs addressed at the (Carelli and Ingersoll, 2014; Hyperion-Power, 2010; Kuznetsov, 2004; IAEA, 2006a,b, 2007, 2011b,a) encompassing all reactor lines without on-site refuelling. These are the reactors that could operate without reloading and shuffling of fuels for a reasonably long period, from 5 to 60 years. Some designers of small reactors without on-site re-fuelling presented their vision of future nuclear energy systems with such reactors and centralized, e.g. regional fuel cycle centers, perhaps under an international control. The designers of other SMRs advocated national approaches to fuel supply, such as indigenous or autonomous fuel cycles. It was also mentioned that different approaches to nuclear fuel cycle may be made complementary and could coexist on a competitive basis. On the other hand, some vendors have tried to take a sustainable and renewable nuclear energy regarding proliferation policies especially based on the MOX or Thorium fuel cycles (Rowinski et al., 2015).

Providing remote small power resources or

high-tech applications: Some documents (Carelli and Ingersoll, 2014; Magwood, 2001; Fairhall, 2012) pointed to the SMR as the abbreviation of the Small Modular Reactors, too. As an especial and interesting case, SMRs are highly flexible to different applications. Since they are designed to be modular, they can be scaled up according to the power requirement. As it noted, modular reactors are perfect power generation at remote, isolated, severe climate locations that lack transportation infrastructure. Mining operations and remote communities can benefit from the local and reliable power generated. If more power is needed, several modules can be used to increase the power output. Unlike conventional power plants, SMR can be assembled fully at the factory and moved to the location whereas for traditional power plants the facility has to be built and parts have to be assembled at the location.

Non-electrical heating loops: Some advanced designs are considered with several secondary loops for industrial heating process as multi-applicable reactors (Carelli and Ingersoll, 2014; Hyperion-Power, 2010; Kuznetsov, 2004; IAEA, 2006a,b, 2007, 2011b,a; Modro et al., 2003; Reyes et al., 2007). Certainly, a multi-purpose SMR could be a good solution to take a cost-effective nuclear industry as well as the multi-purpose research reactors (Hedayat, 2016, 2017). On the other hand, such applications may influence the design characteristics and platforms even for the fuel management and reactivity control systems (Hedayat, 2017). After that, safety features must be completely and carefully rechecked after such modifications (e.g. is there any conflict between such new modifications and passive safety systems or inherently safety features? similarly about costs and benefits, and also about the operation timing and scheduling).

3.2 Safety Trends in Small PWRs

We know that all of main three severe accidents occurred in a water cooled reactor that can produce a lot of hydrogen, steam explosion, and even hydrogen explosion. It means that we may even lose the last conventional physical barrier of defence in depth, called the reactor containment. It follows by release a lot of radioactive material to the environment and public called a nuclear disaster. In other words, lessons learnt from the three well-known severe accidents (Gharari et al., 2018; IAEA, 2018; INRA and IAEA, 2014) can recommend that fully under-ground plant, integral pressure vessel, much more using of passive safety features specially omitting the primary circuit pumps, submerging pressure vessel in a pool of water (for providing long-term cooling system) , seismic strengthen (improving seismic resistance via installing supports and dampers), distributing the radioactive sources over independent smaller modules, reducing required active engineering systems (such as including a self-pressurized vessel), enhancing the inherently safety features (especially by eliminating the soluble Boron from the reactivity control system) can strength the reactor design to be withstand against the severe accidents even a complicated BDBA and even after a complete core melt-down. Such new evolutions can be traced through the new advanced small modular iPWRs especially NuScale, CAREM-25, and IRIS. Similarly, improving the active safety systems have been advised by nuclear safety experts (INRA and IAEA, 2014); in which, reliability, redundancy, availability, and diversity of engineering nuclear safety systems must be improved, too.

The increased reliability of SMRs can be achieved by minimizing the number of active components required to operate and maintain the plant, advanced instrumentation and control with extensive automation, advanced diagnostics and prognostic methods and using highly skilled and trained operators (Hidayatullah et al., 2015). In other words, passive safety systems and inherently safety features must be improved as much as possible (Mezio et al., 2014). It could be noted that, some of them are new problems and may have some unknown operating and transient conditions. As an example, much more advanced calculations indicated that a complete passive heat removal system may have an un-stable domain (Marcel et al., 2013).

On the other hand, regarding special requirements and developing capacities of industrial and developed countries, there is a special interest in reducing the off-site emergency planning requirements for SMRs (Ramana et al., 2013), since this could significantly enhance the economic viability and improve the public acceptance of their nuclear reactors. However, a detailed evaluation of each particular concept or project with a link to the relevant national constraints are required to assess the effectiveness of such approach; instead, there is a negative interest in most of the European countries to the operation and development of the nuclear reactors (IAEA, 2016).

The insight of a presentation on the IRIS was that an off-site emergency planning necessitates the incremental infrastructure costs, such as costs of roads and bridges, and therefore comes an incentive to reduce or eliminate it (Kuznetsov, 2004; IAEA, 2006a,b, 2007, 2011b). The IRIS designers intend to achieve this through a "safety by design TM" approach, i.e. by the incorporation of as many inherent safety features and passive safety systems as achievable at the design stage. Although the current preliminary PSA shows a very low damage core frequency per year for the reactor GEN III+ above (Matzie, 2008), such approach aims to eliminate the possibility of accidents from occurring rather than deal with their consequences, thus significantly it can improve the defense-in-depth and safety characteristics. Benefits may also come from a simplified design or a reduced number of the required safety systems, which enables simultaneously enhancing safety and reducing the plant cost. In other words, the eliminating large piping system and pumps can defeat of economy of scale beside its robustness to eliminate some of usual DBA like LBLOCA and LOFA.

On the other hand, the first barrier of the defense in depth is the fuel cladding. Also, most of the post-accident consequences depend on the fuel pellets and cladding (INRA and IAEA, 2015). Nowadays, several innovative designs and concepts, such as FBNR provide for an incorporation of the refractory fuel forms or/and structural materials and promise a very large margin to fuel failure and perfect retention of fission products at high temper-

atures (Kuznetsov, 2004; IAEA, 2006a,b, 2007, 2011b,a). Similarly, it is noted that, using coated particle based fuels was studied to be used for PWRs (Hussain and Xinrong, 2010). Such fuel performance can increase the number of defense in depth barriers and prevent from the direct interaction between the ceramic fuel pellets (specially damaged ones) with the fuel cladding where fuel swelling could be possible.

Some SMR designers target to provide the total reactivity margin in a hot core so small as to secure the survival of an unprotected transient overpower with no core damage. Such approaches are implemented in the designs of FBNR. The acceptable reactivity margin depends on the temperature margin to fuel failure and is generally higher for the cores based on high-temperature fuel and structural materials.

Some another concepts and patterns provide much more strong inherently safety features mainly molten salt reactors, but there are still some challenges. As an example, the number of defense in depth barriers may be reduced or maintenance tasks may take some higher radiation protection hazard risks.

Anyway, a certain adjustment of regulatory rules and procedures may be necessary to realize the potential of innovative SMRs to defeat economy of scale through a simplification of their design.

3.2.1 Safety Trends in Small PWRs

Improving passive safety systems and inherent safety features of small PWR especially innovative small modular iPWRs can be mentioned as follows (Carelli and Ingersoll, 2014; Kuznetsov, 2004; IAEA, 2006a,b, 2007, 2011b,a):

I. Inherent safety features of reactor core, including:

- Combinations of reactivity effects;
- Features contributing to high degree of design robustness, e.g. offered by advanced fuel designs providing enhanced retention of fission products and/or large margin between operating and damage states;
- Features offered by structural materials;
- Omitting boric acid;

II. Passive safety features:

- Passive primary cooling systems based on natural convection (omitting primary piping system and pumps);
- Passive reactivity control systems, including passive shut down systems and hydraulic control drive systems;
- Passive decay heat removal systems, including those being efficient during the entire duration of a DBA, and even an anticipated transient without scram;
- Passive systems for mitigation of severe accident consequences especially developing long-term fully passive heat removal systems against a complete Station Black Out (SBO).

The following issues can be also identified as important and requiring further R&D:

- Combined action of active and passive safety systems;
- New thermal-hydraulic systems and regimes such as partially two phase flow in the CAREM-25;
- Self-pressurizers (with or without any active safety systems and heaters);
- Stability and un-stability analyses of operations especially for new innovative designs;
- Increasing the defense-in-depth by new advanced materials (e.g. coated fuels and components);
- Choosing and developing the most compatible nuclear data bases and libraries especially based on each specific neutron spectrum and also developing required experiments;
- Developing new standard codes and data for new reactor platforms;
- Experimental facilities and correlations necessary for benchmarking problems and to get the most compatible and reliable Best Estimate (BE) tools especially for safety simulation and analyses;
- Much more passive safety by design options and material optimization especially for high-temperature applications;
- Complete Research and Development (R&D) for new generation of nuclear fuels especially high burn up and irradiation effects based on the fully capable Post Irradiation Examination (PIE) using high flux reactors;
- Much more complete and accurate neutronic-thermal hydraulic coupling analyses to get the most compatible and safe fuel assembly design for each specific reactor design;
- Complete RD for GEN-IV nuclear reactors based on a scaled-down advanced research reactor;
- Developing high-tech Instrumentation and Control (I&C) systems which should be long-term resistance against high flux and fluence irradiating conditions;
- Thermodynamic design improvement especially the thermodynamic efficiency improvement via combined cycles or multi-purpose heating applications;
- Developing special characteristics of modularity for available, reliable, and flexible (modular- or step wise) load following in nuclear reactors;
- Coherent multi-applicability in a unique platform or even hybrid plants as much as possible;
- Developing integrated management systems for such new modular reactors especially for long-term in-core and out-core fuel management programs;

- And, developing cost-effective design deployment to conquer economy of scale via much more well-tested economic patterns and issues like ROI.

3.3 Safety Trends in Small PWRs

Todays, as it noted, new concepts of SMRs provide at least an option of offering non-electrical energy products, such as potable water, hydrogen, district heating, and others along with the electricity cogeneration. Some innovative designs of SMRs, such as MASLWR, FBNR, and NuScale rely on a complex co-generation option with electricity, hydrogen and potable water being produced within a single balance of plant (Carelli and Ingersoll, 2014; Kuznetsov, 2004; IAEA, 2006a,b, 2007, 2011b,a; Modro et al., 2003; Ingersoll, 2009; Reyes et al., 2007).

Many SMR designers are aware of the fact that purposeful use of the rejected heat improves the economy of SMRs. It appears that SMRs may have a strong rule in many non-electrical applications of nuclear energy. On the other hand, there are some another innovative benefits. It is reported that, the spent fuel of the FBNR is in a convenient form and size that can be directly used as a source of radiation for irradiation application (robustly). A variety of irradiators can be easily constructed for applications in industries, agricultures and medicines. On the other hand, some small scaled down of GEN-IV reactors have been using to study carefully about the next generation of nuclear reactors as advanced research reactors (IAEA, 2016).

As an advanced academic and industrial platform, the MASLWR (Modro et al., 2003) is a well-tested prototype for pressurized light water reactor design with a net output of 35 MWe that uses natural circulation in both normal and transient conditions. The power output of a MASLWR plant is expandable as each module is added. It is suited for electricity generation as well as the production of process steam for industrial processes such as desalinization, heating and other non-electric applications (Reyes et al., 2007). It seems that it finally evaluated and developed as the NuScale Project (under safety assessment of the US NRC). It has still leaded multi-applicable platforms of iPWRs to produce both of electricity power and desalination water coherently, reliably and sustainably for near future (Ingersoll et al., 2014).

The ACP100 (especially ACP100+) is also proposed as a powerful multi-applicable SMR with a net output of 100 MWe. Figure 3 shows a trade-mark proposal of this reactor (Sun and Zhang, 2011). It would be expected to start by 2012. Anyway, the IAEA reference book does not show any cited activity of construction or even planning of this reactor instead of the ACP1000 large power plants (IAEA, 2015). Furthermore, Fig. 4 provides a wide range of potential thermal applications for different type of SMRs (IAEA, 2018).

Recently, researchers (Garcia et al., 2016) proposed a hybrid system based on the SMR for multi-purpose applications (Fig. 3-right side). In addition, it is possible to improve the thermodynamic efficiency and work productivity through coordinated dynamic control of energy conversion systems. Researches proposed that secondary heating (or non-electrical applications) of SMRs can be promisingly approachable via a hybrid system regarding a safe, economic, and flexible usage of additional power loads (Garcia et al., 2016).

Feasibility studies confirm that a nuclear power plant and other renewable stations (like solar cells) can be used for energy generation, and yields electricity to meet grid demand and to produce fresh water using excess electrical capacity (Garcia et al., 2016). Such trends can resolve complexities and troublesome situations during load following of a local (restricted) or even (maybe) global grid needs. In other words, safety of nuclear power plants and electrical grid can improve by omitting hard shocks to the electrical grid and/or main components of nuclear power plants (e.g. turbines). Anyway such situations should be checked out carefully against transients induced by any operational fluctuation or anticipated initiated occurrences of electrical grid system using (adapted new versions of) Best Estimate codes (e.g. RELAP, ATHLET and CATHARE codes), CFD and coupling simulation and analyses, and then suitable full-scope simulators.

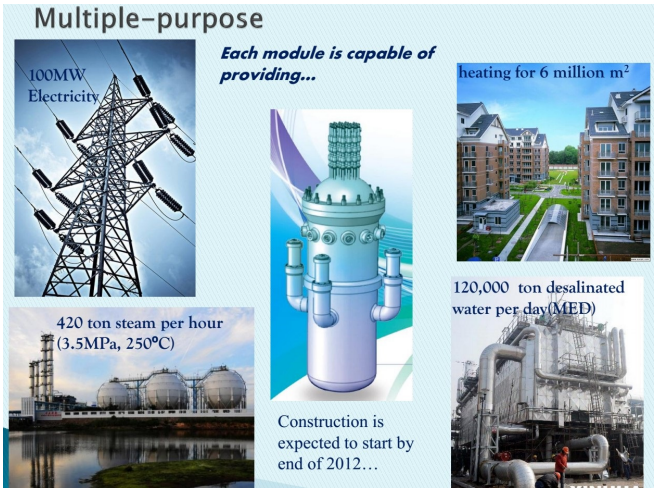

Figure 3: ACP100: A multi-purpose SMR (Brian, 2011; Sun and Zhang, 2011).

3.4 Technological Trends

An enabling technology is the technology that needs to be developed and demonstrated to make a certain reactor concept viable. The enabling technology may be some key technology of a reactor core, such as certain coolant, fuel, or structural material technology. It can be a technology relevant for certain inherent safety features or passive safety design options (e.g. a core configuration to ensure fuel safety and economy); similarly, it may be a technology for a secondary or an auxiliary circuit, or an overall plant configuration; finally, certain calculating technologies and data sets can also cover by this definition.

Many of near-term small PWRs, i.e., MASLWR, NuScale, SMART, IRIS, CAREM, and Westinghouse SMR rely on an integral design of primary circuit with the in-vessel location of steam generators, which is a de-

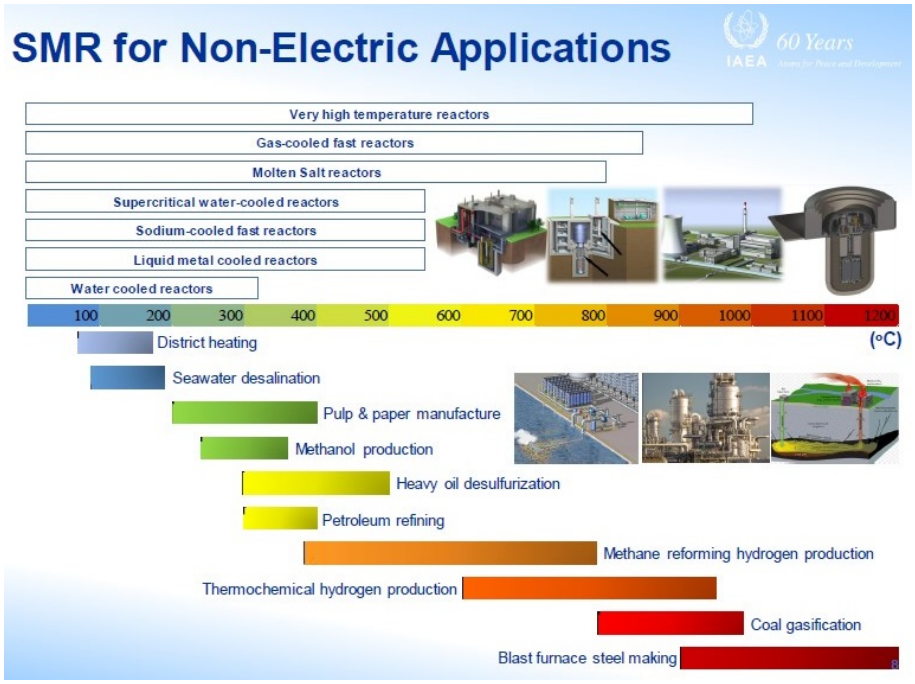

Figure 4: Potential thermal capabilities and applications of different SMRs versus operating temperatures (IAEA, 2018).

sign approach to eliminate large-break loss-of-coolant accidents (LOCA). Then, the designs of some designs (e.g. CAREM-25 and IRIS) implement the in-vessel control rod drive mechanisms (CRDM) too, which is to eliminate accidents with the ejection of control rods. MASLWR, NuScale , and CAREM-25 strongly rely on natural circulation as a complete natural core cooling system. They can incorporate the proven of such technologies (maybe as a strong long-term decay heat removal system instead of a complete natural core cooling system) or even new fuel designs for larger iPWRs (e.g. SMART and IRIS). They will also provide longer reactor life-time (increased from about 40 years to about 60 years).

Another new trend is the fixed bed core technology, in which a movable pebble-bed core is kept in the upper critical position by a coolant flow. Once the coolant flow disappears, the force of gravity moves the pebbles down to a safe sub-critical chamber. This technology was proposed for FBNR. The coated particle, the pebble and the compact fuels were originally designed for the conditions of high temperature gas cooled reactors. Therefore, any case of their alternative use requires a new fuel design to be developed and demonstrated (e.g. for the compatibility of irradiated SiC-coated (TRISO) fuels with an external fuel cladding or cooling water. Furthermore, there are some conceptual design based on the combined cycle to improve thermodynamic efficiency of the reactor (Carelli and Ingersoll, 2014; IAEA, 2011b,a, 2018; Zohuri, 2019).

Some passive decay heat removal systems, such as a water tank surrounding the reactor vessel are common to many innovative water cooled SMRs like MASLWR and NuScale. To abandon the off-site emergency planning, it may be important to develop passive heat removal systems that are effective over the whole run of a design basis accident or even an anticipated transient without scram. This may be a task important for many SMR designs representing several reactor lines. Also, some patterns were proposed to be installed underground completely; such trends effectively reduce the potential risks of radiation hazard to public during a severe accident. The NuScale and the IRIS projects can be mentioned as the best ones.

Although most of the new concepts rely on passive safety systems and a simple physical phenomenon (free convection), there are still some challenges to provide a reliable, sustainable, and stable natural core cooling system especially based on the completely self-pressurized vessels during start up and transient modes. It is predicted that there is still a long way (at least about 10 years) to take a complete technological readiness of new SMRs (Liu and Fan, 2014).

3.5 Reference designs of small PWRs (near terms)

The ongoing interest in the development and deployment of reactors classified as small or medium sized is reflected in the number of SMRs that operate or are under development and the numerous innovative concepts being investigated for electricity generation and for non-electrical applications. As it noted, according to the classification adopted by the IAEA, small reactors are reactors with an equivalent electric power of less than 300 MWe and medium sized reactors are reactors with an equivalent electric power of between 300 MWe and 700 MWe (Kuznetsov, 2004; IAEA, 2006a,b, 2007, 2011b,a). Worldwide, 131 SMR units operated in 25 states, with a capacity of 63 GWe (Kuznetsov, 2004; IAEA, 2006a,b, 2007, 2011b,a; Subki, 2012). Currently there are more than 45 SMR designs under development, only a few of them have received design certification, some of them are under construction

as prototype plants, and the rest of all is under various stages of design development (Hidayatullah et al., 2015).

Small and medium sized LWRs are under development in Argentina, Japan, the Republic of Korea, the Russian Federation, the United States of America, France and Brazil. In Argentina, the Central Argentina de Elementos Modulares (CAREM) reactor, a small, integral type pressurized LWR design with all primary components located inside the reactor vessel and an electrical output of 150300 MWe, is under development. Construction of a 25 MWe CAREM prototype plant started. In Japan, a 350 MWe integrated modular water reactor (IMR) suitable for a hybrid heat transport system with a natural circulation system is in the conceptual design stage. The System Integrated Modular Advanced Reactor (SMART) design from the Republic of Korea has a thermal capacity of 330 MWth, is intended for seawater desalination and has almost reached the final design approval stage. It is equipped with can type pumps installed on the integrated pressure vessel. In the Russian Federation, six light water SMR designs are under development. The ABV-6M, with an electrical output of 8.6 MWe, is a nuclear steam generating plant with an integral pressurized light water reactor with natural circulation of the primary coolant. The RITM-200 is designed to provide 8.6 MWe. It is an integral reactor with forced circulation for universal nuclear icebreakers. The VK-300 is a 250 MWe simplified water cooled and water moderated Boiling Water Reactor (BWR) with natural circulation of coolant and passive systems. The VBER-300 is a 325 MWe PWR conceptual design that can serve as a power source for large floating nuclear power plants (NPPs), too. In addition, the Russian Federation is building two units of the KLT-40S series, to be mounted on a barge and used for cogeneration of process heat and electricity. Another Russian design is the pressurized water reactor UNITHERM, which is at the design stage and is based on the N.A. Dollezhal Research and Development Institute of Power Engineering (NIKIET) design experience in marine nuclear installations. In the USA, three (main) modular iPWR are under development: mPower, NuScale and the Westinghouse SMR. The mPower design consists of four 125 MWe modules. It eliminates the most of primary piping system and strongly improved against severe accident scenarios. NuScale Power envisages an NPP made up of twelve 45 MWe modules and similarly it fully resistance against both of DBA and BDBA while providing multi-purpose uses. It is also developed to be operated without any primary pump. The Westinghouse SMR is a conceptual design with an electrical output of 225 MWe incorporating passive safety systems and proven components of the AP 1000. It seems that, all of them may some troublesome problems with new safety issues and standards of the US NRC specially regarding impacts of Fukushima Daiichi accident. On the other hand, it is noted that, in countries like the United States, vendors are unwillingness to proceed with commercializing SMRs along usual licensing requirements of large nuclear power plants (Ramana et al., 2013).

An international effort started and proceeded with the IRIS International Consortium, which is designing the International Reactor Innovative and Secure (IRIS), an iPWR design with an electrical capacity of 335 MWe. There are also much more innovative designs. The Fixed Bed Nuclear Reactor (FBNR) is a Brazilian conceptual design that does not require on-site refueling. The Flexblue design under development in France is a small seabed NPP with a power output of between 50 and 250 MWe. There are several useful references to follow and study each specific case in detail by following references (Carelli et al., 2010; Carelli and Ingersoll, 2014; Hedayat, 2017; Hidayatullah et al., 2015; Kuznetsov, 2004; IAEA, 2006a,b, 2007, 2011b,a, 2015; Modro et al., 2003; Ingersoll, 2009; Ingersoll et al., 2014; Liu and Fan, 2014; Locatelli et al., 2014; Ramana et al., 2013; Reyes and Ingersoll, 2013; Reyes et al., 2007; Rowinski et al., 2015; Subki, 2012; Zhang et al., 2009).

3.6 New advanced Small Modular especially iPWRs (Advantages and Disadvantages)

A new kind of reactors, Small Modular iPWRs, looks promising for both of the electrical and non-electrical applications in a near future. Anyway, such lower size allows for some design enhancements especially as a multipurpose plant. They have simpler plant layout and higher safety standards using less active components. Some designs like CAREM-25, MASLWR, NuScale, Westinghouse SMR, mPower, SMART, and the IRIS could be classified in this category.

This section gives a contribution to the benefits of specific technological solution adopted in smaller size reactors. The aim is modeling trends and possible discontinuities generated by the adoption of different technological solutions or methods by each specific design. Due to the wide knowledge accumulated on LWR, the most promising designs are those related to the water technology, and in particular to advanced iPWRs.

iPWRs require shorter construction time and reduce the interested financial capitalization upon the invested capital costs. On the other hand, there are new concepts in nuclear industry (e.g. fully natural core cooling system). They must be analyzed and tested against operating, anticipated, and even un-known transients.

Furthermore consecutive multiple unit construction makes a self-financing plan possible. Several authors deal with design simplification achieved by iPWRs and related benefits in economy, through qualitative considerations. A much more quantitative approach in the construction and maintenance cost modeling must be performed upon each specific reactor throughout the plant design, object fabrication in series, transportation, and finally modular installation, operation, and maintenance. They have been designed to be developed simply, rapidly, safely, securely, and economically worldwide. Finally, modular action plans have been proven to be cost effective according to a new modern economy instructions called ROI (ROI-Institute, 2014; Söderholm et al., 2014).

3.6.1 Advantages of Small Modular Reactors

Flexibility: There are several features of SMRs that provide greater flexibility relative to conventional large reactors as follows:

- SMRs can be added incrementally to load centers as demand increases. If electricity demand is increasing at a slow rate, a large nuclear reactor might greatly exceed the required load capacity, making it difficult to justify to ratepayers. Adding small reactors incrementally may better match supply with demand.
- Once a reactor is constructed, additional reactors at the same site will be easier and cheaper to build. Once an initial reactor is approved, the regulatory process for obtaining permits for subsequent reactors would be less onerous (Carelli and Ingersoll, 2014).
- SMRs can be used for a variety of energy applications that conventional large reactors cannot, such as desalination, industrial processes, hydrogen production, oil shale recovery, and district heating (Solan et al., 2010). Such versatility allows for SMRs to meet energy needs for more than just large base-load power.
- Multiple small reactors can also improve operating time, as a single site can have three or four SMRs, allowing one to go off-line for refueling while the other reactors stay online (Atkinson, 2010). This allows power to be continuously generated, whereas in a conventional nuclear reactor, the entire plant must go offline to refuel. Finally, SMRs can be built to be grid-independent or even as a remote power station (Anderson, 2010).
- In remote areas where it is not be cost-effective to build a larger nuclear power plant, or in places where the transmission grid is not well-developed (i.e. developing countries), they can provide a source of base-load power.
- Developing a flexible, robust, and safe action plan for non-electrical applications may be promisingly possible via introducing a hybrid plant made of SMR, clean technologies (e.g. solar cells), high capacitance batteries, and also a separate auxiliary heating plant even far from the SMR (Garcia et al., 2016). Anyway, the multi-applicability could be chosen as the best way to overcome high capital cost of nuclear energy, and to improve the flexibility of the reactor operation and utilization as well as multi-purpose research reactors (Hedayat, 2016).

Improved safety features based on the more passive safety systems: SMRs can offer improved safety by design over conventional large reactors because of specific design features inherent to small reactors interested as following:

- A smaller reactor core involve less radiation hazard risks (Anderson, 2010);
- Due to their small size, they are better able to incorporate passive safety features those that do not require human or electronic actions to function properly (Energy, 2009). These include cooling systems that use gravity instead of relying on access to power, natural convection systems, and passive heat removal systems (Aksan et al., 2009). For example, in the event something goes wrong, Westinghouse SMR is designed to keep the reactor cool for several days without the need for operators or power stations (Westinghouse, 2011). While the latest reactor designs are incorporating passive safety features, they are inherently easier with small designs due to a smaller reactor core and thermal power amount;
- They can benefit constructors from a simplification of design, using less components, resulting in a more compact reactor (Carelli and Ingersoll, 2014). Their designs can reduce or even eliminate the need for primary coolant piping system which are considered Large Break Loss of Coolant Accident (LBLOCA) as the most significant safety challenge of usual PWRs during the development of nuclear power plants (Ingersoll, 2009).
- An integral design, in which the primary reactor core, the steam generator, and the pressurizer are incorporated into a single integrated pressure vessel, is only possible in a small design (Ingersoll, 2009). In comparison, large reactors have components outside the containment vessel, increasing the chance of an accident. On the other hand, unlike large reactors, SMRs can be also installed fully underground, reducing the vulnerability to a terrorist attack or natural disaster (Hyperion-Power, 2010). A design from GEN IV, a nuclear reactor vendor, seals off the reactor underground. This allows for it even to never be opened once it is installed, enhancing proliferation resistance (Hyperion-Power, 2010). It would also operate for 10 years before refueling needed, compared to conventional large reactors that require refueling every 18-24 months (Xie, 2010).
- On the other hand, small sized nuclear power plants especially those bearing new concepts of GEN IV reactor can be fully tested and experienced as small scaled-down (similar) reactors (IAEA, 2016).

Lower Upfront Costs:

- The greatest challenge facing the nuclear power industry is the upfront cost of new reactors. Although large reactors have some advantages of economy of scale, there are economic advantages to small designs. Large reactors require substantial upfront investment, with long permitting and construction times before the final (high-risk) return on investment can be realized. These upfront costs make investing in a large nuclear power plant highly risky, even if the final cost per kilowatt-hour is profitable. A large advanced nuclear power plant can cost typically between 6 and 9 billion dollars, often exceeding

the financing capabilities of most financial institutions, utilities, or even small countries (Schlissel and Biewald, 2008). Westinghouse design for the small modular reactors at commercial scale could produce a 100 MW plant for 250 million dollars (Ondrey, 2009). Due to lower upfront costs and shorter lead times, SMRs may present lower financial risks, allowing for significantly lower costs of financing. The shorter lead times for SMRs allow for much more certainty for investors, and the ability to change with market conditions (Carelli and Ingersoll, 2014). The smaller project size of each additional reactor also reduces the risks of investment (Solan et al., 2010). This translates not only to lower absolute costs, but also lower upfront capital costs, making it easier for projects to attract financing, at better rates (Carelli and Ingersoll, 2014); shorter construction times also provide a quicker revenue stream. SMRs can be built in roughly one-half to one-third of the time required for conventional plants (Ondrey, 2009).

- Even comparing multiple small reactors to the equivalent installed capacity of one large reactor, SMRs allow incremental capacity to come online while the large reactor is still under construction. SMRs create revenue generation immediately after each small unit is completed, and the owner can retire debt before the next increment is constructed (Anderson, 2010). Similarly, the SMR units can be under parallel construction (multiple reactors under construction simultaneously), allowing the full SMR project to be completed before the large nuclear reactor. This is a significant cost advantage for SMRs over large reactors. Another major drawback for conventional large reactors is the lack of standardization. This leads to long, expensive, and uncertain time periods for licensing and site selection. SMRs can overcome this problem with standardized designs, standardized components, and enhanced safety from reduced reactor size (Carelli and Ingersoll, 2014).

- Newcomer countries, especially in the Middle East and the Southeast Asia regions, are expected to represent a significant share of the projected growth of nuclear energy, and special attention has been paid to the conditions in which nuclear energy can be developed in these countries. Identified barriers to this development include financing, public acceptance in the wake of the Fukushima Daiichi accident, higher costs due in part to enhanced safety regulations after Fukushima Daiichi, human resource capacity building, and a lack of appropriate energy policy and electricity market incentives (IAEA, 2015; Energy, 2014). Then small nuclear buildings and installations (mainly iPWR) are much more economic and approachable even for training and education for those countries.

3.6.2 Major Challenges for SMRs

There are, however, several obstacles that are slowing the development of SMRs as following:

Institutional Obstacles: The most difficult challenge currently facing SMRs is the institutional barriers. Despite the variety of SMR designs from several nuclear vendors, the licensing process for a new design takes several years at a cost of hundreds of millions of dollars in industrial countries (Solan et al., 2010; Hopf, 2011); also, many regulations create a difficult environment for small reactors and favor large reactors. For example, the US NRC requires 10 mile emergency planning zones around nuclear power plants, making it difficult to site a small reactor near urban centers where it could be used for energy applications other than centralized electricity generation (Anderson, 2010). SMRs will need to overcome this long history of institutional bias towards large reactors. As the most prominent licensing body for the nuclear industry worldwide, the US-NRC to a certain degree, shapes the global future for nuclear power. If the national regulatory bodies dont lead on small modular reactors, it may be a serious challenge for the SMR industry (Ramana et al., 2013).

No Performance History: The nuclear industry has maintained a high performance standard with its fleet of large light water reactors, and SMRs (especially new iPWRs) need to demonstrate the same high performance. However, as with any new technology, new SMRs dont have enough record to prove their performance and safety in different situations. The industry lacks a credible demonstration project that informs future projects and inspire confidence (Anderson, 2010). New advanced SMRs need to demonstrate advantages over conventional plants, including advantages in cost, safety and flexibility. In order to bring costs down, nuclear vendors may need high-tech manufacturing facilities to produce high reliable and high performance small reactors. In other words, such facilities must be justified and well-experienced. NuScale is a good example which brings high-tech well-experience companies in the project.

New Safety Concerns: While there are real safety benefits of SMRs, there are some new safety features and concerns that are not involved in conventional nuclear plants. As an example, the capability and reliability of full operation by natural convection or stability (Pilehvar et al., 2018; Moghanaki and Hedayat, 2018) and reliability of a complete self-pressurized reactor should be carefully determined and investigated. On the other hand, the owner of SMRs need to manage, inspect, and maintain more reactors for the same amount of power output as a single large reactor (Adee and Guizzo, 2010). The industry needs to prove that the inherent safety benefits of SMRs over large reactors outweigh the downsides. Then iPWRs especially those that omit the primary pumps and piping may be the good solution to overcome economy of scale (of large reactor) regarding improved passive safety performances. Anyway, some minor active control systems may be still required.

In addition, the increased reliability of SMRs is

achieved by minimizing the number of active components required to operate and maintain the plant, advanced instrumentation and control with extensive automation, advanced diagnostics and prognostic methods and highly skilled and trained operators. On the other hand, SMRs may require some development of the current nuclear codes (especially for ASME codes and standards) for modularization, factory fabrication, and new materials and processes (Hidayatullah et al., 2015).

Nuclear Waste: Disposal of spent nuclear fuel has confounded the nuclear industry for decades and the problem of waste disposal. It still needs to be dealt with and concern about SMRs worldwide (as a global policy) especially if a back-end once-through methodology chosen for all without any reprocessing. On the other hand, such modular waste management can be simpler and cost-effective via an Integrated Management System (IMS) for each country individually without additional transformation and reprocessing cost.

It is a recommendation that the establishment of a consent-based approach to siting a waste facility, the development of interim storage seven facilities, the creation of a separate government entity tasked only with addressing nuclear waste, as well as several other recommendations (Makhijani, 2013).

Some near terms small PWRs and SMRs are proposed by longer core life time or to be off-site refueling (once through fuel cycle) or even disposed completely as an integral core facility for developing countries (Carelli and Ingersoll, 2014; Kuznetsov, 2004; IAEA, 2006a,b, 2007, 2011b,a).

Anyway, the nuclear severe accidents and waste management are still the most challenging items with green communities or even general public opinion especially for the European countries (IAEA, 2016). If usual fuel management methodology with one to five refueling tasks is used, SMRs may concern about some disadvantage of waste management programs respecting large PWRs. As it noted in the text, a modular spent fuel repository is proposed for SMRs based on the once-through fuel cycle. It is addressed as a safe and robust action plan according to the V model of the Return of Investment (ROI) methodology (ROI-Institute, 2014; Söderholm et al., 2014).

Low Natural Gas and Oil Prices: Another problem that is not unique to SMRs, but plagues the nuclear industry as a whole, is the current low prices and large sources of natural gas. Prices have plummeted, and the Energy Information Administration (EIA) estimates that prices will rise very slowly over the next two decades. For example, in the 2012 Annual Energy Outlook, the EIA predicts that natural gas prices will not rise back above 6 dolar per million Btu until around 2030 (Gagarinskii, 2012). According to the US economies, SMRs may need natural gas prices to reach 7 or 8 dollars per million Btu to be competitive (Outlook, 2012). This makes any new nuclear power plant, including an SMR, uneconomical compared to natural gas unless natural gas prices rise more quickly than expected or it considered for other distributed industrial demands and household use. Undoubtedly, general policies and trends of industrial and developing countries can be completely different and diverse. Developing countries need to a perform comprehensive research and study in all types and class of nuclear reactors. Similarly, todays we have a low oil price instead of the previous predictions (Outlook et al., 2010). Anyway, the proposed high blue map pattern can be effectively beneficent and promising for the development and construction of new nuclear reactors by 2050 to reduce greenhouse gases and global warming effect (Energy, 2014); also some countries like China and Russia chose a very strong nuclear road map even for GEN-IV reactors (IAEA, 2015, 2016; Energy, 2014).

The influences of Fukushima Daiichi accident: Studies show that the severe accidents including Three Mile Island, Chernobyl, and especially Fukushima Daiichi accident had very strong negative impact on the nuclear reactor design, construction, and operation especially based on the negative impact on public opinion about nuclear power plants and new regulating authorities (IAEA, 2015, 2016; INRA and IAEA, 2014). On the other hand, it completely seems that Lessons learnt from Fukushima Daiichi accident have especially influenced and affected the specific design of new iPWRs like the MASLWR and NuScale, CAREM-24, ACP100+, SMART, mPower, SMR-160, W-SMR, and IRIS.

Insufficient nuclear data, codes, and experiences: It seems that SMRs may require some development of the existing nuclear codes (especially for ASME codes and standards) for modularization, factory fabrication, new materials and processes (Hidayatullah et al., 2015). They (Hidayatullah et al., 2015) lists some safety expectation of SMRs; in which to be expected Core Frequency Damage (CFD) can be decreased to a domain of about 10^{-6} to 10^{-8} by means of new safety concepts and performances. Then new SMR concepts may be comparable with (or even better than) the G-III+ reactors like AP1000 (Matzie, 2008) regarding final PSA results.

Anyway, new SMR concepts should be tested carefully against a broad range of transients using best estimate tools and experimental facilities especially against operational perturbations and un-stabilities (Marcel et al., 2013); where some major active engineering safety systems (especially primary pumps) may be completely removed from a complete natural core cooling system or a (complete) self-pressurizing vessel for small iPWR. Similarly, it is mentioned that there is some concern about proposed changes for licensing policies; and it has been argued that weakening regulatory requirements for SMRs could erode any inherent safety features provided by their design (Ramana et al., 2013).

Required much more high-tech instrumentation and maintenance systems: It seems that new SMRs needs much more complicated in-core instrumentation systems specially full range neutron detectors that they should be resisting against higher radiation effects where they are installed closer to the core (Hidayatullah et al., 2015). It could be noted that such irradiation examinations needs high-flux research reactors to be high performance (during desirable time of experiences) especially due to an extended reactor life time from 40 to 60

years (IAEA, 2016).

Complicated time-consuming licensing programs: Studies show that the promised safety enhancements in SMR designs could be offset by a simultaneous relaxation of licensing requirements of large nuclear power plants (Ramana et al., 2013) instead of new safety concerns by means of lessons learnt from Fukushima Daiichi accident. Anyway, some national regulations and authorities mainly including site selection rules may be changed for new fully-underground SMRs.

Some raised criticism or technological challenges: Studies show that (almost all of the) new modern SMRs (based on the iPWRs) have been still reviewing and developing to get final detail design or licensing requirements. The construction of the first prototype unit of the CAREM-25 was started; also Russia has the most number of completed design or even under-constructed planes, but they are partially modified based on the current nuclear power plants (Hidayatullah et al., 2015; Ramana et al., 2013).

In countries like the United States, vendors and potential customers, such as utilities, are unlikely to proceed with commercializing new SMRs without a profitable reduction of some licensing requirements such as providing a long-range of prohibited urban area without population similar to hard licensing requirements established for large nuclear reactors. At the same time, changes of some iPWRs via safety by design raise the concern that new involved safety features may be offset by a simultaneous relaxation of licensing requirements especially by siting SMRs closer to urban areas (Ramana et al., 2013). Some fully-underground installations may be the final solution.

Finally, we have much more closer IC in compact and integrated installations during a longer reactor life-time (for 60 years). Maintenance programs may be harder and high-tech instruments should be resistance against high temperature, high pressure, and high neutron and gamma irradiation. They should be tested via high-flux research reactors (IAEA, 2016). On the other hand, there are some new components in nuclear industry such as (hydraulic driven-based) internal control rod drive mechanism (of CAREM-25), internal helical coil heat exchanger (of NuScale), or can type pumps which should be installed on a high-pressure integral vessel (of SMART). Similar ideas could concern about omitting Boric acid when usual PWRs use it widely to help reactivity control system, moderate power fluctuations, decreasing PPF, reducing uses of control rods, and also to get a more uniform and softer fuel burn up distribution (Hedayat, 2017).

4 Economy policies and issues

It is noted that SMRs are a suitable choice (for developed or industrial countries) when the power to be installed is in the range of 1-3 GWe and the social aspects of the investment, such as the creation of new employment positions, is a goal of policy makers (Locatelli et al., 2014). Similar trends can trace via economy of scale based on the current operating nuclear power plants. In addition, this tendency could be resulted of the documented constructed or planned medium and large PWRs worldwide by the IAEA (IAEA, 2015).

On the other hand, marine applications have been completely designed and developed based on the SMRs including small regular PWRs (Carelli and Ingersoll, 2014; Kuznetsov, 2004; IAEA, 2006a, 2007, 2011b,a); also, small PHWRs have been operated successfully in Canada and India; where there are some new trends towards Thorium based fuel cycles in order to provide a sustainable energy resource and keep proliferate policy (Rowinski et al., 2015).

Undoubtedly, SMRs can represent the ideal solution for newcomers in nuclear science and technology without significant prior experience in building and operating nuclear reactors; while building and operating SMRs (specially small iPWRs) require much less prior knowledge than large nuclear reactors. It is also noted that SMRs are attractive in scenarios with limited financial resources where the utilities can add modules to exploit the self-financing options (Locatelli et al., 2014). There are some terms and condition should be concerned about economy polices:

- The risk of a large investment relative to the size of the company may affect the business case for a nuclear power plant (Rosner and Goldberg, 2011);
- SMRs exploit the economy of multiples rather than the economy of scale (Locatelli et al., 2014);
- SMRs offer a number of advantages that can potentially offset the overnight cost penalty that they suffer relative to large reactors; indeed, several characteristics of their proposed designs can serve to overcome some of the key barriers that have inhibited the growth of nuclear power plants. These characteristics include as following (Carelli and Ingersoll, 2014; Kuznetsov, 2008, 2010; Kuznetsov and Barkatullah, 2009; Kuznetsov and Lokhov, 2011; ROI-Institute, 2014; Söderholm et al., 2014):
  - Reduced construction duration;
  - Investment scalability and flexibility;
  - Cash flow or initial investment;
  - Better power plant capacity and grid matching;
  - Factory fabrication and mass production economies;
  - Learning effects and site selection economies;
  - Design simplification;
  - Reduced mass (including primary piping) and active safety systems (including pumps) for advanced SMRs;
  - Economy of scale;
  - Design and construction costs;
  - Fuel costs;
  - International energy policies and strategies considering clean technologies and the high blue map strategy;

- Operation and Maintenance Costs;
- And, total benefits per costs ratio via Return of Investment (ROI) methodology.

4.1 Economy of scale

Studies show that SMRs that directly scaled down of large plants cant be cost effective in general. Figure 5 (Carelli and Ingersoll, 2014; Söderholm et al., 2014) shows that using a regular scaled-down pattern of a large nuclear power plant increases costs. But on the other hand, performing and involving much more advanced programs of Researches and Developments (R&D), developing accurate experiences via real-time test loops and simulators, performing flexible site selection via modular units, developing the project steps via a suitable knowledge management system (to take a high performance learning curve), well-scheduled construction, optimized timing, proposing and providing demands, and enhancing global marketing, also reducing costs due to small modular phenomena can be reduced and balanced economies of small modular reactors.

Active safety systems and off-site emergency planning zones and programs have been significantly reduced in some near-term small modular PWRs using much more passive phenomena. The mPower plant is a good example of reduced PWR in lesser mass produced plant (Carelli and Ingersoll, 2014).

Clearly, one of the main factors negatively affecting the competitiveness of small reactors is the economy of scale. However, SMRs offer advantages that can potentially offset this size penalty. As it is noted, SMRs may provide significant economic benefits (Kuznetsov and Barkatullah, 2009; Mycoff et al., 2007) due to shorter construction duration, accelerated learning effects and co-siting economy, temporal and sizing flexibility of deployment, lower initial investment, much more simple transportation and installation tasks (even for remote or non-developed areas), and design simplification. On the other hand, they need lower initial investment. They do not need infrastructure as large as large nuclear power plants. Outcome takes delay respect to the large ones; on other hand, they can compete with large nuclear power plants via their modular and multi-applicable deployment, too. When these factors are properly taken into account, then they may be cost effective in a near future even regarding another clean technologies.

Anyway, developed countries must provide a big portion of their electricity demands by clean technologies without any greenhouse gas production to limit the global warming effect. The high blue map roadmap proposed by IEA and NEA (which is proposed to limit the global warming to only 2°C increases by 2015) is still promising for the future of nuclear power industry although some industrial countries like China and Russia chosen a strong roadmap for nuclear power plants (IAEA, 2015; Energy, 2014).

It is noted that the medium sized reactor of about 700 MWe LWR does not appear to have a promising future at this time: those reactors are too big to be factory built but too small for recouping the benefits afforded by the economy of scale. For instance, the AP600 received the final design certification of US-NRC in 1999 but no orders were ever placed, while the AP1000 is under construction in USA, China and regarded as viable options in several other countries (Carelli and Ingersoll, 2014). It seems that such consideration depends on the each reactor type and characteristics. As an example, small sized PHWRs (220 MWe) and medium sized CANDU are well experienced and distributed over India and Canada (Rowinski et al., 2015). On the other hand, it seems that PWR type of SMRs can be much more beneficent by means of new advanced small modular iPWRs within a multi-applicable platform.

In addition, low-developed or even developing countries need bigger fraction of researches, efforts, and costs to develop nuclear technologies and industries. Small sized and especially modular iPWRs may provide an attractive and affordable nuclear power option for developing countries with small electrical grids, insufficient infrastructure and limited investment capability (IAEA, 2015; Subki, 2012) as well as their high safety performances in inherently and passive safety features (Carelli and Ingersoll, 2014; Kuznetsov, 2004; IAEA, 2006a,b, 2007, 2011b,a). Then SMR can be also competitive and admired for developing countries, too.

4.2 Initial investment and total benefits per costs

SMRs may provide an attractive and affordable nuclear power option for developing countries with small electrical grids and limited investment capability. The adverse impacts of the economy of scale is compensated by offering the economy of mass production of multiple prefabricated modules, a simplified and standardized design, shorter construction time, less operation and maintenance cost, the option of incremental capacity increase, cogeneration and non-electric applications (Hidayatullah et al., 2015). Anyway providing a multi-applicable action plan can overcome high capital costs and initial investment of a nuclear power plant as well as multi-purpose research reactors (Hedayat, 2016).

First of all, the need to break an economy of scale was clearly identified as an objective of prime importance for all SMRs. Several factors arising from the on-going liberalization of energy markets were mentioned as being particularly in favour of the NPPs with SMRs, among them: the economy of multiple small modules and the associated financial risk reduction. An option to spread the investment costs in time by applying a modular approach to the NPP design; the diversity of SMR designs, capacities, and applications as a factor of merit in liberalized markets; and the flexibility of an SMR-based energy system not only as a desirable feature but as a principle requirement to such systems. It is mentioned that SMRs do not benefit from the economy of scale, but they can have an economy of multiples. To achieve this, an appropriate global market is needed, and one option to expand to a worldwide market is increasing international cooperation (Goulden et al., 2014).

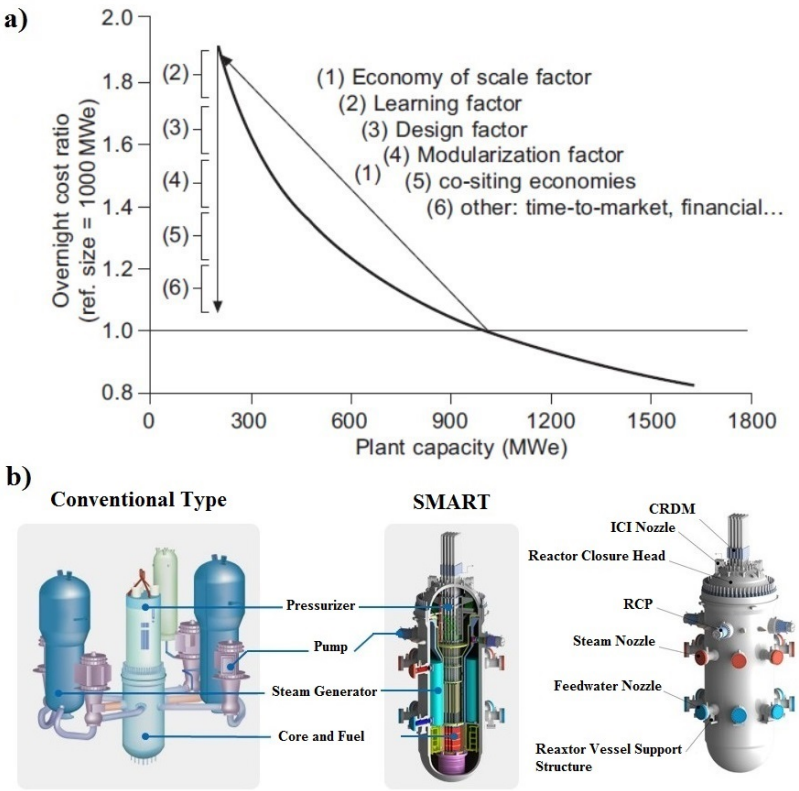

Figure 5: Generic view of factors affecting comparative costs of SMRs and large reactors. a) Developing a cost-effective SMR (Carelli and Ingersoll, 2014). b) Economy of scale through integral safety systems for SMART: An advanced SMR (www.smart-nuclear.com).

Studies show that less-developed and even developing countries may try to attract the industry to use an off-peak load and/or to use the power plants that are capable of a load follow operation; while usually nuclear power plants have been used to provide the base load of the electricity demand; also there arent enough required infrastructure to construct large nuclear power plants. SMRs can be compatible with portable or outland regions, too. They are also much more suitable for load following programs (Modro et al., 2003). Maybe they can compete or even coupled with smart grids (Goulden et al., 2014) in future.

In this situation, design, construction, and maintenance costs, NPP and total thermal efficiencies, and also net revenues and benefits should be considered and analyzed to select reactor type for each country or even each specific region and state. They can be generally discussed as follows:

Costs:

- At low power rates, additional savings may result from the elimination of some components or systems through design simplification.

- Low stored energy is a characteristic in small reactors which permits use of passive safety systems for safety functions such as a complete passive heat removal system. This eliminates the redundancy needs of active components. This is believed to improve plant safety, while simultaneously reducing plant costs (including construction, operation, and maintenance). Instead, we need new experiences, test loops, and standards for new (involved) passive safety systems.

- Small nuclear reactors keep a promise of reducing the cost of nuclear plant construction. These reactors can utilize modular construction techniques such that plant sub-assemblies can be built and assembled onsite thus reducing the construction costs. The total cost of a large nuclear plant is a major issue where 2,000 megawatt plants may exceed frm[o]–5 billion dollars (GEN III+). In addition, studies show that the small size makes it applicable to the chemical industry for process heat thus minimizing carbon dioxide emissions and finally global warming effect.

- Clearly, by building a smaller reactor, the capital cost and required infrastructures are smaller than for a large plant. However, per GWe, the capital cost of an SMR may be higher if there are no economy of scale for the smaller plants (based on a single plant). However, the benefit of several modules on one site (to achieve the same power output as a single or twin large unit) is that there is a notable reduction in cost through increased learning experience (Miller, 2005) and procurement strategy at a single site. The economy of scale is replaced here with the

economy of serial production of many small and simple components and prefabricated sections; hence, the "modularization" part is a key. Also, it could be concerned that, some integrated pattern may overcome the economy of scale too via lesser used objects and mass produced. However, the major advantage that SMRs have been regarding capital expenditure is that it allows more operators and/or investors the opportunity to consider a nuclear program. For example, the level of investment for a single or twin large plant (of the order of several billion dollars) is not affordable to many companies. In smaller nations, such as in the Eastern Europe, South America, Africa, and some part of Asia (specially middle east) such a multi-billion investment represents a large proportion of their Gross Domestic Product (GDP) and thus make it unfeasible as an option. By use of a staggered build program and the ability to build smaller units more quickly, the total cumulative cash flow for an equivalent several-module unit on a single site has been shown to be of the order of one-fifth that of a single large plant (Petrovic et al., 2006). As one module is finished and starts producing electricity, it will generate positive cash flow for the next module to be built. At least 4 to 5 SMR was chosen to compete with large units regarding at least 1 year delay to get a positive cash flow (Carelli and Ingersoll, 2014).

- For the industrial countries, due to its smaller size, the initial cost is much lower than a conventional nuclear power plant. A conventional reactor typically has a cost of 5 to 15 billion dollars before any power can be produced while estimating SMR cost of about 25 to 200 million dollars per unit. Maintenance costs are also reduced for SMR. Since SMRs are passively cooled by convection and there is not any primary pump (for advanced small modular type), it is safer, cheaper and more reliable to maintain and operate. On the other hand, needs to provide additional emergency power supplies and remote diesel generators are so much lesser than those requirements of usual large PWRs especially regarding new safety issues after the Fukushima Daiichi accident. Instead, we have can type pump that must be installed and operating on high-pressure integrated pressure vessel. Similar difficulties may be concerned for the maintenance of the internal (radioactive) equipment.

- In some of advanced small modular PWRs, pumps, emergency sumps, backup generators, heat containment systems, can be omitted. On the other hand, off-site emergency planning can be reduced significantly; also they can use a restricted water capacity as the final condenser based on the natural convection phenomena (Carelli and Ingersoll, 2014; IAEA, 2011b,a; Rosner et al., 2011; Subki, 2012). Then, they will be much more robust and flexible for site selection and less effective on the natural water resources, too.

- Developing countries need bigger fraction of researches, efforts, and costs to develop nuclear technology and industries. On the other hand, well-experience high-tech companies may concern and solve difficulties. Finally, it seems that international consortiums like the IRIS project can share the investment, tasks, and knowledge to get a unique economic, high-qualified, high-performance, and safe design.

Revenues and Efficiency:

SMRs (specially small iPWRs) looks promising for the future of electrical and thermal energy demand especially according to the proposed high-blue map roadmap. Energy output diminution seems apparently disadvantageous looking at efficiency, but lower size allows for some design enhancements: simpler plant layout and higher safety standards using less active components.

Assuming all type of SMRs, HTGR plants can achieve a thermal efficiency of about 42% by even employing subcritical super-heated steam turbines or reaching ∼45% when supercritical steam turbines are installed (Zhang et al., 2009). Eventually, the efficiency could be improved even further when adopting some direct helium gas turbines or choosing a combined cycle. In addition, the high-temperature heat sources provided by HTGRs can be used in many industrial processes to replace coal, oil or natural gas, and specially to produce hydrogen fuel (as a completely clean fuel).

PWRs can gain a lesser thermal efficiency with regard to the other types, Table 2 shows a comparison between the typical efficiency of an advanced small modular PWR and some gas cooled SMRs. Studies show that Gas Cooled Reactors (GCRs) particularly Very High Temperature Gas cooled Reactors (VHTGRs) can have the most nominated thermodynamic efficiency (Rowinski et al., 2015). Then VHTGR could be the best choice for (high-performance) non-electrical applications requiring very high temperature applications such as high-beneficent hydrogen fuel production and high-temperature oil-petrochemical processes; while PWRs can highly cost effective for naval application, districted local heating, and specially for sea water desalination.

4.3 An economic decision making via an efficient Return of Investment (ROI) methodology

SMRs are making a small trade-off on costs. Therefore, it is important to balance slight losses with major gains in lower capital cost. Although they can't compete with large units regarding total cash flow, they can produce revenues immediately after each small unit is completed. It seems that, the ability of knowledge management and modular deployment for small independent units are highly compatible with the methodologies of Integrated Management System (IMS) in nuclear industries (IAEA, 2006a, 2013) and Return of Investment (ROI) in modern economy issues (ROI-Institute, 2014; Söderholm et al., 2014).

Todays, some new economy concept and methodology are proposed and even successfully used for nuclear industry. ROI institute (ROI-Institute, 2014) supposed a step-

Table 2: Thermal efficiency of some SMRs.

Reactor	Type	Power (MWe)	Efficiency
mPower	PWR (ASMR)	150	31%
HTTR	High-Temperature Test Reactor	300	47%
PBMR	Pebble Bed Modular Reactor	80	41%
GT-MHR	Gas Turbine - Modular Helium Reactor (General Atomics)	285	47%

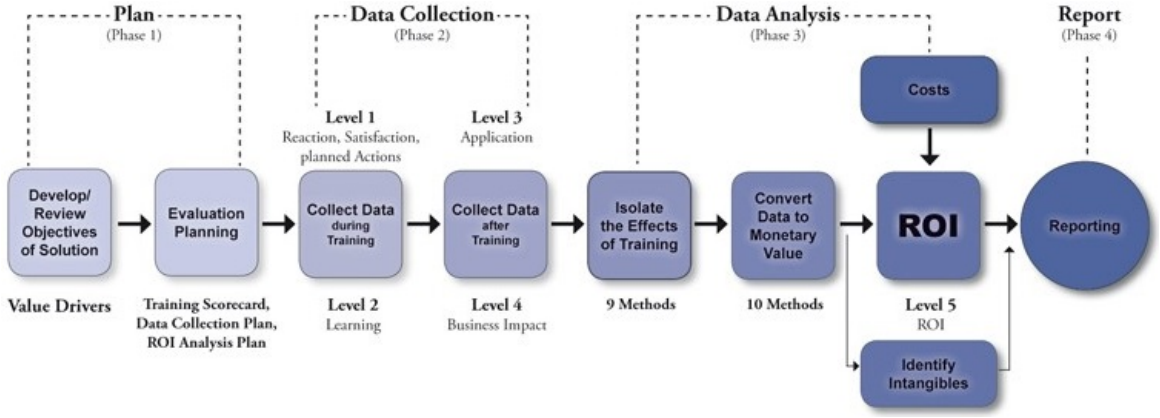

Figure 6: ROI modules to get a cost effective plan (ROI-Institute, 2014).

by step guide for developing Return Of Investment (ROI) impact studies for programs, projects and solutions (Fig. 6). Also, there is the V model (Fig. 7) starting by payoff needs (here lower capital cost and smaller required infrastructure could be mentioned); and goes through business (in this situation global marketing should be enhanced), performance (it can effectively enhance via multi-applicable deployment and by reducing active safety systems using more passive safety systems), learning and preference need (here required codes and standards, test loops and full-scope simulators, and best estimate tools should be adapted and developed); then the project can be introduced and proceed. Objectives can be considered and chosen according to a combinatorial multi-objective optimization to get a safe and multi-applicable platform) in this situation; also, hybrid systems can be introduced and developed to get a much more available, reliable, robust, flexible, and high-performance action plan.

In this case, new calculating tools and test loops should be developed to take suitable and reliable reaction. New codes and standards should be developed to improve learning factors. As it noted, a combinatorial multi-objective optimization can be introduced regarding economy issues, robust and flexible power production regarding electrical grid needs, and flexible non-electrical applications; in which main objects of a high performance economic action plan can be identified as the optimization objectives; also, corresponding Operating Limits and Conditions (OLCs) should be chosen as the optimization constraints. Regarding high performance non-electrical application, safety features can be also chosen and affected to impact optimization objectives via safety by design (instead of only OLCs as optimization constraints). Such trends can be recognized and developed based on the improving passive safety systems and inherently safety characteristics. Finally, ROI factors (especially benefits per costs ratio) can be identified and graded. Then, a safe and economic action plan can be proceed to take ROI targets.

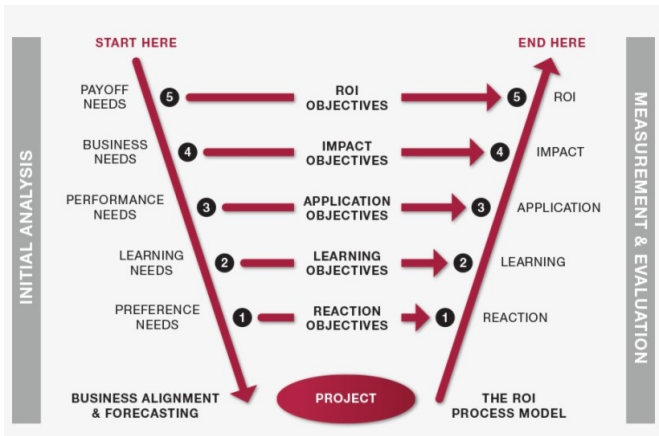

Figure 7: General methodology of the ROI to design and run an economic action plan (ROI-Institute, 2014; Söderholm et al., 2014).

In addition, we can take (some of) primary outcomes of the project by taking responses (using calculations, simulations, and safety analyses). Maybe a redesign process should be required during different stage of main project or even during final licensing process by each corresponding regulatory body (INRA and IAEA, 2015). Learning factors can be notable during modular design process and development especially based on new practical concepts and transient situations of natural core cooling systems. Improving secondary non-electrical applications, reducing

active safety systems and mass produced (e.g. primary pumps and piping) within iPWR patterns can lead a cost-effective project. Impacts should be identified carefully according to the safety issues and integration capacities. Particularly, inherently safety features and passive safety systems are the most influential items on the final target of ROI. Regarding only electrical power generation, we have a delay related to the large nuclear power plant (for developed countries); but, we can significantly improve outcomes and benefits by developing and using a multi-purpose action plan as well as multi-purpose research reactors. As a weakness of nuclear industry, marketing and commercializing methods should be improved keeping nuclear safety and security issues.

Recently, this new methodology was successfully taken into account modular spent fuel programs (Söderholm et al., 2014). A deep insight into this methodology (Figs. 5 and 6) concerns about evaluation planning, data collection, data analysis, and reporting. Introducing and performing an IMS (IAEA, 2013) could be complementary in this situation. Although they are compatible with modular structure of such new rectors, there are still some problems with new advanced reactors. As it mentioned, new hard licensing requirements (especially after Fukushima Daiichi accident), also loss of enough codes and data could concern about projects breakpoints and delay in scheduling and timing which have strong effect on economy of the project. It mainly includes required new standards (e.g. ASME), adapted codes and software for nuclear safety analyses based on natural core convection (specially where primary pumps are omitted and a complete self-pressurized vessel would be established), test loops, and experimental code validation (Hidayatullah et al., 2015; Rowinski et al., 2015).

4.4 Improving the total cash flow by means of multi-applicability and hybrid plants

Anyway, we can improve overall ROI factor by means of multi-applicability as well as multi-purpose research reactors (Hedayat, 2016). To balance between reactor costs, revenues, and ROI, following non-electrical applications (heating processes) have been included in advanced reactor designs (Carelli et al., 2010; Carelli and Ingersoll, 2014; Garcia et al., 2016; Kuznetsov, 2004; IAEA, 2006b, 2007, 2011b,a; Modro et al., 2003; Rosner et al., 2011; Subki, 2012) as follows:

- Sea-water desalination and production of potable water and or producing brine for tuna etc.,
- Naval applications and other high-tech applications including space crafts,
- District heating,
- Heat for industrial processes,
- Hydrogen production:
  - At fuelling stations by water electrolysis
  - At central nuclear stations by
    - high temperature electrolysis
    - thermo-chemical processes
    - hybrid processes,
- Coal gasification,
- Petroleum applications (e.g. to convert natural gas and water to produce gasoline)
- Enhanced oil recovery (e.g. from oil shale and tar sands),
- Learning performances particularly scoping new concepts and GEN-IV plans in scaled down small reactors.

It should be noted that, due to the PWRs operating temperatures some applications are much more interesting and reported to be used for non-electrical applications by PWRs. They include a partial usage of electrical output for local industrial applications or simple heating process such as producing potable water, water desalination, district heating, and naval applications. Anyway, PWRs are also reported to be used for Hydrogen production (as a clean and green fuel which is producing water after the combustion).

Recently, researches (Garcia et al., 2016) proposed hybrid power plants based on the SMRs, clean technologies especially solar cells, and high capacitance storage batteries. They may be used (in a near future) to get a more flexible, economic, and safe load following, and to take high performance secondary heating applications especially water desalination and gasoline production. Such plants may also solve or at least reduce the difficulties of a flexible load following of nuclear power plants. Briefly, a flexible, robust, and safe action plan for non-electrical applications could be developed regarding advanced small modular iPWRs based on modern economy issues and developing new required codes and standards. Modularity, multi-applicability, hybrid operations (of SMRs and the other clean technologies), also providing a robust control of additional heating process can significantly improve the performance of the next generation of advanced nuclear reactors in a near future.

Finally, each modern action plan of SMR design and construction can be scheduled accurately based on the V model of ROI. Then ROI model can accurately determine economy impacts of new concepts. Furthermore, national safety regulation bodies may prolong the licensing process and time via redesign tasks. Then fully submerged installations underwater and fully constructed containments underground may effectively reduce such troublesome problems regarding both of nuclear safety and security issues. On the other hand, new required codes and standards are also required for the new advanced SMRs. Finally, international consortiums (like the IRIS) should be encouraged and developed; also, global marketing should be enhanced worldwide.

5 Conclusion

Recently, Small and Medium sized Reactors (SMRs) have been much more developed and interested in nuclear industries worldwide. They have many benefits and advantages to be compatible for restricted, portable, or local energy demands as multi-applicable nuclear power plants as well as multi-purpose research reactors. They have required flexibility and robustness for smaller electricity grids and infrastructure, options to match demand growth by incremental capacity increase, tolerance to grid instabilities, load following based on the modular operations, flexible and robust site selection and emergency zone planning, and shorter construction period as the modularization. They are also supposed to be matched with other clean technologies as a hybrid, robust, and flexible power plant and industrial utilization coherently.

Other advantages can be mentioned as: lower upfront investments of capital cost (per installed unit), but perhaps higher capital cost per MW, shorter and more reliable transportation and construction, easier financing scheme, potential for enhanced safety systems based on more passive and inherently safety features, reduced in necessary infrastructures and off-site emergency planning zones especially for fully-underground plants. Reduced complexity in design and active safety systems maybe also solve economy of scale and improve operation, and safety performances as well as compatible multi-application layouts. Anyway the compatibility of secondary non-electrical applications and hybrid plants should be carefully checked out against passive safety systems and inherently safety features.

Regarding the new nuclear safety and nuclear security issues as the most important item, lessons learnt from the three well-known severe accidents (especially Fukushima Daiichi accident) can recommend following items as: fully under-ground plants, integrated pressure vessels without any large primary piping system, much more uses of passive safety features specially omitting the primary pumps, submerging pressure vessel in a pool of water (for providing long-term cooling system and even also to condense leaking vapor), seismic strengthen (improving seismic resistance via installing supports and dampers), having smaller radioactive sources over independent smaller modules, reducing required active engineering systems (such as including a self-pressurized vessel at top of the pressure vessel), enhancing the inherently safety features (especially eliminating the soluble Boron from the reactivity control system), increasing remote power supplies or reducing the system dependency and functionality on emergency power supplies in a long-term SBO, and omitting the accident roots via improving safety by design (especially LBLOCA and LOFA).

Such considerations and modifications can strength the reactor design to be withstand against the severe accidents (to prevent any harmful radiation hazard to the public) even after a complicated BDBA and even after a complete core melt-down. It seems that, new advanced small modular iPWRs like CAREM-25, NuScale and IRIS will be good solutions for the next generation of iPWRs in a near future.

Anyway, high blue map strategy of the global energy policy is promising for nuclear industry to get an effective reduction of global warming affected by green-house gasses by 2050. On the other hand, a good combination of reduced mass structured, nuclear safety and security improvements, and thermal performances via a multi-applicable platform may promisingly compete by the other clean technologies and sustainable energy resources in a near future as secure, safe, economic, high performance and efficient, robust and flexible action plans. SMR may be also a good solution to overcome grid losses beside smart grids in the future especially for outland and remote stations as well as great performances for naval applications. On the other hand, it seems that SMRs are much more compatible with an Integrated Management System (IMS) to be graded, assessed, qualified, controlled and developed in different small modular units. There is also a modular potential (of standby units) to be matched within a local industrial smart grid systems. Hybrid plants are also promising.

As the most interested and constructed case worldwide, small modular PWRs (especially integral type) can be highly robust and flexible to be used in different applications and regions. Since they have been designed in modular forms, they can be partially scaled up according to the power requirement. Integrated and self-controlled systems can be also designed and applied for such advanced types. Improvements include integrated self-pressurized components, internal heat exchangers which are compatible with the passive natural circulation, and internal control drive mechanism within pressure vessel especially based on the passive hydraulic systems. CAREM-25 could be mentioned as the most improved safety by design within a domain of new iPWRs. It is used the most passive and inherently safety features regarding small modular iPWRs. Also, NuScale could be nominated as the most well-experienced and high-reliable small modular iPWR. It seems that they are compatible with high-performance secondary heating applications, too.

In addition, SMRs are perfect for power generation at remote, isolated, severe climate locations that lack transportation infrastructures, and especially naval applications. Mining and hard drilling operations, also restricted and remote communities can benefit from the local and reliable power generated as well as restricted local heating and sea water desalination. Then global marketing should be enhanced worldwide especially for new comers of less-developed and developing countries. If more power is needed, several modules can be used to increase the power output. Unlike the conventional power plants, an advanced small SMR can be assembled fully at the factory and easily moved to the location whereas for traditional power plants the facility has to be built and parts have to be assembled at the location. Some concepts are considered with several secondary loops for industrial heating process as multi-applicable reactors. The CAREM-25 and NuScale (MASLWR) are notable in such applications. On the other hand, some SMRs have been designed and evaluated to be used in marine applications. The ABV-6M,

Flexblue, KLT-40S, RITM-200, and UNITHERM are notable in the marine applications.

Some challenges can be also remarked as follows: delays due to proposed new and innovative designs for SMRs especially due to license requirements, higher maintenance costs and inspections. They may be necessary for the most of iPWRs especially for internal active safety systems such as internal control rod drive mechanism and heat exchangers. Another cases are as following: higher total cost and longer required time to produce a logical electricity power (regarding a large nuclear power plant output), real estimation of costs and benefits, difficulties and unknown responses of the new passive safety systems mainly required reliability and stability analyses (Pilehvar et al., 2018; Marcel et al., 2013; Moghanaki and Hedayat, 2018) of such new systems, much more complex design and fabrication of new cartridge-type fuels (to perform once-through and one-cycling fuel management), and maybe a voluminous nuclear disposal based on a modular back-end once-through nuclear waste management strategy.

In particular, advanced small modular reactors (SMRs) specially iPWR type have been proposed and developing to overcome economy of scale, balance between initial investments and total capital cost, reduce infrastructures, project timing and progress, and also improve reactor safety and performances as a multi-applicable NPP. New modern economy issues and project planning methodologies like the ROI may help to solve such difficulties as well as a proposed action plan of a modular development for nuclear waste management of SMRs (based on the V model of ROI). However, new generation may also have some troublesome items with regulatory bodies. They may need much more complicated instrumentation and control systems and even maintenance programs. High-Tech I&C should be tolerate much higher radiation effects (in closer and compact core configuration as well as internal drive mechanisms) for a longer reactor life time (extending from 40 years to 60 years). Some fabrication processes and maintenance tasks may be much more complicated, harder, and time consuming in an integral pressure vessel. There are also (probably) some troublesome problems in technology readiness of some new engineering safety systems especially using small can-type pumps directly over a high-pressure integral pressure vessel. Effects of corrosion, fatigue, and finally flow blockage may need much more careful R&D within a domain of new internal heat-exchangers. Low buoyancy driven force maybe produce insufficient pressure head in order to overcome pressure losses (of required and added supporting structures and measuring instruments). New codes and standards should be developed specifically for new concepts and designs. Nuclear data, codes and software should be developed for new incoming practical phenomena in nuclear industry. And finally, transients and system responses should be carefully simulated and experienced against operating conditions and variations, anticipated occurrences, and even unknown transients. Secondary heating loops should be compatible with a complete passive heat removal system. The redundancy, reliability, availability, and diversity of new safety systems (of iPWRS) should be checked out carefully against different transients where some active safety systems are completely omitted of the system. Then multiple internal heat exchanger like the CAREM-25 may be the solution to be compatible with some of high-performance secondary heating applications, too. Similarly, flow instabilities should be carefully checkout against industrial shocks (via accurate 3-D CFD modeling and required experiments).

Briefly, innovative concepts of SMRs have been improved regarding some troublesome problems with regulatory bodies to prove and confirm a reliable nuclear safety and security. MASLWR proposed a cost-effective multi-applicable layout followed by NuScale. FBNR can emerge out off-site or even on-line refueling pattern and using graphite coted fuels, CAREM-25 proposed the most involved passive safety features especially an internal integrated self-pressurizer doom above the integral pressure vessel; also some larger SMR like SMART propose new can-type of primary pumps that should be directly installed on the pressure vessel. ACP-100 proposed a complete multi-applicable safe platform without any proven experience. Recent review papers propose some challenging items to predict the future of SMRs. Scientists also proposed new advanced hybrid systems based on the SMRs for non-electrical application. Such new studies may propose, imagine, and induce some prediction and new performances as following:

- Small modular reactors may be more approachable and compatible for the new comers and developing countries.
- While Medium sized modular reactors may be more economical for industrial and developed countries.
- Marine applications and small PHWR are the most experiences of SMRs.
- ROI issues may recommend the advanced SMRs for the future if some troublesome items will be solved (e.g. required new codes and standards, or reducing off-site emergency planning).
- Flexible load following based on the modular operation and extra heating load system can be promisingly developed.
- Using DC electrical storage such as battery set may be a good solution for power smoothing process.
- Using secondary boilers for secondary heating applications may be developed in a near future even far from the nuclear sites.
- An independent management system can be introduced and developed for modern SMRs that controls the heating loads for different applications. Modularity and object oriented developments will be complementary.
- Using additional loads for other heating system could be provided especially to produce potable water and sea water desalination.

- Using hybrid systems will be possible and efficient regarding rejected heat and or extra electrical power generation.
- Multiple and hybrid system of parallel turbines may be developed and practical to be used for advanced SMRs.
- Using much more parallel internal heat exchanger with in an integrated pressure vessel (e.g. CAREM-25) may be a good solution for high-performance non-electrical applications that should be compatible with new passive safety systems especially those ones involve a complete passive core cooling system.
- Using scaled down plants for advanced experimental studies are an ongoing solution specially for GEN-IV reactors.
- Introducing and using some secondary applications beside another non-electrical applications (heating processes) such as producing high-dose industrial radioisotopes which need high neutron fluence (e.g. industrial graded of Co-60) in the reactor reflector part.
- Developing Marine applications and other high-tech utilities such as space crafts.
- Developing smart grid systems based on small modular capacities and hybrid load following of heating system to develop an optimum and safe IMS of local industrial regions.
- It is noted that, there is still a long way (at least about 10 years) to take a complete technological readiness of new SMRs.
- Both of near-term small or medium sized PWRs (like the IRIS, Westighouse SMR, and WWER 300) and advanced small modular type (like the CAREM 25 MWe, MASLWR 35 MWe, and NuScale 45 MWe) can have their applications and advantages based on the demands and capacities of power grids. They can be also started and proceed along the current status and technologies of the large GEN III+ PWRs to develop nuclear industry and technology readiness.
- SMRs have been developing to be used effectively in marine vessels, hard drilling or mining works, producing potable water, sea water desalination, H_2 production as well as much more uses of inherently safety features and passive safety systems. Then they can compete with other clean technologies and sustainable energy resources in the future (e.g. some new RD of PHWRs). They will be lesser mass produced within integrated platforms; also, they can introduce and make a learning curve and native technological backgrounds and history to design and construct large NPPs, too. They can be even a good solution to scope and study GEN-IV reactors fully in detail via a smaller size reactor and having smaller radioactive sources regarding a testing nuclear installation without any sensible radiation hazard risks (even in a sever accident situation).
- It seems that multiple internal heat exchangers through a passive heat removal system (e.g. CAREM-25) will be an economic solution to get a safe, high-beneficent, and high performance multi-applicable platform for non-electrical applications. On the other hand, (induced) instabilities of industrial shocks and tolerances of secondary heating loops over main natural core cooling system should be carefully studied and analyzed based on a complete and accurate CFD modeling and required experiments.
- Finally, international consortiums (like the IRIS) should be encouraged and developed; also, global marketing should be enhanced worldwide.

Obviously, this conclusion chosen and discussed based on a preliminary study; and a comprehensive study and analyses should be performed depends on each specific situation. New modern management system like IMS and economy issues like the ROI are also compatible with modular development; and they can be also complementary for such decision making.

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