UNIVERSITY OF GRONINGEN

BACHELOR'S THESIS PROJECT

Review of small nuclear reactors and assessment of deployment feasibility in remote regions.

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Abstract

Nuclear energy is emitting the lowest amount of carbon dioxide equivalent per unit energy produced when considering total life-cycle emissions. Therefore, nuclear energy, coupled with other renewable energy sources, should play an important part in the production of clean and sustainable electricity in the future. This project aims to review small modular nuclear reactors technology and assess the possibility to have such a reactor power small to medium size remote communities.

Contents

1. Introduction

1.1 Motivation

The growth in the world's population, together with rapid urbanization, will result in a substantial increase in energy demand over the coming years. Nuclear energy is emitting the lowest amount of carbon dioxide equivalent per unit energy produced when considering total life-cycle emissions. Therefore, nuclear energy, coupled with other renewable energy sources, should play an important part in the production of clean and sustainable electricity in the future.
The number of people without access to electricity has fallen substantially, and is now below one billion. However, despite significant progress, over 11% of the world's population still lacks access, mostly in rural areas.

1.2 Aim of this research

Current nuclear reactors provide about 10% of the total energy production worldwide (Figure 1).

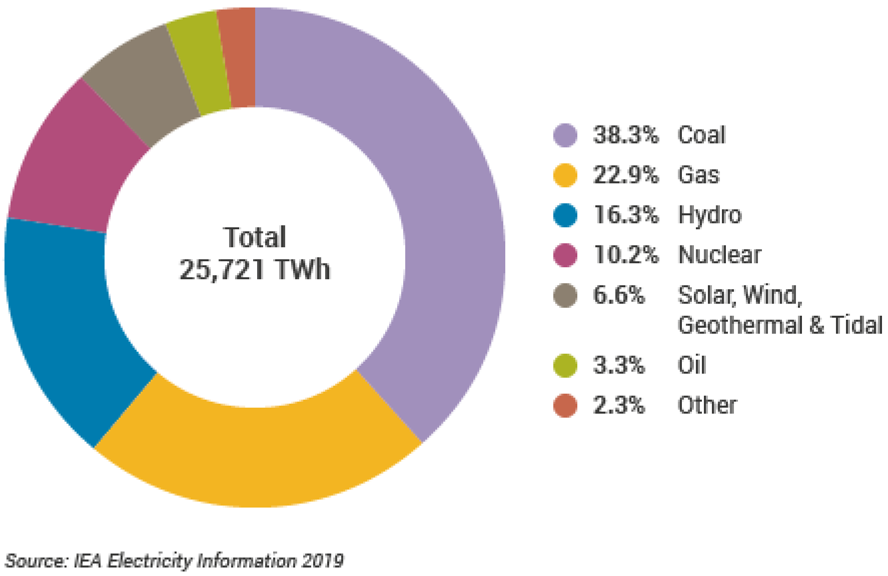


Figure 1: World electricity production by source [1].

The purpose of this research project is to review the current small nuclear reactors technology and to assess the possibility to have such a reactor power small to medium size remote communities.

After a brief note on the history of nuclear reactors, a description of the current nuclear reactor technology and reactor types will be given.
Next, we review the need for and on-going research of small reactors.

Finally, an example of deployment of a small modular reactor will be provided and a review of its impact on the environment and its applicability on small areas.

2. Nuclear energy and current technology

2.1 History of Nuclear Reactors.

It wasn't until the 1940s, after some years of research and investigation on the process of fission by scientists like Niels Bohr, Albert Einstein and Enrico Fermi that the first nuclear reactor was built. In 1942, during the Second World War, the Manhattan Project was created with the main goal of creating nuclear weapons. The same year, the first nuclear reactor was built and achieved a self-sustaining chain reaction.
At the end of the war, a lot of scientists and organizations such as the United Nations were working on a campaign to develop ''peaceful'' uses of nuclear power.
Finally, in 1951 the first reactor was turned on to produce electricity near Arco, Idaho, USA.

The first reactors models deployed were the Light Water Reactors (LWRs) which include Pressurized Water Reactors (PWR) and Boiling Water reactors (BWR). The PWR was developed to supply power to maritime stations in the Navy in 1955 and later on, it was used for electricity generation in 1958 [2].

2.2 Evolution and current Nuclear Power Plants

The rise in oil prices and the lack of energy security motivated the construction of nuclear power plants (NNPs). The first NNP connected to a grid was in the USSR in 1954, with a RBMK prototype reactor.
In the late 1970's, as a result of the 1973 oil crisis, France and the USA built around 50 NPPs, using PWRs as reactors.
As can be seen from Figure 2, the number of NPPs built and connected to a grid has seen a sharp increase in the 1960's, culminating in the early 1980's.

After the 1980's peak, the NNP construction slowed down all over the word, motivated by factors like the high costs of nuclear energy, the slow rate at which the electricity demand was growing and perhaps more importantly the accidents that occurred at the Three Mile Island generating station in 1979, Chernobyl in 1986 and Fukushima in 2011 [2].

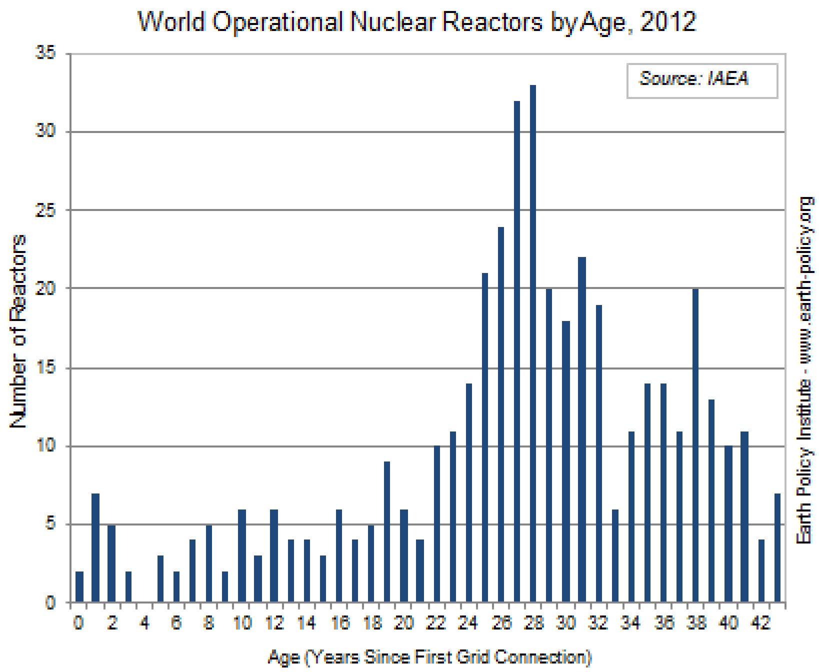


Figure 2: Number of nuclear reactors since 1954 [1].

From then on, many governments started to revise the safety strategies of their NNPs. Some countries shut down the reactors for some years, like in Japan or China and others improved the safety measures in their NPPs and worked closely with safety agencies.

Nowadays 454 reactors are connected to grids in 31 different countries, mainly in the USA, France, China, Russia and South Korea and produce more than 10% of world's electricity

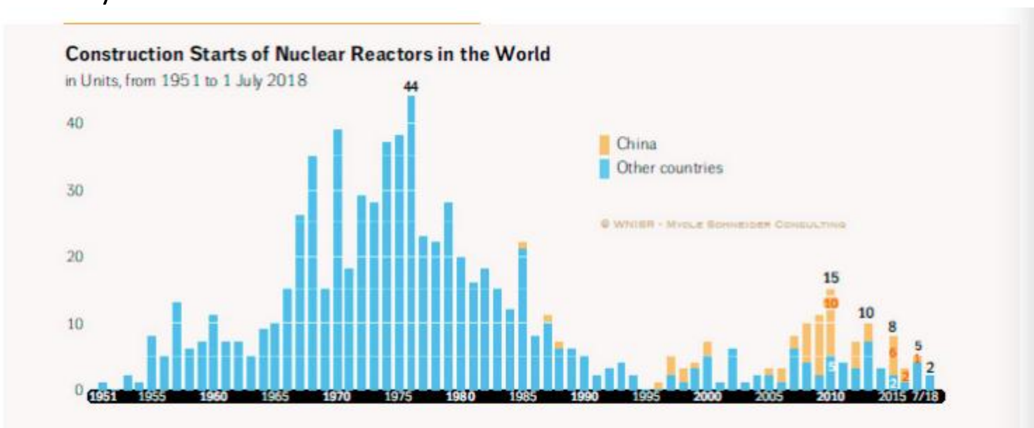


Figure 3: Construction starts of NPPs in the world and China [2].

Figure 3 shows the number of NPPs currently being built. From the 54 reactors under construction approximately 1/3 is located in Asia, especially in China where the nuclear power generation has been increased by 18% in 2016-2017 [2].

2.3 Generation timeline

The nuclear power plant evolution during the last 50 years has been divided in different generations:

-Generation I refers to the first prototypes and designs at the beginning of nuclear energy production (from 1950s to 1970s). The firsts reactors connected to the grid were part of this generation.

-Generation II refers to the reactors operating currently all over the world. It includes PWR, BWR, and advanced gas-cooled graphite moderated reactors (AGR). They have in common that they rely on active safety systems that involve mechanical actions to work. The operation lifetime of these reactors was 40 years but a lot of them have been operating for 50 or 60 years, with a life-time extension.

-Generation III and III+ represent an improvement of generation II reactors. They came into operation in 2000 and are still in use today. They feature a reduction of the construction time, have simpler designs, use more passive systems and improve the protection for events such as aircrafts crashes or core meltdowns.
Generation III+ designs assume a next step in safety measures and designs with respect to the Generation III ones.

-Generation IV regards advanced and new reactors designs, which are planned to start operating from 2030. Some countries realized that they wanted to reach similar goals in nuclear energy development and they decided in 2000 to work together in a new generation of reactors in the Generation-IV International Forum (GIF). These countries follow a common Research and Development Program (R&D) to achieve:

- Sustainability: to provide the world with a future clean energy and minimize and manage their wastes causing as less impact as possible.
- Safety and reliability: improving safety measures, reducing core damage likelihoods and eliminating the need of exterior emergency response.
- Economic competitiveness: the cost will be advantageous and the financial risk comparable with another energy.
- Proliferation resistance and physical protection to provide more protection for the population and reduce the risks of proliferation.

Models included in generation IV are:

- Gas-cooled fast reactors (GFR)
- Very high temperature reactor (VHTR)
- Supercritical water-cooled reactor (SCWR)
- Sodium-cooled fast reactor (SFR)
- Lead-cooled fast reactor (LFR)
- Molten Salt reactor (MSR)

Generation IV reactors are considered as extensions of the first reactors that include features such as simpler designs, reduced costs and improved safety systems comparing with the first commercialized reactors (LWR, PWR and GCR) [3].

2.4 Current nuclear reactors

A nuclear plant transforms thermic power into mechanical and finally electrical power. The thermal energy is obtained from fission reactions of the fissile nuclei in the fuel and this energy is used to produce steam in a steam generator. The steam transforms the thermal power in mechanical power by spinning turbines. These are connected to electric generators that produce electricity.
At the heart of a NPP is the nuclear reactor, which initiates and controls a self-sustained nuclear chain reaction.
The neutron moderator slows down the fast neutrons to a thermal velocity, because thermal neutrons are more susceptible to start a nuclear chain reaction.
The coolant is used to conduct the heat generated in the core to the steam generator. Reactors can have one or two coolant loops depending on the model.

The classification of reactors can be done in terms of the coolant used, the moderator or the spectrum of the neutrons. Reactors can use light water, heavy water or graphite as moderator.

2.4.1 Light Water Reactors (LWR)

This type of reactor uses enriched uranium from 0.7% to 4% to compensate for the loss of fissile neutrons by coolant absorption. They produce 2.43 neutrons for 1 uranium atom fissioned, which in turn create other fission reactions and generate a chain reaction. This chain is controlled varying the amount of control rods or burnable poison in the core, both neutron absorbers.
They have a negative temperature coefficient, which means that when the temperature increases the response of the reactor is to decrease the generated power. This happens because the moderator expands inducing less amount of fuel and coolant per unit volume. This feature is remarkable because it is a safety passive system to avoid a collapse in the reactor power production.

The two types of light water reactors are:

- Pressurized Water Reactors (PWR): This model has two coolant loops connected by a heat exchanger so the steam is free of radioactivity, in case of an incident. It uses pressurized light water as moderator and primary coolant. It uses enriched uranium fuel, which added to its high-power density leads to a compact core. However, it needs to be shut-down for the refuelling and the coolant propitiates core corrosion.
- Boiling Water Reactor (BWR): This reactor only has one coolant loop that makes the design simpler but also allows the possibility of the radioactivity from the core to be transferred to the steam. It operates at a lower pressure and temperature than LWR.

2.4.2 Pressurized Heavy Water Reactors

These reactors use heavy water as moderator and coolant. For the coolant the water is at high pressure to avoid boiling. A successful example of such a reactor is the Canadian CANDU reactor. Contrary to light water reactor designs, where the core is contained in a large pressure vessel, the fuel bundles in CANDU are enclosed in smaller metal tubes (Calandria tube). The heavy water coolant is circulated inside the bundles. The reactor uses natural uranium and can be refuelled online.

2.4.3 Graphite-moderated reactors

Gas Cooled Reactors (GCR) use graphite as neutron moderator and carbon dioxide as coolant. They use natural uranium. These reactors are inherently large and have presented some structural problems, which led to many being replaced by PWR or the next generation of gas-cooled reactors, Advanced High Temperature gas-cooled reactors, which are moderated with graphite but cooled with Helium [4].

3. Small modular nuclear reactors

The interest in small reactor units is due to the need of having a simpler electricity production unit, reducing the cost of the bigger current nuclear reactors and developing new technologies for nuclear power.
''Small reactors'' and ''Medium reactors'' were defined by the International Atomic Energy Agency (IAEA) as reactors with a capacity under 300 MWe and between 300-700 MWe, respectively. In this thesis the focus is on the small size reactors.
The research on small power reactors began in the 1950's to supply remote areas with electricity. For instance, the USA produced 8 units and deployed some of them in places like Alaska, Greenland or Antarctica.

3.1 Current Small modular reactors

Small Modular Reactor (SMRs) are specifically designed for modular technology. The different modules are fabricated in factories, in a chain production, and then moved to their operating location for assembly. By building numerous versions of the same product in a controlled production line environment, units become more affordable than a stand-alone bespoke major project. This enhances the economy of production and leads to a shorter construction time. SMRs are also a good option to supply the growing electricity demand, while providing a clean environment. Their reduced capacity is compatible with the old and current coal-fired plants used for electricity production. This means that they can replace these plants and/or be placed on brownfield lands.
It is important to mention the differences between small conventional reactors and SMRs:

-Modularization construction: the components are factory produced and then shipped and assembled on site. At the end of the cycle the reactor can be sent back to the factory avoiding the waste disposal problem.
-Standardization: creating some common patterns for each model.
-Passive safety systems: to prevent accident initiators and manage the consequences using as few external elements as possible, leaning on natural forces and inherent characteristics.
-Design flexibility: there are a lot of designs with different coolants other than water. Therefore, SMRs can be placed in remote areas away from water supply [5].

Most reactors have a basic water-cooled design with a reduced size, which gives the benefit of deployment on land or on a barge. The SMRs available for commercial deployment nowadays are:

Land-based reactors:
-Heavy water reactors (HWRs):
The FOAK (First Of A Kind) was the Canadian model CANDU.
The mean lifetime of this type of reactors is 40 years.
Reactors with heavy water as coolant typically use an on-line refuelling system and can work in a cogeneration mode, for example desalinating water.

-Pressurized water reactors (PWRs):
The general characteristics of this model strongly depends on each unit. The lifetime varies between 40 and 60 years and the power output is around 30-45 MWe.
The refuelling timeframe goes from 1 year to 1.5 years and they include passive safety systems.

Barge-mounted PWRs:

Figure 4: Barge-mounted KTL-40 reactor [6].

The operational lifetime of such reactors is 40 years.
The fuel used is LOA type and is changed after every cycle on the barge. Fuel bundles (fuel structuration elements) are shuffled every two years.
The output restrictions have a maximum of 80 MWe. They can be used to generate other products apart of electricity (co-generation) and to operate in co-production mode of heat for district heating.

The plant size is relatively small. The core containment is less than 12 m and the surface of the plant is divided between a floating part of 15.000 m^2 and another land-based part of 8000 m^2.

The FOAK was KLT-40, a Russian reactor used to provide power in some icebreakers boats [6].

The distribution of the current operating models is shown in Table 1.

Table 1: Current operating small modular reactors [6].

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

3.2 Advanced SMRs designs

Advanced SMRs are small units of new designs under development as part of the Gen-IV designs.

The reactor models more pursued to be deployed in small units are the light water reactors (LWR-SMRs), fast neutron reactors, high temperature reactors (HTGR) and molten salt reactor (MSR).

Due to their versatility, a lot of advanced SMRs projects are being developed all over the world. Figure 5 shows the power range of many SMRs under development or construction.

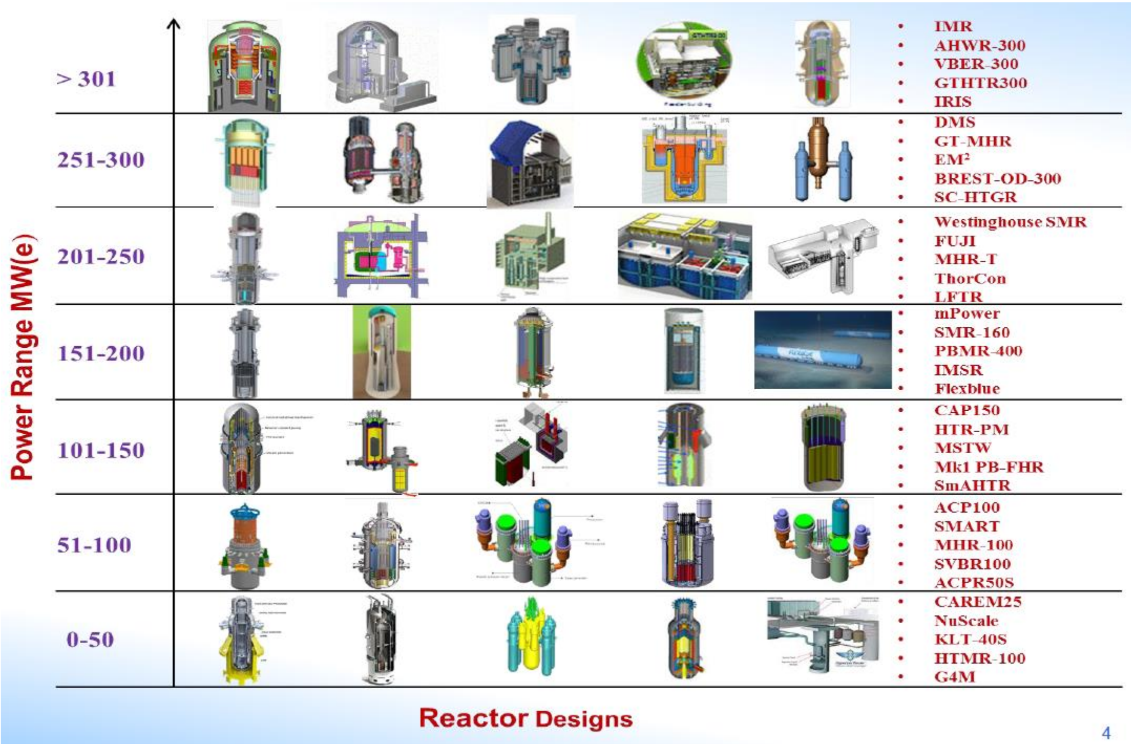


Figure 5: Power range and designs of SMRs [7].

3.3 Features of SMRs in an advanced stage of development

This category of SMRs are either based on larger designs of reactors or on new ones specifically developed for small capacity.

Pressurized water reactors are the most widespread, representing 61% of the current reactors operating. Depending on where the pressurizer system is housed they can be self-pressurized PWRs with in vessel steam-generators. The pressurizers and the steam generators are located inside of the reactor vessel and there is a space reserved for the steam under the dome of the vessel.

-Compact modular PWRs: these are different compact modules connected with short pipes leak resistant. One module contains the reactor core and internal devices, there is also the steam generators, the pressurizers and the coolant pumps. The first coolant system is inside the pressurized vessel.

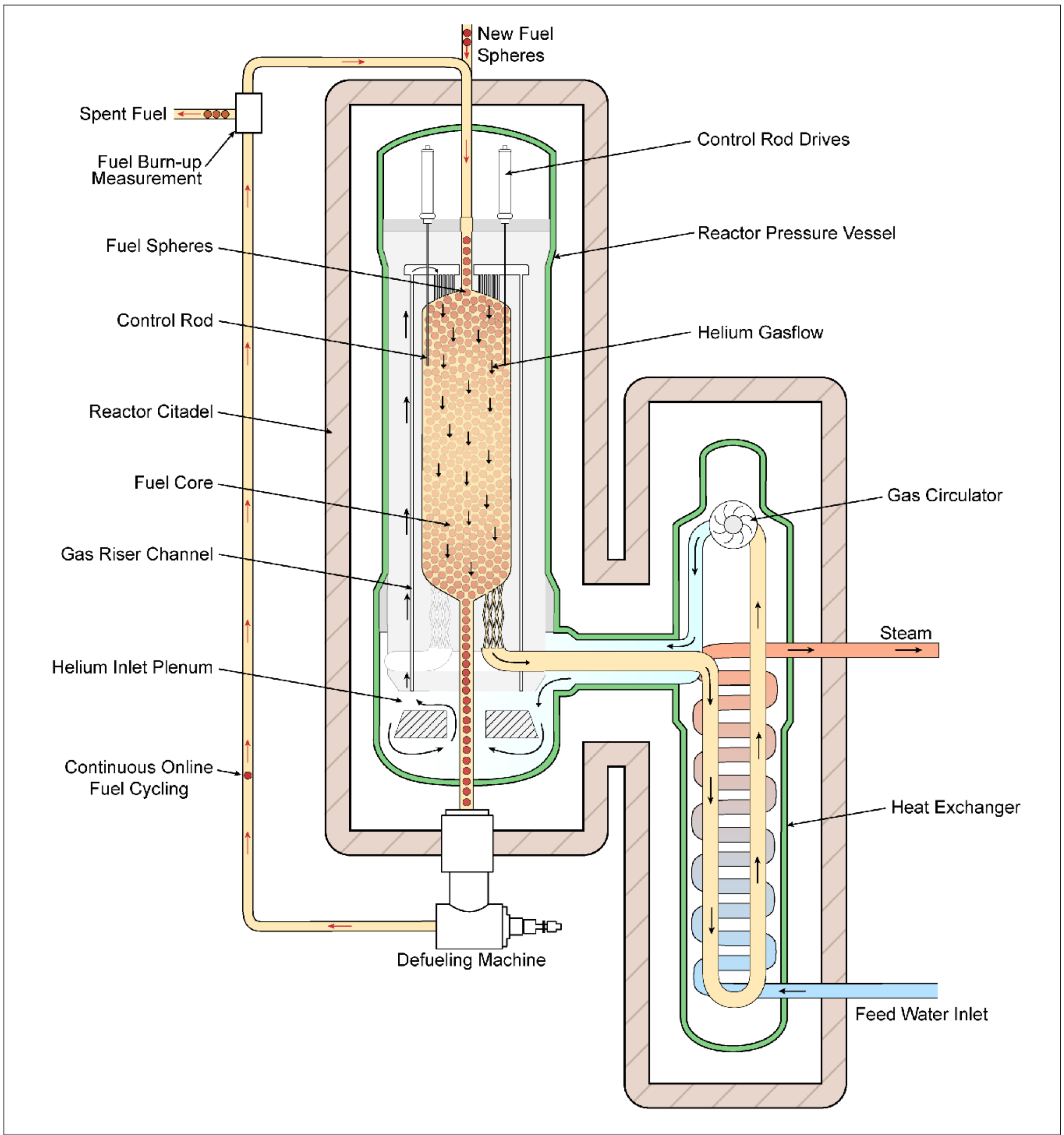
Their operational lifetime is similar to the one for larger PWR, i.e. 60 years. The electric power output ranges from 15 MWe for the smallest SMRs to 350 MWe for the largest ones.
The location of the reactors is mostly land-bases but not exclusively as some future designs include barge-mounted deployment as well.
The fuel used is UO_2 LOA with a general enrichment of less than 5% in U-235 and the refuelling intervals are between 2-4 years achieving longer timeframes than current SMRs. The plant size is highly dependent on the type of PWR but analysing all the models that are being developed, the minimum size for a land-based plant is 8900 m^2 for a single unit.

Boiling water reactors are the second most used type of reactors, 21% of the current reactors are BWR. The BWR-SMRs do not use control rods or recirculation pumps, but rely on the natural circulation of the coolant, using a passive system.
The main lifetime for this reactors is 60 years with an availability of 90%.
BWR SMRs will use low enriched UO_2 and the refuelling will be done partially in batches. The construction times will be reduced to 2-5 years, compared to bigger BWR due to the experience in constructing BWR buildings.
The size of the plant is in line with the common BWR, though it can be smaller, 5000m^2 for a single module unit.

Advanced heavy water reactors represent 10.5% of the currently operating reactors.
Given that the CANDU reactor is the dominant reactor technology in the field of heavy water reactors, we compare the features of the conventional Pressurized Heavy Water Reactor and the SMRs versions.
Large reactor units use an indirect energy conversion cycle and SMRs works with a direct steam condensing cycle for converting the energy.
The water conducts the heat generated in the core to the steam generator where it is transferred to the secondary coolant loop. To generate this circulation common PHWRs use pumps inside and outside of the core as the pressure tubes are in a horizontal position. However, SMRs-HWRs rely on the natural circulation of the coolant and use vertical Calandria tubes in the core.
The fuel for HWR-SMRs is a mixed oxide thorium, Pu-Th or U-Th, as the fertile Th-232 converts to the fissile U-233. For CANDU rectors natural UO_2 is used.
The mean lifetime for HWR-SMRs is 100 years but realistically, components would have to be replaced during this time. The typical power for these small reactors designs is 300 MWe.
These SMRs rely on passive systems for heat removal while larger units don't. They can also operate in co-generation, for seawater desalination in addition to the generation of electricity. The predicted plant surface is small, about 9000 m^2.

Current High Temperature Gas-cooled Reactors (HTGRs) have a large variation of designs. One of the most innovative is the Pebble Bed Modular Reactor (PBMR), shown in Figure 6.
PBMR is a helium-cooled graphite-moderated high temperature reactor and is part of the Generation-IV reactors. It has the particularity of using spherical pebbles of graphite

containing tiny spheres of UO_2 as fuel. This reactor is refuelled online and has no possibility of melt-down, but the balls can crack and produce a large amount of waste.



Source: Pebble Bed Modular Reactor Company

Figure 6: Pebble bed modular reactor [8].

The mean lifetime of these reactors is 60 years to the pin-in-block or non-moveable distribution and 35-40 years with the pebble bed or moveable design.
All the HTGR are included in the category of SMRs, despite the maximum thermal power for these innovative designs being 600 MWth, due to the passive features for decay heat removal and the use of an indirect energy conversion cycle.
As mentioned previously, for the pebble bed fuel the refuelling is on-line and for the non-moveable fuel elements a partial refuelling with batches is employed.
The size of the reactor vessel is smaller than for other SMRs, with a diameter around 6.5-8 m and a height of 23-30 m and HTGR SMRs are provided with a single or double protective wall in the reactor building as secondary containment.
The area is remarkably small with around 11600 m2 for an 8-module plant.

This model is specifically considered to work on co-production mode, due to his high operation temperature. It can produce hydrogen or desalinated water as well as electricity.

Two Sodium-cooled Fast Reactors (SFR-SMRs) are currently being developed, a small one of 10 MWe and another with 311 MWe of capacity.
The lifetime of the smaller unit is about 30 years without refuelling, in continuous operation. The refuelling is done after the 30 years of cycle life and the fuels used are specific of each model, U-Zr or UPuZr, the last one comes from depleted products of LWR used fuel.
The shape of the reactor is highly dependent on each model, a pool type reactor is a proposed distribution. It also relies on passive decay heat removal systems and uses exceptional mechanisms for the reactivity control.
A co-production of oxygen and hydrogen mode is considered.

Lead-bismuth-cooled Fast Reactors (LFR) in larger size were mainly studied in Russia. The lead-bismuth eutectic used as coolant causes corrosion in the core so special materials have to be used. Also the need of continuous heating because the eutectic expands in phase-change and the melting point is quite high. It accumulates volatile reactive elements that enhance the proliferation after the cycle life of the reactor. The need of a factory construction and refuelling is highly recommended.
Despite these drawbacks, such reactor also has strong points, for example the mixture used as coolant is inert in water and air, eliminating undesirable reactions in the core. The solidification temperature is at room temperature and helps curing the cracks. They use an indirect energy conversion cycle.

Small modular reactors of the LFR type have a lifetime of 50-60 years with a capacity varying between 25 and 100 MWe. All the designs are supposed to be pool type reactors using an indirect energy conversion cycle.
The construction is planned to be in factories and the refuelling too and the predictions for fabrication times are promising for this type of reactors, being especially short, around 3.5 years.
The future predicted location is both land and barge-based with mostly multi-module grouping.
These reactors start the operation with a load based on a LOA uranium fuel, and some of them of them can add different fuels later on. The refuelling timeframe is variable from 7-20 years with continuous operation in the middle.
Within the innovative security measures included in these future designs are the external coolant of the core with air or water.
Operational pressures are very low and the size of the reactor vessel has a maximum of 10 m, using a pressure compact containment and being relatively small [9].

3.4 Power conversion systems

In nuclear electricity production, some energy transformations are involved between the core, where fission reactions produce heat and the generator where the electricity is produced and sent to the grid. These changes are carried out in heat transformation systems.
Collecting information about the new SMRs designs, it has been noticed that there are four power conversions systems that are taken in consideration:

-The classical system used for the first reactors in the 1950s, using the heat produced in the core to heat and boil water until it turns into steam. This system will run in simplified models of the current reactors.
-Using natural convection of water to remove heat from the core. This is the most advanced system and its efficiency is a bit lower than the current reactors one, around 30%.
-Another option is to use supercritical CO_2, operating above his critical pressure which is relatively small (7 MPa) and this fact allows the reactor to use small turbines and steam generators. The CO_2 can be directly compressed and easily heated as a supercritical fluid before the expansion.
-Also, other supercritical fluids have been considered, such as water. This model has been considered for low capacity SMRs (30-150 SMRs). The advantage is that as a supercritical fluid, water doesn't have to change its phase. On the another hand, the critical point of water requires a pressure two times larger than the conventional pressure of a steam system, 22.1 MPa at 647 K.

A gas-cooled reactor could be a possible SMRs design, but the gas heat removal capability requires a big surface of the core. The adaptation of this type to SMRs is difficult [10].

3.5 Special issues

3.5.1 Load following mode

Nowadays, two operational modes are known. The Baseload Mode, in which the output power produced by the reactor cannot be adjusted to the demands and the Load Following Mode. In this last configuration, as opposed to the first one, the electricity produced varies depending on the external demand.
SMRs are designed for both modes. The power output variations and the level of this power switches is similar in SMRs and in NPPs.
Even though we don't have specific information about Advanced SMRs adjustment to this issue, SMRs are likely to adjust their production to the demand. This is due to their origin, as they derive from propulsion reactors and consequently were designed to allow a fast power change.
Regarding others new reactors, some co-generation plants with SMRs are planning to use a thermal output that allows to match hourly load changes during the day with the demand.

In case of the non-water cooled SMRs the load-following-mode is inherently improved due to their low linear heat rate of the fuel elements. So, in bigger non-water reactors a baseload mode is applied and small units operate in adjustable load following mode [11].

3.5.2 Grid availability

There's an important rule to follow to make the reactor and the grid work compatible. The capacity of the plant should not exceed 10% of the grid capacity. Naturally, small units, like SMRs, are more promising to be deployed using existing grids than other larger reactors or other larger sources of power [11].

3.5.3 Modularity

There are two options to operate SMRs to produce electricity.

-The first one is to consider multiple SMRs operating in a single plant. These SMRs can work as independent units or in twin-mode and the size of such a NPP can be equal or even smaller than the size of a plant with a single larger reactor and the same capacity. The costs of these plants can be similar to larger plants but SMRs will always be more flexible than bigger units. And as soon as one SMRs has been installed it can start to operate and produce some positive cash flow that can be used to deploy the rest of the units of the plant.

-Single SMRs can also be deployed totally independently. This option is particularly important for developing countries in which the grid is limited [12].

3.6 Co-generation products

The co-generation of different products that are not electricity has always been considered in nuclear plants. For bigger units are usually dedicated to producing electrical power but there are some examples of NPPs that works in a co-generation mode.
The Bilibno NPP in extreme north Russia co-produces heat for district heating, the Beznau NPP in Switzerland also provides a 20000 inhabitant's community with heat and in Japan there is a plant that produces desalinated water to supply the needs of the plant.

SMRs due to some inherent features are more likely to operate on a co-production mode. The fact that they're designed for being deployed in isolated areas, where these non-electrical products have a high value, makes them suitable to co-generation mode. It was shown previously that SMRs have the perfect capacity to replace the actual Heat and Power Plants (CHPs) and larger reactors that do not fit with the grid requirements.
Moreover, the transport of products like desalinated water or heat is expensive and locating SMRs close to the users, would minimize the cost of these co-generation products.

Table 2 and Table 3 show the energy products offered by water-cooled and non-water cooled SMRs, respectively.

Table 2: Energy products offered by water-cooled SMRs [13].

SMR [Source]	Technology line	Electricity MWe (net)	Heat GCal/h	Desalinated water m³/day	Process steam t/h (°C)
QP300 [4.9]	PWR	300	No	No	No
CNP-600 [4.5]	PWR	610	No	No	No
KTL-40S [4.29]	PWR	2x35	2x25 at 2x35 MWe	20 000-100 000 option	No
CAREM-25 [4.30]	PWR	27 (gross)	No	10 000 at 18 MWe option	No
CAREM-300 [4.1]	PWR	300 (gross)	No	No	No
SMART [4.1]	PWR	90	150 at 90 MWe option	40 008	No
IRIS [4.1]	PWR	335 (gross)	option	option	option
IMR [4.1]	PWR	350 (gross)	option	option	option
ABV [4.2]	PWR	2x7.9	Up to 2x12	Up to 20 000 option	No
VBER-300 [4.1]	PWR	302	150	option	No
mPower [4.7]	PWR	125-750 or more, depending on the number of modules	No	No	No
NuScale [4.8]	PWR	540 (12 module-plant)	No	option	209.2 (264°C) option
NHR-200 [4.30]	PWR	Option	168	option	330 (127°C)
VK-300 [4.1]	BWR	250 (gross)	400 at 150 MWe	option	No
CCR [4.1]	BWR	400	option	option	option
CANDU-6 [4.27]	HWR	670	No	No	No
EC6 [4.28]	HWR	700	No	No	No
PHWR-220 [4.9]	HWR	202	No	6 300 option	No
AHWR [4.1]	AHWR	300	option	500 (using reject heat)	No

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

Table 3: Energy products offered by non-water cooled SMRs [13].

SMR [Source]	Technology line	Electricity MWe (net)	Heat GCal/h	Desalinated water m³/day	Hydrogen t/day	Process steam t/h (°C)
HTR-PM [4.1]	HTGR	210* (two-module plant)	No	No	No	No
PBMR (previous design) [4.1]	HTGR	660 (4-module plant) 1 320 (8-module plant)	No	No	option	No
GT-MHR [4.1]	HTGR	287.5* (per module)	No	42 000	200 at 600 MWth	option
GTHTR300 [4.1]	HTGR	274*	option	option	126	option
4S [4.2]	Na cooled FR	10 *	option	34 008 option	6.5 option	option
SVBR-100 [4.2]	Pb-Bi cooled FR	100-1 600, depending on the number of modules	520 at 380 MWe (4-module plant 400 MWe)	200 000 at 9.5 MWe per module option	No	No
PASCAR [4.14]	Pb-Bi cooled FR	35	option	option	option	option
New Hyperion Power Module [4.15]	Pb-Bi cooled FR	25* (per module)	option	option	option	option

* Gross electric output

As we can see from the 27 SMRs, 7 of them operate without co-generation and 6 haven't even considered the option. In opposition to this there's one SMRs deployed in China that is operating without electricity production goal.
Among the different products that can be co-generated there's desalinated seawater (AHWRs), production of heat for district heating (BWRs, PWRs and lead-bismuth cooled reactors) and generation of Hydrogen (in high temperature gas cooled reactors, HTGRs and HTR-PMs) [13].

3.7 Safety systems

The SMRs designs do not assume a big difference with larger reactors technically speaking, but these designs have some distinctive goals in the field of safety. The common set design principles for SMRs are firstly to try to eliminate as much as possible accident initiators inside the reactor, for example the design is made to try to avoid the loss of coolant and the possibility of accidents caused by this factor will be decreased.
Secondly to reduce the probability of accident occurring before they happen and finally, the designs try to reduce the consequences of a possible accident after/if it happens.

Advanced SMRs designs profit from the inherent features of the reactors to implement safety features. They also rely on passive safety systems more than the actives ones (passive systems do not require any external input and they don't work until they're needed).
It could be natural to ask why bigger reactors do not incorporate more of these safety measures as long as they are beneficial for the reactor design and cost. The truth is that SMRs are better at responding to inherent safety systems due to the following reasons:
-With their reduced size, the ratio surface-to-volume is large in SMRs and this leads to a better heat removal capacity.
-Lots of designs have the option to be situated in a water pool and this coolant system can suppress a lot of initiating events.
-All the systems based in natural convection of the coolant and the ones that rely on natural forces such as gravity, are more efficient in SMRs due to their lower core power density.
-Since the SMRs are smaller, their fuel inventory is smaller, therefore reducing the amount of radioactive material in the reactor.

Analysing the current and future designs proposed, it is possible to do a compilation of some common safety features. These include elements to manage internally or externally that could jeopardize the operation of the reactor.

3.7.1 Internal factors

Most of the designs rely on natural convection of the coolant and other elements to remove the heat from the core instead of using pumps as is required in bigger reactors. Regarding accidents caused by a loss of coolant (LOCA) some modifications have been made in the containment structures of SMRs to reduce the possibility of these accidents

to happen. SMRs can be designed as compact structures with all the principal elements integrated in a first container or as separate modules connected with reinforced pipes.
Reactivity levels are controlled by online refuelling, burnable neutron poisons in some cases, and control rods working by gravity or static pressure. However, some designs incorporate some active systems to support the passive and inherent ones, like mechanical control rods or pumps.
A shutdown is initiated first by using passive primary shutdown systems like negative reactivity feedback or natural heat removal from the core, then by using control rods (passive or active), and poison injections.

3.7.2 External factors

Almost all of the SMRs designs incorporate a single or double containment structure to protect them from external events and some of them are designed as pool water reactors. Their shapes has been modified depending on the model and the location of deployment, to make them less likely to crack due to an earthquake, for instance. To prevent aircraft crash, a lot of SMRs will use underground or partially underground locations. Some events like natural floods or climate change haven't been considered yet.

There are two ways of quantifying the risk to which a reactor is exposed. The first one is the Core Damage Frequency (CDFs) and it is referred to the likelihood of an accident to cause severe damage to nuclear fuel or material in the core. The second one is the Large Early Release Frequency (LERFs), which represents the frequency of accidents in which the leakage of dangerous material or the severity of the accident in itself affect the surrounding population before evacuation.
The value of the CDF for current NPPs is $5x10^{-5}$, 10^{-6} for generation III/III+ reactors and between 10^{-7} and 10^{-8} for SMRs. The value for LERFs is normally one order of magnitude lower [14].

3.8 Advantages and disadvantages of SMRs

3.8.1 Advantages

After analysing the available and future SMRS designs, it seems that these small reactors make for attractive options to supply the future energy needs and replacing bigger nuclear power generation plants.

It has already been mentioned but the modularity is a plus point. The designs are simpler and safer, the economics and the quality are better guaranteed in a factory production. Also, the construction time-frames are shorter and the construction and deployment of the reactor are more flexible than with an entire on-site construction.

SMRs can be deployed in a wide selection of places. They can be placed where the electricity demand is not enough to deploy a bigger reactor and also in places were the grid cannot afford a bigger plant. SMRs provide also a good alternative to replace old

fossil fuel plants. These reactors can be deployed in isolated paces and in sites with a limited water supply because they don't necessary need a big amount of water to cool the core. They'll also fit with smaller electrical markets or small grids installations.
SMRs can produce electricity and others products. They can also be coupled with other energy sources like renewable energies and improve their efficiency.

Nowadays, the concerns about security in the nuclear energy field are particularly prevalent around the world. In the scientific world, the safety and security enhancements are evolving fast and the SMRs are being designed and constructed taking in account all these current concerns. Therefore, SMRs structures are being protected for external phenomena and sabotage and their safety systems are enhanced comparing with current NPPs.
SMRs are specifically designed to be proliferation resistant. One of the main strategies is to prevent the access to the nuclear material or fuel by planning longer refuelling time intervals in factories, instead of on-site. SMRs are fuelled in factories, shipped for power generation and returned at the end of the cycle life to be refuelled at the factory. Following this pattern, transport and handling of nuclear material is reduced. In addition, the IAEA establishes, depending on the design and fuel used in the reactor, inspections that include revision of the radioactive material and interviews with the operators about the activities involving nuclear material. Also, the concept of ''security by design'' reduce the theft and diversion of nuclear material.

Finally, SMRs should be advantageous from an economic point of view. The fact that SMRs can supply the growing electricity demands and that they can replace retiring electricity generation plants will result in an increase in the domestic manufacturing, construction and operating work.
As an example, it was calculated that a 100 MWe SMR that will suppose \$500 of investment to make it operate will create 7000 jobs, \$1.3 billion in sales, \$35 million in taxes and \$404 million in payroll [15].

3.8.2 Disadvantages

Firstly, while SMRs produce less waste than a NPP, the spent fuel remains dangerous for the population and the environment and should only be handled by professionals.
Secondly, the underground location can suppose a problem to recover the waste of the reactor in case of accident. It can also pose a bigger challenge for the decommissioning of SMRs after their cycle life.
Thirdly, it is true that nuclear energy and specially SMRs are low CO_2 emission producers. This make them promising to solve some current environmental problems. But the truth is that SMRs are not a near term solution, it will take a decade or more to deploy them.
Regarding the proliferation, is important to notice that SMRs need a lot of non-proliferation systems and safeguards because due to where they can be deployed (remote areas, small countries, large numbers, developing countries) they're naturally a hazard and radioactive material more likely to be stolen or lost.
The public opinion poses a big problem against the deployment of these reactors. After the last accidents, some governments, institutions, investors and populations are afraid of radioactivity and nuclear energy production in general.

Finally, the modular construction demands a high level of manufacturing control. There are still a lot of questions without answers, such as the decommissioning of these plants, the management of the nuclear waste, and so on [16].

3.9 Economy of SMRs

The economy of nuclear power can be split in four parts:

- Capital costs: for programming, licensing, preparing and construction of the reactor.
- Plant and operation costs: maintenance and operation of the reactor.
- External cost to the society: in case of an accident that the current government will pick up
- Taxes and other costs for the unit's transport.

Regarding the SMRs future possibilities of success in the world's market there are different factors, both positives and negatives, to take in account.
In the first place, the growth of nuclear power will be balanced with the fossil fuel prices and renewables energies. In the best case scenario, if the electricity and energy demand grow, the capacity of nuclear supply will grow by 56%. In a low forecast situation, if the demand keeps growing steadily, nuclear power will only improve by 1.9% of the current capacity during the next decades.

The future presence of SMRs in the energy plans will depend on the evolution of the risks to invest in these projects: the fear of radiation and concerns about safe operations, the management of waste, proliferation and high capital investment. There is a lack of funds that should improve to enhance the SMRs economy. This risk can be reduced by introducing SMRs first in the supplier's countries and once they're tested, to offer them to other countries.
The Economy of Scale affects the SMRs economy negatively. The smaller an industry or production is, the more expensive the production of each unit is. To offset this negative effect SMRs have to enhance their best qualities like design simplification, mass production economy, sharing facilities, shorter construction periods with the aim to decrease the costs. The factory production applied to the whole plant is an excellent approach to increase SMRs competitiveness and consequently, the economy.
Another positive element for their economy is the short construction timeframe. Taking in account that 80% of the costs of the plant construction is focused on this phase and that the delays in this process suppose a big increment in financial risks, the shorter this process is the safer and affordable the project is.
It is necessary to establish a regulation about the SMRs construction, so producers will be able to standardize and deploy the different models. Vendors will be able to construct enough units to see the benefit in the cost of learning. This learning of fabrication is a positive factor.
The new passive and inherent safety features decreases SMRs cost.
SMRs can also have a positive impact on national industries, contributing to their own infrastructures, employment and development, and this fact make them attractive for countries that will introduce nuclear energy for the first time on them. SMRs visibility is

enhanced because military groups are interested in them as long as they need electricity supply in some bases quickly.
Eventually comparing larger units with SMRs; the fuel costs are bigger for SMRs and the maintenance and operational costs are smaller for SMRs than for larger units [17].

4. Comparisons with other reactors

4.1 Cost comparison

Regarding the new SMRs designs under construction, we can divide them into two groups depending on the origin of their designs:

- SMRs based on current larger reactors: the designs are scaled-down versions of existing large nuclear plants. Within this group there's a set called integral Pressurized Water Reactors iPWR. They are small versions of PWR. These reactors are designed for an early term deployment
- SMRs based on innovative designs. This are predicted to be deployed in a long term due to the lack of experience in their activities and also because they are F.O.A.K. reactors.

The current bigger reactors and the SMRs have different overnight, financing and variable costs and for this reason it is difficult to make a comparison in terms of cost. PWR-derived SMRs designs provide the best cost comparison with current LWR because the rest of the SMRs that use gas, liquid metal or molten salts as coolant have different capacities for fuel management.

The variables which can be compared include fuel enrichment, average burn-up, and plant thermal efficiency. By using these values, the cost of electricity generation can be calculated including an important additional cost, the fuel cost.
Here a long-term cost comparison between PWR-derived SMRs and larger LWR is established. It is interesting to emphasise that for long term economies the fuel cost are more relevant than for short and medium terms, where the economics is driven by the construction cost.
The five SMRs NuScale, B&W mPower, SMART, Westinghouse SMR and HI-SMUR are considered in this simulations, together with six larger reactors: VVER 1000, AP 1000, ABWR, EPR, US-APWR. Data for a Heavy Water Reactor, CANDU-6 are also provided.

Some of the parameters such as average burn-ups or thermal efficiency are provided by public organisations but fuel cost has to be calculated for each model. To estimate it, it is necessary to know the cost of each part of the fuel fabrication from the mill to the reactor. The parameters taken into account are the price of the natural U_30_8, the cost of the conversion of this U_30_8 into UF_6 and the cost of the enrichment. This last expense in quantified using Separation Work Units that are a measure of the electricity needed to achieve a level of enrichment in the fuel.

The fuel average fuel cost for the current LWR is 3.86 $/ MWth and the average for the SMRs is 5.84 S/MWth. As we can see the fuel price is larger for SMRs and ranges from 15 to 70% depending on the reactor model. Actually, the fuel cost per unit electric energy produced is also larger for heavy water reactors than for larger LWR.

A difference between larger reactors and SMRs designs is that the current SMRs designs include different functions apart of electricity production and they aim higher goals than larger reactors, that's why they don't follow economy of scale in the fuel price.

The trend of the variation of the fuel cost depending on some parameters is interesting to analyse:

- The fuel economy increases in the same way as the burn-up rate. The more fuel the reactor uses the cheaper it is. And this relation is much more noticeable in the SMRs than in larger reactors as can be seen in Figure 7.

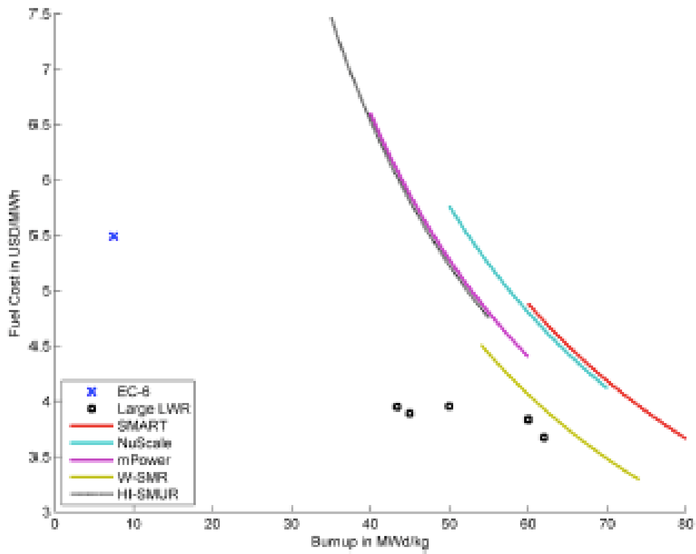


Figure 7: Fuel cost sensitivity to discharge burn-up [18].

- At the same time that the efficiency of a plant increases the price of the fuel decreases. Higher fuel enrichment goes hand in hand with higher burn-up. The relation for LWR is followed at high efficiencies and really low fuel costs (Figure 8).

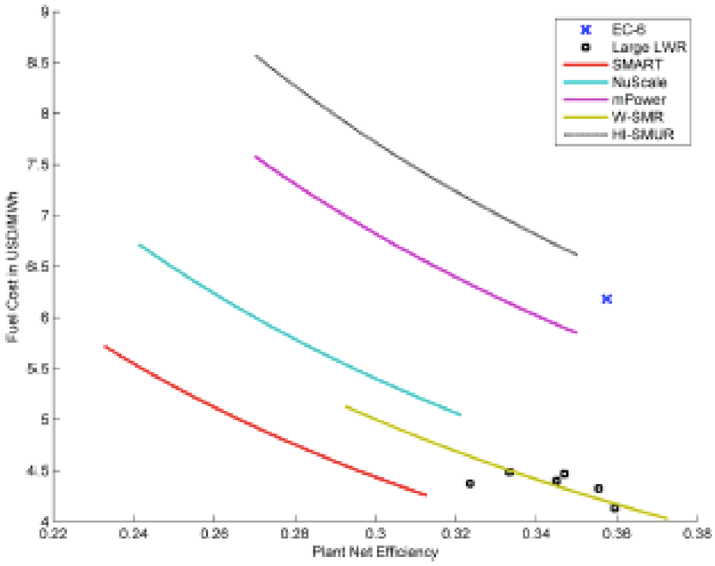


Figure 8: Fuel cost sensitivity to plant net efficiency [18].

- The fuel enrichment has a negative impact on the fuel economy. To do a proper analysis of this parameter we should also include the burn-up factor because the burn-up increases hand in hand with the enrichment of the fuel. That's why, the LWR doesn't follow this pattern like SMRs units (Figure 9).

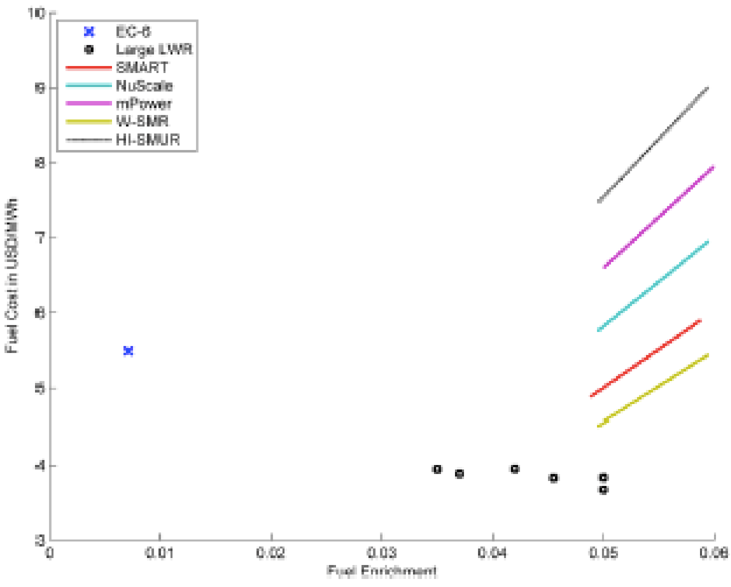


Figure 9: Fuel cost sensitivity to average fuel enrichment [18].

It is also interesting to see the distribution of the fuel cost depending on the model and size. The percentage derived at each phase is similar in larger LWR and in small iPWR

SMRs. Otherwise it is different for large PWRs that use natural Uranium and do not have any cost on enrichment (Figure 10).

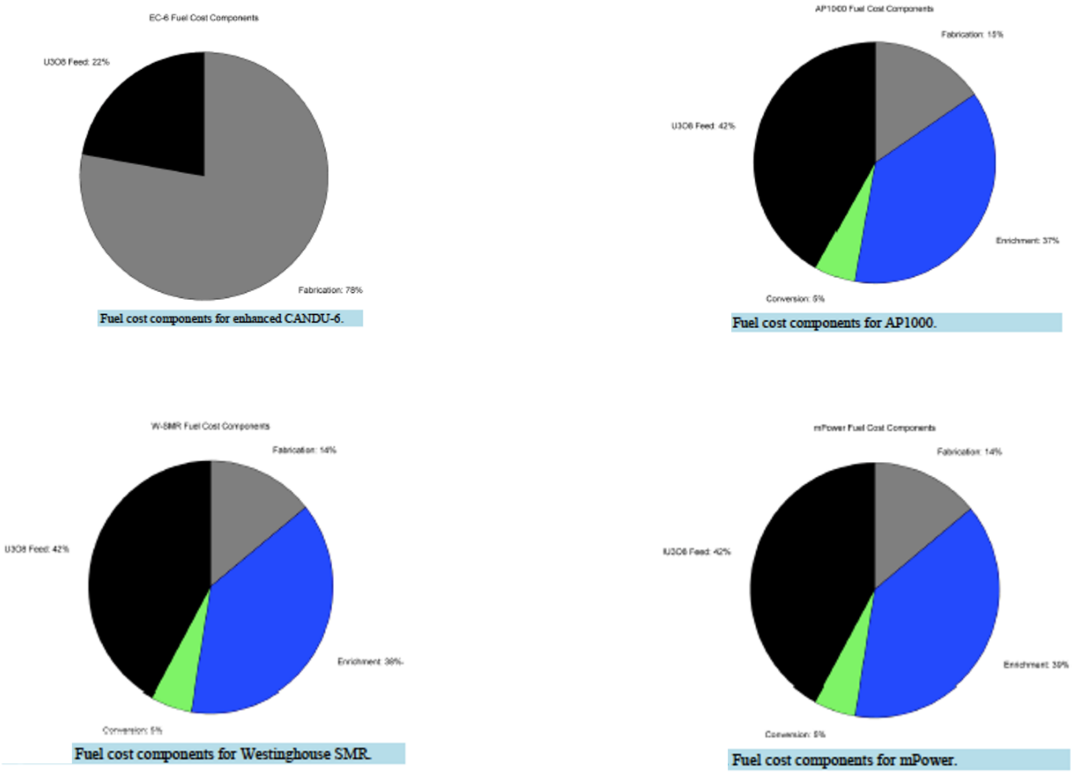


Figure 10: fuel cost comparisons for various reactors [18].

To sum up this comparison, the SMRs fuel cost was supposed to be cheaper than in larger LWR but it is shown that is between 15 to 70% more expensive and the construction cost has been priced similarly. It is true that SMRs are expected to be easier to license and more accepted by the public. In the future, the experience in operating SMRs is supposed to increase the efficiency. So this approximation is likely to change in favour of small reactors [18].

4.2 Safety and support system comparison

The basic difference in the safety systems between current-generation reactors and future SMRs is that the latter rely passive safety systems instead of active systems like larger reactor. For example, larger reactors need pressure injections, emergency pumps, emergency diesel generators or emergency initiators for the coolant systems in the core but in the case of smaller SMRs almost all this processes are carried on naturally or using passive systems.

Regarding in the timeframe after the shutdown of the reactor, while current reactors need a lot of active systems to remove the heat created and stored in the core, SMRs have the capability of using passive safety systems to remove the decay heat.

There are other support systems to this primary safety measures that differs from large to small reactors. As long as the SMRs cores are compact designs they don't need to worry about seals and their failures and prevention, this was a big concern in larger rectors. Other example is the room coolant systems (ventilating or air conditioning) that backs active safety systems in current reactors. This is not necessary in SMRs designs because the plant designs inherently avoid this need.

Moreover, SMRs are more water friendly. They don't need extra closed water circuits to support heat removal. While current reactors use external water sink like rivers or lakes, SMRs don't need this rejection system for heat because they use natural convection of heat. To sum up SMRs have less impact on their environment [19].

5. Examples

5.1 Icebreakers

In this report information about SMRs is collected and contrasted in order to analyse their future capabilities to provide electricity. As we have seen, due to their small size, there is no need for water as coolant and accident risks are reduced. SMRs have a high placement flexibility. They are likely to be deployed in places were current reactors cannot, like remote areas where energy is needed but a large grid cannot be setup. They can also be placed near the potential users which allows to provide heating or other non-electricity products to these users.

The use of nuclear power to this purpose, started earlier that you can expect. Russia was the forerunner of this technology. They have been using nuclear reactors in icebreakers ships that work in extremely cold weather conditions. Icebreakers have the task to reduce the ice loads in the extended ice fields to improve manoeuvrability. These reactors provide power to drive the boats, as well as electricity and heat for the crew and the plant.

The first model was the Lenin reactor-ship. It was launched in 1957 and was a F.O.A.K model. The Lenin ship used the soviet PWR OK-150 first (90 MW) and then the OK-900 reactor (171 MW), his successor. This change was driven by two accidents that took place during the operation in 1965 and 1967. OK-100 uses 5% enriched uranium fuel and OK-900 uses 90% enriched uranium. It was decommissioned in 1989 and by this time other similar structures were already operating [20].

There are two nuclear-powered icebreakers currently deployed. The Taymyr-class and the Artika-class ships.

Taymyr-class icebreakers: there are two ships Taymyr and Vaygach both using the same plant and reactors. The nuclear power plant has 1 KLT-40M of 171 MWe of power that produces superheated steam and can work at temperatures of -50 degrees.

The motor propulsion system is a nuclear-turbo-electric powertrain, the steam produced is used in two main turbo-generators (18400 kW each), and consisting in steam turbines coupled with Siemens generators, to produce electricity. This electricity rotates the propulsion motors consisting in three shafts with 12 000 kW motors. This las ones are coupled with four bladed fixed pitch propellers rotating at 180 rpm.
The maximum velocity that this ship can reach is 34 km/h in water and 5.6 km/h in ice.
If the nuclear plant cannot work, there are other two diesel engines and two emergency diesel generators to run the motors and also to supply power to the 120-138 crew on board [21].

Arktika-class icebreakers: six units of this type were deployed by Soviet Union. They use OK-150 or OK-900 reactors depending on the model, normally more than one unit.
The six ships are: Arktika (1971), Sibir (1974), Rossiya (1981), Sovetskiy (1983), Yamal (1986), 50 Let Pobedy (1989).
They are provided with two 171 MWe KO-900 reactors. In the plant, water is continuously pumped in the reactor to remove the generated heat which is directed to two boilers. Here the heat is transferred to a secondary coolant loop. The steam generated in 1 boiler is connected to two turbines (4 in total). Each turbine is coupled with three dynamos.
The electricity production system is connected to three shafts with one motor each one that provides propulsion to three propellers. The motors run at 120-180 rpm leading a mean velocity of 41 km/h in water and 5.6 km/h in ice.
There are 5 extra turbines each one producing 30 MW of electricity to other utilities apart from propulsion to the ship and the 100 passengers that work on it [22].

5.2 Power analysis and comparisons

To get an idea of how much electricity this nuclear technology produces we can compare the power of these reactors with the energy consumed by some common electrical equipment or houses.

To make this comparison we have to introduce a new term called kilowatt hour. Kilowatt hour is a measure of amount of energy consumed or produced while a watt is a measure of power. To make it clear, imagine a gadget of 1000 W. It needs 1000 or 1 kW to work and 1 kWh is the amount of energy that you'll need to keep this gadget running during 1 hour. If you have a light bulb of 100 W you'll need ten hours to accumulate 1 kWh and backwards, an electronic device of 2000 W only needs 30 mins to achieve 1 kWh [23].

As long as the amount of electricity consumed is expressed in kWh, we will transform the power produced by Taymyr and Arktika reactors from megawatts to kWh to compare the values.

- Taymyr class power is $1{,}71 \cdot 10^8$ W. This corresponds to an amount of energy produced of $1{,}71 \cdot 10^7$ kWh.
- Arktika class power is the double of this, because it has two 171 MW reactors. So it has $3{,}42 \cdot 10^8$ W of power and $3{,}24 \cdot 10^7$ kWh.

Table 4 and Table 5 show the electricity consumed by household electrical appliances [23] and my own calculations for how long the Taymyr and Arktika reactors can supply electricity to these items.

Table 4: Energy in kWh used by electric devices.

	Energy needs; kWh	Taymyr				Arktika			
		hours	days	months	years	hours	days	months	years
50'' LED TV	0.016 per hour	$1{,}07 \cdot 10^7$	$4{,}45 \cdot 10^5$	14800	1236,98	$2{,}14 \cdot 10^7$	$8{,}91 \cdot 10^5$	29700	2473,96
Refrigerator	54 per month			316666.65	26388.85			$6.33 \cdot 10^5$	52777.7
Air conditioner	3 per hour	$5{,}7 \cdot 10^6$	$2{,}38 \cdot 10^5$	7916,5	659,7	$1{,}14 \cdot 10^7$	$4{,}75 \cdot 10^5$	15833	1319,4
Oven	2.3 per hour	$7{,}45 \cdot 10^6$	$3{,}09 \cdot 10^5$	10326,05	860,5	$1{,}49 \cdot 10^7$	$6{,}19 \cdot 10^5$	20652,1	1721

Table 5: Particular example for a washing machine.

	Energy needs, kWh	Taymyr	Arktika
		loads	loads
Washing machine	2.3 kWh per load	$7{,}44 \cdot 10^6$	$1{,}49 \cdot 10^7$

And, for how long could a nuclear generator supply a house with electricity? There are different factors that affect to the consumption of electricity like the size of the house, the ages of the home, the number of people living there, the type of house and other ones. Also the cost of kWh varies depending on where you live.
Based on this, the approach of the amount of electricity consumed by a house in 1 year is [24]:

- House of 1 person that works everyday fulltime consumes 2000 kWh.
- House inhabited by a small family with full school and work consumes 3200 kWh
- House of 4/5 students that spend some time in it consumes 4900 kWh.

Table 6: Estimates of electricity budget for houses.

	Energy needs	Taymyr	Arktika
1 person	2000 kWh	8550 years	17100 years
Family	3200 kWh	5344 years	10688 years
Students	4900 kWh	3490 years	6780 years

Table 6 shows that the reactors under consideration are capable of supplying electricity for (very) long periods of time to houses.

Finally, let's take an average of this three measures and say that a house will consume 3367 kWh per year approximately and that the inhabitants are three on average. The population of Groningen was approximated on the 1st of January of 2020 as 232922 [25]. This leads to an average of 77.741 houses. An estimate of the energy needs for the city of Groningen (only for houses, not businesses) in one year is 261.416.125 kWh (Table 7).

Table 7: Capability of reactors to supply electricity to houses in Groningen.

	Energy needs	Taymyr (weeks)	Artika (weeks)
Groningen	261.416.125	3.5	7

It is clear from the examples given above that small modular reactors have a place in the mix of energy sources for the future.

6. Environmental considerations

Nuclear energy produces less greenhouse gases than current coal plants. Nuclear energy represents, in general, a less harmful energy source for the atmosphere. But regarding the different reactor types, SMRs will have potential if they solve some problems that can be exacerbated compared with current larger reactors.
In waste management, which is one of the biggest concerns about nuclear energy, Advanced models, especially fast reactors, the spent fuel is one third of the amount of fuel used in a bigger LWR which then reduces from 9 to 6 the storage waste.
Analysing the different types of wastes, the spent fuel has to be partitioned in three groups: fission products, uranium, and trans-uranium minor actinides. The first ones are hazardous because they stay radioactive until they can beta-decay to stable isotopes. The uranium is the part which we're interested in retrieving to recycle and create a new fuel cycle. The minor actinides are a very strong neutron source and that's why they have to be removed in order to achieve an efficient reprocessing of uranium and plutonium. Fast reactors offer again a real advantage in producing minor actinides comparing with larger LWR.
The last factor that can be controversial in nuclear energy is the freshwater consumption. A current coal plant with a 40% of efficiency ejects around 75 MW(th) to the cooling water systems, while the use of gas turbines represents a reduction of 27% with respect to the coal plant. That's why nuclear plants are less damaging in this aspect. But going further, the new heat exchangers systems that are planned to be used in SMRs future designs can produce a reduction in the heat pump up to 60%. Even some of them don't need any heat dumps to the water which allows them to be deployed anywhere in the globe independently of the water supplies.
To summarize the most respectful option for the environment will be an advanced modular reactor using the new systems for heat exchanges [26].

7. Potential solution for remote areas

Many remote locations are facing problems in providing their population with electricity. This is due to the population size or distribution, geographical isolation, exorbitant infrastructure costs, weak transport infrastructures or extreme harsh weather conditions.

These isolated communities need a continuous supply of diesel or other carburant to produce electricity, heat or other products the lack of which can be a serious problem in harsh weather conditions. Here the health or the safety of the population may be at risk. Using SMRs these areas would not have to rely anymore on this generation or transportation infrastructures. They also will create jobs and contribute to a steady economy and a social developing.

On the another hand, 25 % of the worldwide population lives in rural zones or ghettos, and the well-being of the inhabitant can be restricted by the lack of good enough infrastructures to provide them with electricity. In these countries SMRs can be deployed solving this problem and supplying enough energy to increase population health and social and economic development.

This can be done due to some characteristics already named like the ability to fit small grids, requiring smaller land areas. In addition, they have a lower and less risky initial capital investment and lower operating and maintenance cost [27].

8. Conclusion

After this review we can affirm that SMRs are a promising alternative to supply energy to the world in the future.

They are designed based on modularization to reduce construction times. Due to their small size they can fit in locations where bigger plants cannot be accommodated. The flexibility of this reactors is enhanced as they could add units and they can be an alternative in countries with small grids.

They main causes of the nuclear accidents have been taken in account in the reactors designs and they incorporate inherent safety measures that make them a real option to provide secure energy.

The future locations of SMRs are easy to fit, they can be deployed near urban centres, in places where there's not a big water supply like away from the coast or rivers or in isolated places.

They reduce the severity risk in pre-construction and other phases causing a reduction in the investment risks. This implies that SMRs can expand nuclear power application to countries with limited financial risks or limited technological deployment.

This reactors still rely on human interaction. Even so, SMRs have some challenges to face to become a real available alternative. As long as they are penalized by the loss of economy of scale they should recover using other reduced costs to increase their competitiveness.

Nuclear energy investments suppose a high risk investment due to the public opposition to nuclear power and the lack of political support in certain countries.

All the improvements summarized in this report have to be demonstrated by the first phases of these reactors to be successfully commercialized and the new designs also need technology maturity and operability performance to become real future energy sources.

The energy demand is planned to grow in several countries in the future and nuclear energy is expected to rise steadily worldwide to satisfy this growth, specially is Asia and in the Pacific (Figure 11).

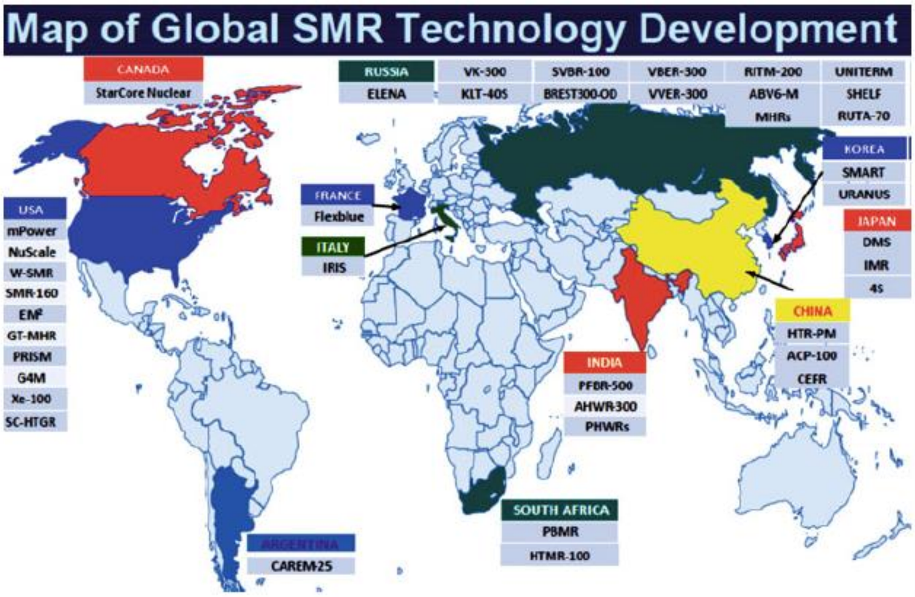


Figure 11: SMRs research and development by country [28].

What is clear is that a new cheaper, simpler, smaller, safer and respectful of the environment, reactor is needed to increase nuclear energy presence in the energetic plans of developed and developing countries, and to rely on this source to supply worldwide energy needs. SMRs are, according to the predictions, a promising option to reach this goal [28].

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