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A Global Review of PWR Nuclear Power Plants

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Featured Application: This work shows a global review with three analyses of the PWR nuclear design: (i) technical evolution; (ii) level of implementation in the world, and (iii) life extension scenario.

Abstract: Nuclear energy is presented as a real option in the face of the current problem of climate change and the need to reduce CO_2 emissions. The nuclear reactor design with the greatest global impact throughout history and which has the most ambitious development plans is the Pressurized Water Reactor (PWR). Thus, a global review of such a reactor design is presented in this paper, utilizing the analysis of (i) technical aspects of the different variants of the PWR design implemented over the past eight years, (ii) the level of implementation of PWR nuclear power plants in the world, and (iii) a life extension scenario and future trends in PWR design based on current research and development (R&D) activity. To develop the second analysis, a statistical study of the implementation of the different PWR variants has been carried out. Such a statistical analysis is based on the operating factor, which represents the relative frequency of reactors operating around the world. The results reflect the hegemony of the western variants in the 300 reactors currently operating, highlighting the North American and French versions. Furthermore, a simulation of a possible scenario of increasing the useful life of operational PWRs up to 60 years has been proposed, seeing that in 2050 the generation capacity of nuclear PWRs power plants will decrease by 50%, and the number of operating reactors by 70%.

Keywords: nuclear energy; power; pressurized water reactor; operating factor

1. Introduction

Currently, due to the growing demand for energy worldwide, nuclear energy has regained the relevant role it played throughout the past 20th century, as an alternative to CO_2-emitting electric power generation technologies. This generation technology presently accounts for 10% of the electrical energy generated in the world. Over the past eighty years, various nuclear reactor designs have been developed around the world, which can be classified according to (i) their configuration and objectives, or (ii) their generation stage. Within the first classification, it is necessary to distinguish between (i) fast reactors and (ii) thermal reactors. The first ones, fast factors, are capable of generating more fissile material than they have consumed. On the other hand, among thermal reactors there are several combinations of moderators—in charge of reducing neutron energy—and coolants—the fluid that transmits the heat generated in the reactor—that have been successfully developed in different nuclear reactor designs.

The second classification (thermal reactors) is the most used [1–3] and allows defining the following generations of nuclear reactors (Figure 1): *Generation I*: prototypes built between 1957 and

1963; *Generation II*: commercial production, built from the mid-1960s onward; *Generation III*: advanced reactors—safer and with greater generation capacity, built since the early nineties; *Generation III+*: nuclear reactors with structural safeguards and/or passive safety features, designed from the 21st century; and finally *Generation IV*: the highly efficient reactors of the future, with advanced safety features and generating small amount of spent nuclear fuel.

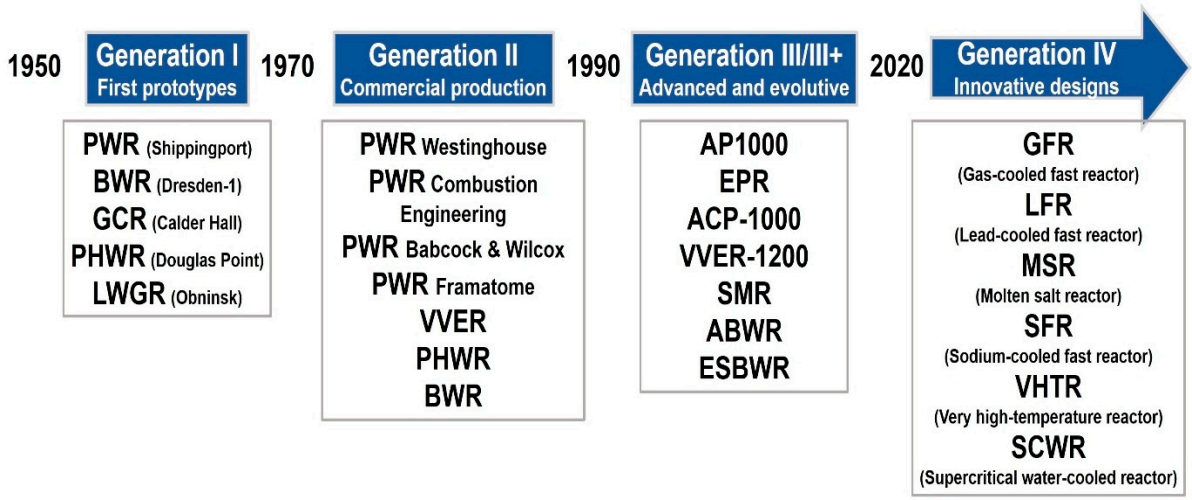


Figure 1. Generations of nuclear reactors throughout the past seventy years.

Throughout history, the most developed nuclear reactor designs have been Generation II (Figure 2), with different fundamental characteristics [4–6]: (i) PWR (pressurized water reactor): in whose vessel the coolant does not reach boiling temperature. It developed from the 1950s; (ii); BWR (boiling water reactor): uses light water as moderator and coolant. It developed like the PWR from the 1950s; (iii) PHWR (pressurized heavy water reactor): in which heavy water—deuterium dioxide, D20—was incorporated as moderator and coolant. It was developed in Canada from the sixties; and (iv) GCR (gas cooled reactor): the reactor design that uses graphite as a moderator and gas as a coolant. It was developed in the UK after World War II. Table 1 summarizes the main characteristics of these four designs (PWR, BWR, PHWR, and GCR), as they are the most important within Generation II.

Furthermore, in this group of Generation II reactors, there is another design known as LWGR (light water graphite reactor) or RBMK in its Soviet variant, from the Russian *Reaktor Bolshoy Moshchnosty Kanalny*. This latest RBMK design is known to be the one that caused the fatal accident at the Chernobyl nuclear power plant (Ukraine) in 1986. The RBMK design is very different from the rest of the power reactors, since it is used simultaneously for both the production of plutonium as for the production of electrical energy.

The basis for the data research on Nuclear Power Reactors is the Power Reactor Information System (PRIS) database from the International Atomic Energy Agency (IAEA) [6]. Other authors have taken data from this database for their research in nuclear science [7,8]. To study the obtained data, a parameter called *operating factor* (OF) has been used in this paper, which is defined as the relative frequency of PWR reactors operating around the world (in percentage):

$$\mathrm{OF} = \frac{n_i}{N} \cdot 100 \quad (1)$$

where n_i is the number of a specific PWR design i, and N the total population of operating PWR in the world ($N = 300$ currently, according to [6]).

It is worth noting that the parameter OF is different from that known as the operation factor, which is defined by IAEA as the ratio of the number of hour the unit was on-line to the total number of hours in the reference period, expressed as a percentage [6].

The 447 nuclear reactors operating in the world as of January 2020 are distributed as follows: (i) PWR: 300 operating reactors, representing 67% of the operating nuclear reactors and an electric power generation capacity of 284 GWe; (ii) BWR: 69 operating units, representing 16% of the total and an

electrical power generation capacity of 69 GWe; (iii) PHWR: 48 operating units, representing 10% of the total and a capacity of 24 GWe; (iv) other designs: the remaining 7% of the operating nuclear reactors in the world are capable of generating 17 GWe, among which are different designs such as GCR and LWGR (Figure 3). It should be noted that these data correspond to January 2020 and that they may vary from the current ones depending on (i) the start-up of a reactor that was previously under construction or (ii) if there has been a permanent shutdown of a reactor that was in operation.

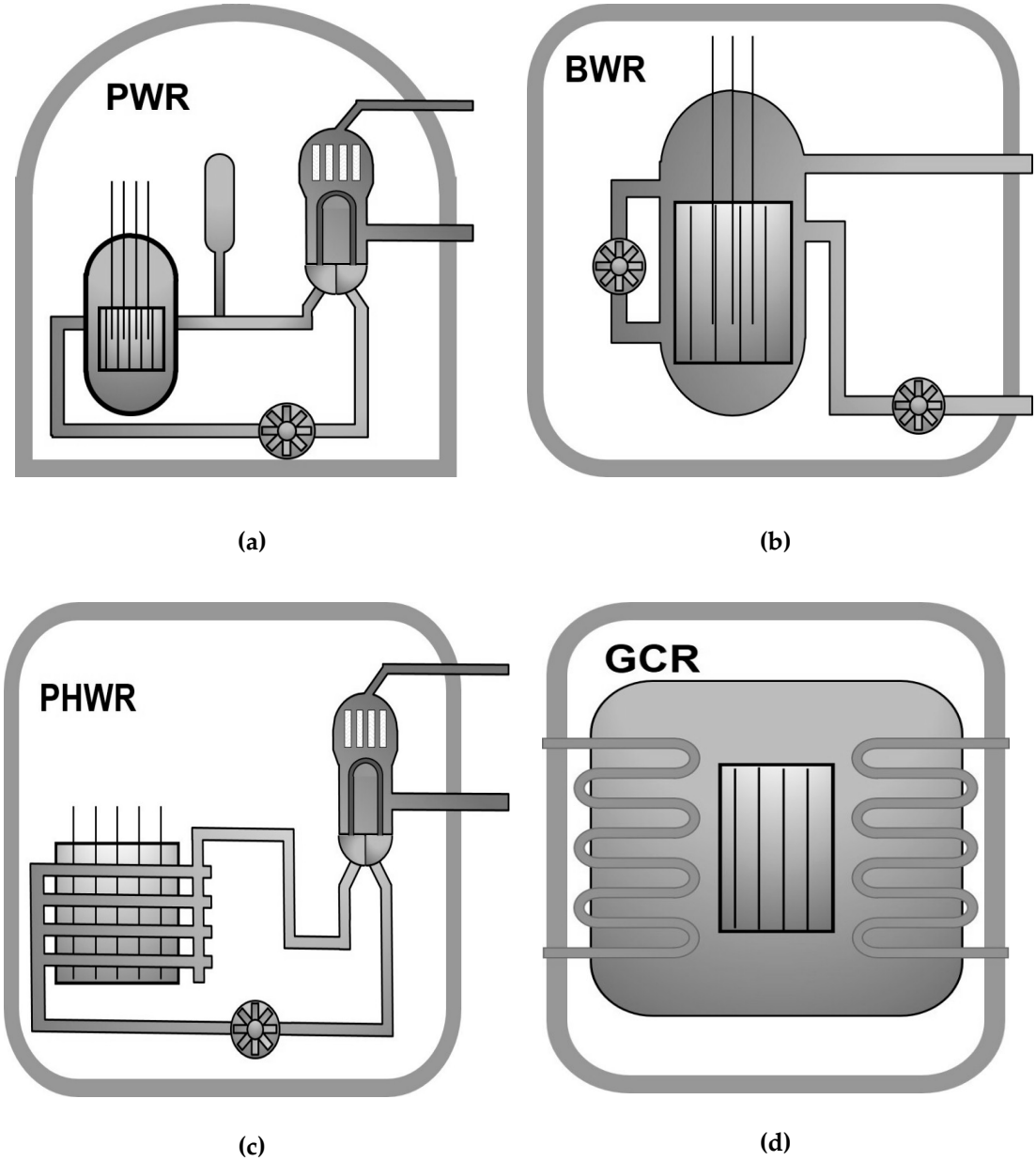


Figure 2. Generation II designs: (**a**) Pressurized Water Reactor (PWR); (**b**) Boiling Water Reactor (BWR); (**c**) Pressurized Heavy Water Reactor (PHWR); and (**d**) Gas Cooled Reactor (GCR).

Among the 300 PWR nuclear reactors currently operating in the world [6], there are several design variants. To obtain a safer and more efficient PWR reactor, the different components of this technical system have been taking different forms over time due to various technical factors (performance, safety, availability). Thus, several references have dealt with the evolution of nuclear reactor designs globally, analyzing the different factors modified in different generations [9–11]. Besides, other authors discussed the evolution of the PWR design throughout the different Generations [12–14] and other references developed the technical evolution of aspects of the PWR design as relevant

as control rods or fuel [5,15,16]. Given these results, it can be assured that the PWR design: (i) is that which currently has the highest implementation percentage (67%) in the world (Figure 3); and (ii) has given rise to different variants depending on various technical factors.

Table 1. Main characteristics of the Generation II designs.

Main Characteristics	Generation II Designs			
	PWR	BWR	PHWR	GCR
Country of development	United States, Germany, France, Japan, South Korea and Russia	United States and Japan	Canada	United Kingdom
Fuel	Enriched Uranium (<3.5% U-235)	Enriched Uranium (<3.5% U-235)	Natural Uranium (UO_2 natural)	Natural Uranium (<0.7% U-235)
Coolant	Water (H_2O)	Water (H_2O)	Heavy Water (D_2O)	CO_2
Moderator	Water (H_2O)	Water (H_2O)	Heavy Water (D_2O)	Graphite

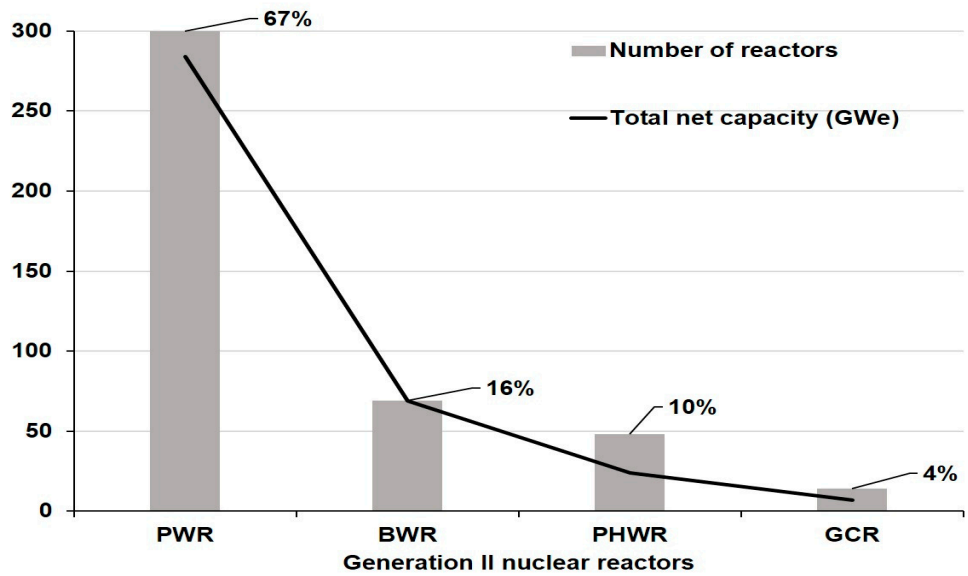


Figure 3. Operative reactors in the world (data collected from [6] in January 2020).

From a simple consultation in SCOPUS on the number of articles that include, in the title, abstract, or keywords, the names of Generation II designs (PWR, BWR, PHWR, and GCR), Figure 4 was obtained. Thus, a total of 22,457 papers in the SCOPUS database include the denomination of the Generation II designs (data collected in April 2020). Among this criterion, 11,762 (around 52%) of the total published papers include "PWR" or "pressurized water reactor", so this design gets the highest number of papers among Generation II nuclear reactors. On the other hand, approximately one half (48%) of the published research papers are linked with the rest of Generation II designs. In this group, 6341 papers containing "BWR or "boiling water reactor" (approximately 28%); 958 papers containing "PHWR" or "pressurized heavy water reactor" (around 4%); and 3396 papers containing "GCR" or "gas-cooled reactor" (around 15%) in the title, abstract or keywords. It should be emphasized here that the GCR design exhibits a higher scientific interest than expected, since its OP is only 4% in the world (Figure 3). This may be due to the GCR nuclear power plants are mainly concentrated in the United Kingdom—where this nuclear reactor design was developed. In this country, approximately

93% of the operational reactors are GCR (14 GCR nuclear power plants) and 71% of the total permanent shutdown reactors are also GCR. Therefore, nuclear scientific research in this country is specialized and focused on GCR design.

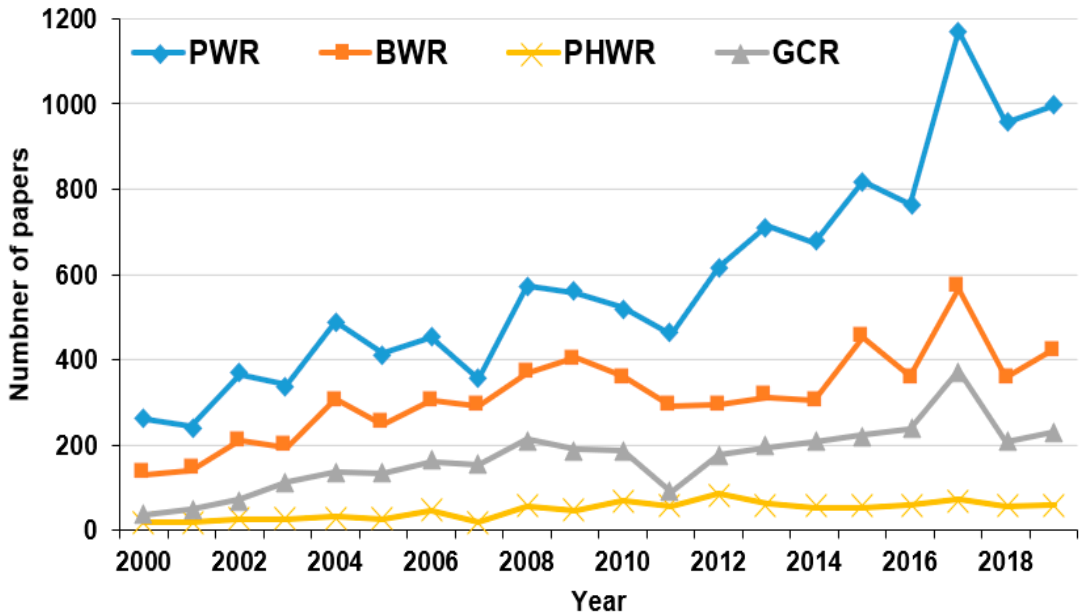


Figure 4. Number of research papers indexed in SCOPUS related with the Generation II designs (data collected on April 2020).

Taking into account the data exposed in Figures 3 and 4, which indicate the scientific interest in PWR nuclear design, the objectives of this article are to analyze both (i) the technical evolution and (ii) the different expansion mechanisms and the OP of the different variants of the PWR nuclear reactor design developed in all Generations (Generation II, Generation III, and Generation III+). The analysis carried out in this article focuses on the nations that have the most developed nuclear energy as a source of electricity generation: the United States, France, Russia, and China.

2. International Development of the PWR Design

This section shows the study of the technological development of the PWR design. For this, it is necessary initially to understand the operation of a nuclear power plant with a PWR reactor, and from that moment, to analyze the different variants that have been made of this design. Thus, in this chapter the North American variants are first developed, carried out by the companies *Westinghouse, Babcock & Wilcox*, and *Combustion Engineering*. Later, the variants designed by the French company *Framatome* are explained. To continue the study, the different variants of the Soviet version of the PWR design, called VVER, developed by the *Rosatom Company* are developed. Finally, Chinese design variants, designed by *China General Nuclear Power Corporation* (CGN) and *China National Nuclear Corporation* (CNNC), are studied.

2.1. Operation of a PWR Nuclear Power Plant

Nuclear power plants operate for the same purpose as a thermal power station: to convert the heat generated into electricity. Its operating principle is also the same: the use of a fuel that enables water vapor to be obtained, which is used in a turbine to transform its heat output into rational speed and, in turn, into an electrical output voltage for the alternator. In the fuel is just where the fundamental difference between both technologies lies. While thermal power plants use fossil fuels, nuclear power plants use fissile fuel that enables a fission chain reaction to be obtained. In a PWR design nuclear power plant there are three cooling circuits (Figure 5): (i) primary circuit; (ii) secondary circuit or steam cycle; and (iii) tertiary circuit [17].

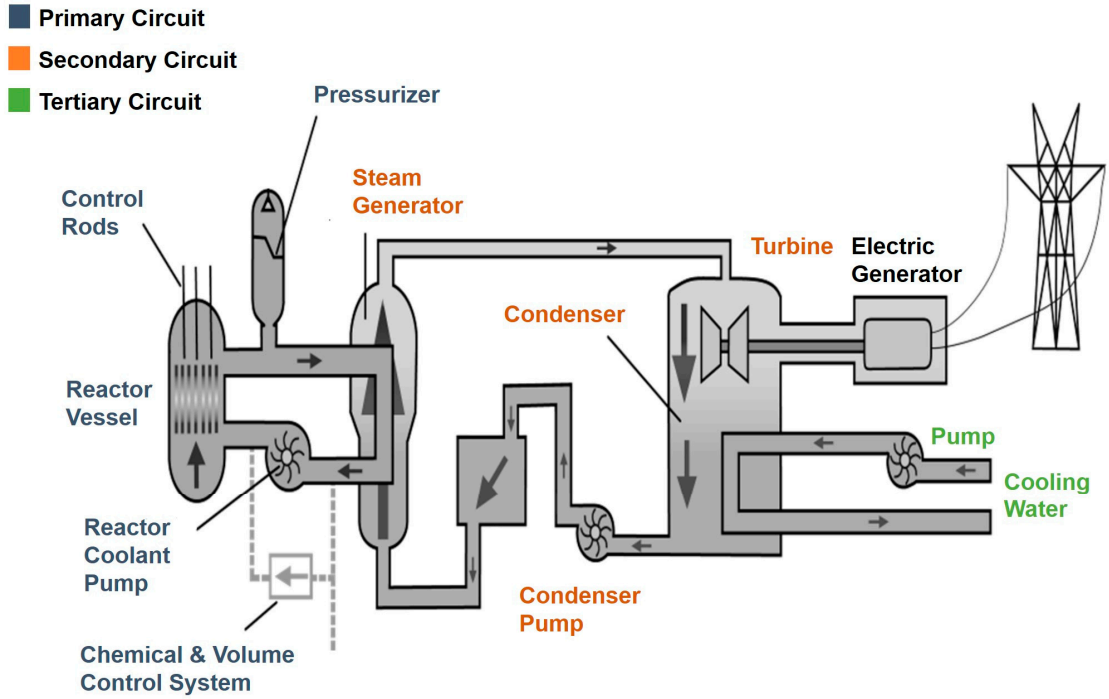


Figure 5. PWR layout and main circuits.

Until now, pending the commercial application of nuclear fusion, within the vessels of the different designs developed in the successive Generations (Figure 2), the process of division of the atomic nuclei (nuclear fission) takes place, causing the increase in temperature of the coolant that circulates initially around the cladding of the fuel elements and later through a closed circuit, called the primary circuit. The reactor vessel is the main component of this circuit, also called the coolant system reactor (RCS).

Each primary circuit is made up of the pipes necessary to maintain the coolant, a reactor coolant pump (RCP) and a heat exchanger called a Steam Generator (SG). The pressurizer is installed in one of these primary circuits, a component in charge of controlling the process pressure (Figure 6). The primary circuit is around 150 bars of pressure and 300 °C of temperature, so the water does not reach its boiling point, thus avoiding the formation of bubbles that would hinder the transfer of pod-coolant heat. If there was no cooling focus, the temperature of the coolant could continue to increase over time.

Making an everyday simile, the PWR design vessel behaves like a pot express. The fuel elements inside the vessel heat the water, while in the express pot the fire is in charge of heating the water inside. To prevent the temperature from continuing to rise over time, a cold focus is designed through which the coolant contained in the primary circuit can be cooled so that it returns to the reactor vessel and is again heated as a consequence of the transfer of heat between the coolant and the fuel elements.

In the pressure cooker, the cold focus is the release of steam to the outside through the discharge valve. In the PWR design, the cold focus is the steam generator, which has two goals: (i) to act as a barrier between the primary and secondary circuits, and (ii) to transform the thermal energy generated in the reactor into latent energy utilizing steam generated. This steam is led through the secondary circuit to the different turbines and the electric generator, in charge of converting the shaft rotation energy into electrical energy, a process similar to that performed by a dynamo on a bicycle.

The steam used in the turbines goes back to a liquid state in the condenser, thanks to the cooling originated in this component by a tertiary circuit. Once this steam has condensed, it is used again as feed water in the steam generator. Finally, the heat transferred in the condenser to the water used in the tertiary circuit is evacuated to the outside through a cold focus, either in the form of a reservoir, river or cooling towers (Figure 5).

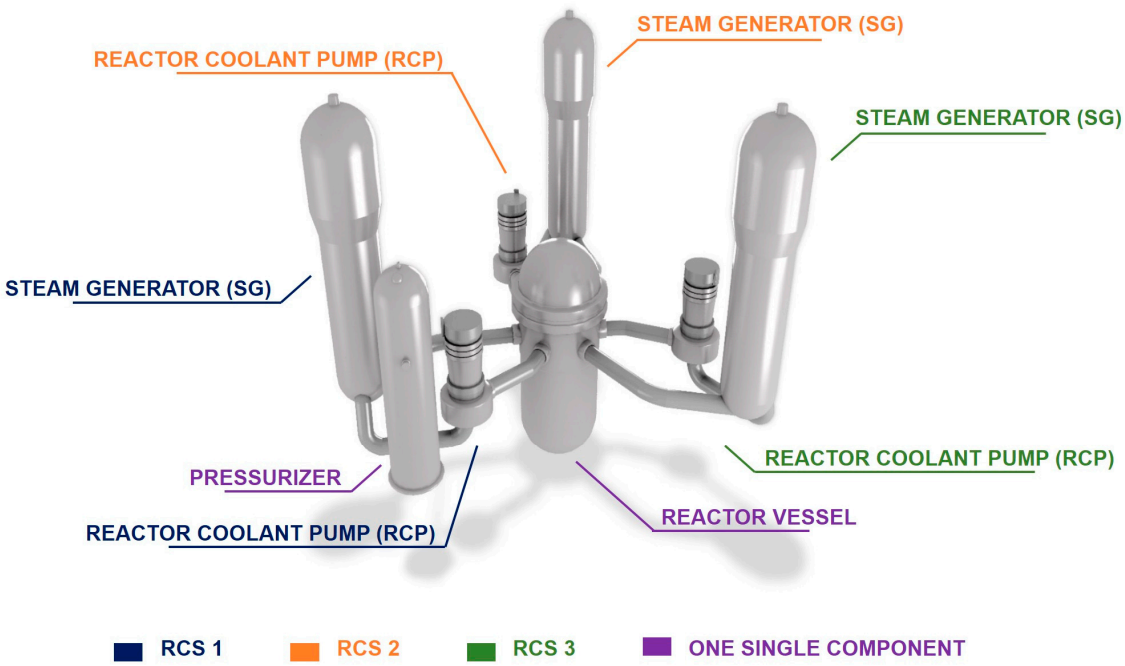


Figure 6. A 3D view of a PWR design with RCS and main components.

2.2. American PWR Evolution

Although the United States also developed the BWR design across different generations, the PWR design has been the one with the highest OP (Figure 3). In the 1950s, PWR design became the preferred choice when developing a nuclear-powered armada. Subsequently, the country's first nuclear power plant, *Shippingport*, with a PWR reactor inside, was the origin of the most powerful nuclear reactor design to date. In fact, its reactor served as a reference to those built and later used in the United States and to those exported by North American companies [3,18,19].

Given the high growth expectations of the US nuclear industry, the companies *Babcock & Wilcox* (B&W) and *Combustion Engineering* (CE), initially focused on the manufacture of the main components of Westinghouse's BWR and BWR nuclear reactor designs by General Electric, joined the nuclear race with the development of their own PWR reactor designs [13].

The different variants of the PWR nuclear reactor design developed from the 1960s by these three US companies are described below: (i) *Westinghouse,* (ii) *Babcock & Wilcox,* and (iii) *Combustion Engineering.*

2.2.1. Westinghouse PWR Design

After checking the technical feasibility of the technology at *Shippingport*, it began its commercial development. Two new nuclear power plants, *Connecticut Yankee* and *San Onofre*, began commercial operation in 1968 and featured a PWR design supplied by the Westinghouse Company under a turnkey contract [20]. In the case of the Connecticut Yankee nuclear power plant, a 4-loop PWR design and a generation capacity of 490 MWe were chosen (Figure 7d). The vessel of this reactor was at that time the longest in the world, and was designed and built by the company *Combustion Engineering*. In contrast, *San Onofre* had a 3-loop PWR and 365 MWe electrical output design (Figure 7c) [21,22]. That same year, 1968, the first nuclear power plant in Spain, *José Cabrera*, came into operation, which had a Westinghouse PWR with 150 MWe electrical output [23], becoming the only operational 1-loop PWR around the world (Figure 7a). Following these first plants, the North American company developed in parallel throughout the 1960s and 1970s the variants PWR 2-loop (Figure 7b), PWR 3-loop (Figure 7c), and PWR 4-loop (Figure 7d).

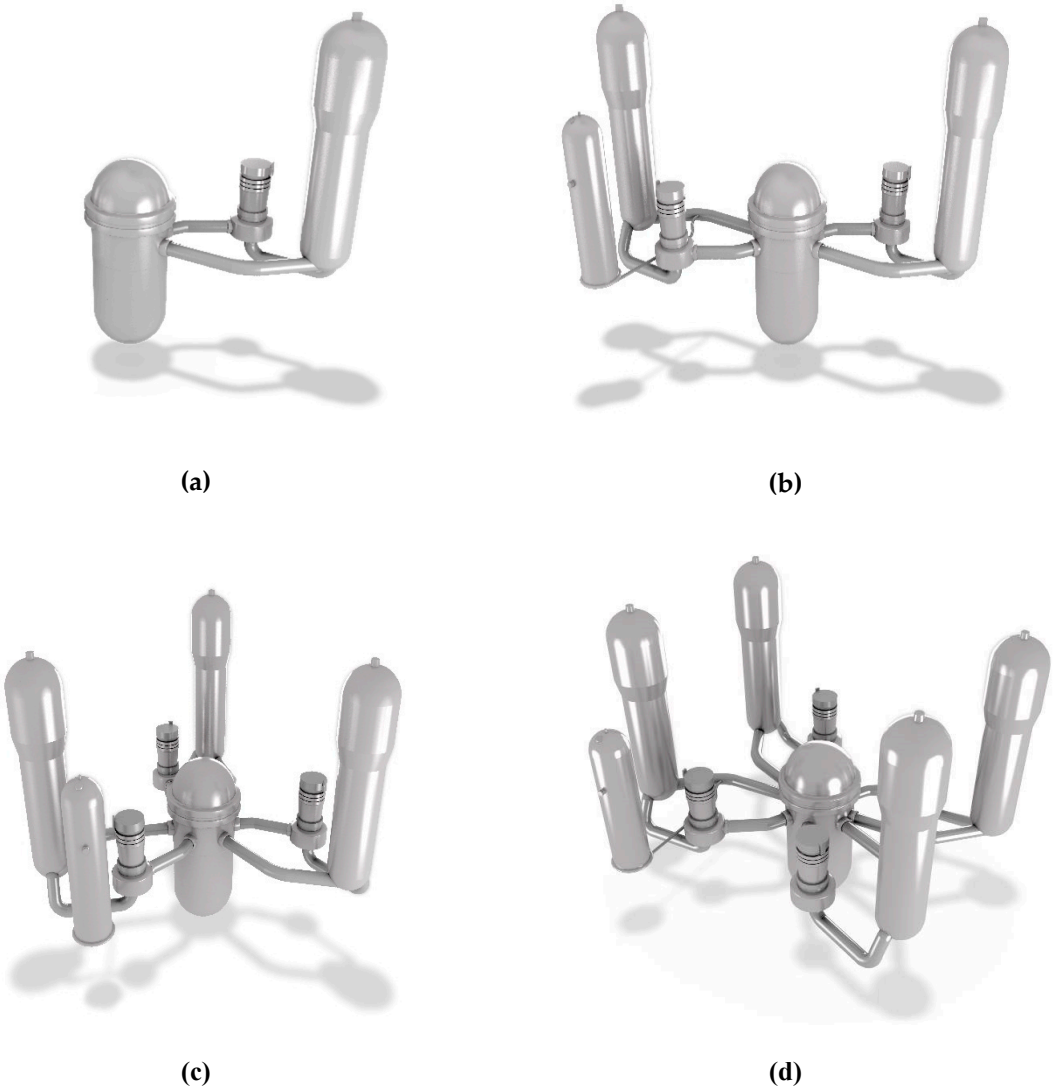


Figure 7. Westinghouse PWR designs: (**a**) 1-loop; (**b**) 2-loop; **(c)** 3-loop; and **(d)** 4-loop.

Starting in the 21st century, the US company has continued to bet on PWR design, developing Generation III design AP1000, 2-loop 1150 MWe PWR (Figure 7b) that uses the forces of nature and simplicity of design to enhance plant safety and operations and reduces construction costs [24,25]. AP1000 design continues to use prove components, and the inherent safety and simplicity of the AP600 design. The AP600 design was Westinghouse's initial start-up as Generation III PWR design, but predictions of a lack of competitiveness for this design prompted the company to develop the AP1000 [26].

2.2.2. Babcock & Wilcox PWR Design

Throughout the 1970s and 1980s, 10 Babcock & Wilcox (B&W) PWR-designed nuclear power plants began commercial operation: *Three Mile Island-1 and 2, Arkansas Nuclear One-1, David Besse-1, Oconee 1-2 and 3, Indian Point-1, Rancho Seco-1,* and *Cristal River-3*. In the B&W PWR design the primary circuit is based on 2-loops each formed by (i) a pipe from the vessel to the top of the steam generator, called the hot branch, and (ii) two lines that came from the lower part of the SG and connect to the vessel, called the cold branch of the primary circuit, in each of which a reactor coolant pump is installed (Figure 8). One of the most important differences between Babcock & Wilcox PWR and other PWR designs is the steam generator. The B&W PWR uses a type of steam generator called a *once-through steam generator* (OTSG), in which the heat transfer between the coolant—which enters through the top and descends inside a bundle of tubes—and the water from the supply, occurs in

countercurrent, thereby generating steam at constant pressure in any power range. This difference supposes an operational advantage for other designs, since in a traditional steam-generator, i.e., U-tube steam generator (UTSG), the vapor pressure depends on the power [27–28].

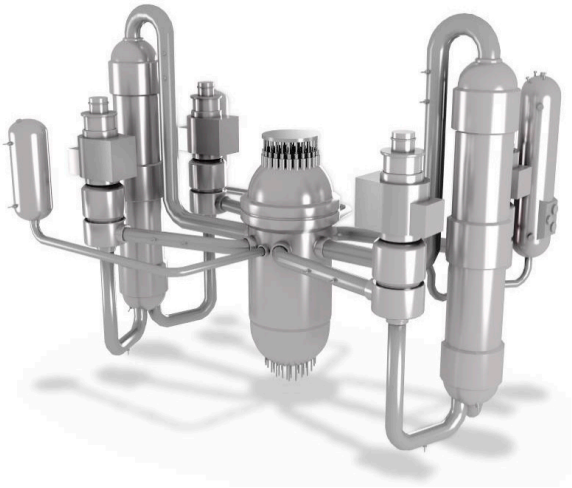


Figure 8. Babcock & Wilcox PWR design.

2.2.3. Combustion Engineering PWR Design

Combustion Engineering (CE) built 15 nuclear power plants in the United States: *Arkansas Nuclear One-2, Calvert Cliffs 1 and 2, Millstone-2, Palisades, Palo Verde 1-2 and 3, St. Lucie 1 and 2, and Waterford-3, Maine Yankee, San Onofre 2 and 3.* This company's PWR design (called CE80) [10], is made up of 2-loops connected to the reactor vessel, located in the central part of the system. Unlike other variants, in each primary circuit there are two cold legs—connecting the steam generator outlet with the vessel—and in each of these legs a reactor coolant pump is installed (Figure 9). This first major modification of the traditional PWR design was due to the second fundamental modification in this variant, the increase in dimensions of the steam generator. This increase in the size of the steam generator results in an increase in the volume of the coolant, and therefore results in an improved design response to accident conditions with reduced inventory.

Another of the most characteristic modifications of the Combustion Engineering design (called CE80) was the 33% increase in the volume of the presser, which allowed for more efficient management in the case of Loss of Coolant Accident (LOCA). Likewise, this availability of a greater quantity of coolant in the pressurizer avoids the reactor trip during transients or load rejections. Unlike the rest of other PWR design variants, in the CE80 design the possible power variations during the design operation are only corrected with the control rods, so the need to adjust the boron concentration in the short term is reduced.

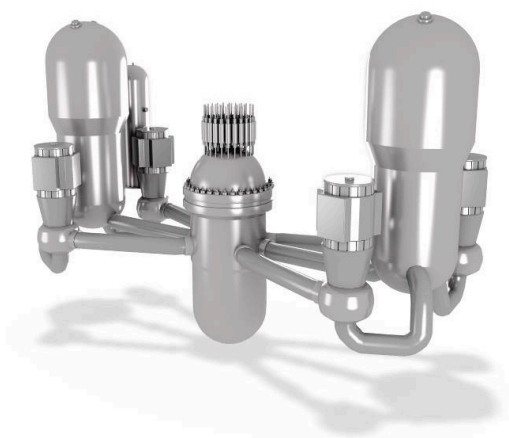


Figure 9. Combustion Engineering PWR design.

2.3. French PWR Evolution

France, one of the great world powers that developed nuclear energy as a source of electricity generation, opted in the initial phase of its nuclear program for gas-cooled reactors (GCR) and fast breeder reactors (FBR). However, in collaboration with Belgium, a PWR-designed nuclear reactor is being built at the *Chooz-A* nuclear power plant, very close to the border between the two countries [29]. Its construction began in 1961, and in 1967, the operation of the first commercial PWR nuclear reactor in Europe began.

In the 1970s, several series of the PWR design [30,31]—all of them 3-loop and 900 MWe electrical output—were developed in stages in France. These new series based on the PWR design were named CP0, CP1 and CP2. The CP0 series, fully under Westinghouse license, was only implemented during the 1970s, in the aforementioned Units 1 and 2 of *Fessenheim* and Units 2, 3, 4, and 5 of the *Bugey* nuclear power plant. Instead, the CP1 and CP2 series were implanted throughout the 1970s and 1980s, totaling 28 built nuclear reactors. These CPI and CP2 series benefited from the feedback obtained from the design, construction, and operation studies of the CP0 reactors. Unlike the design studies for the CP0 series, which were conducted separately for each site, the design studies for the CP1 and CP2 series were standardized. As a result, the CP1 and CP2 series differ from the CP0 series in (i) the design of the containment building—which was modified to facilitate operations inside, (ii) the location of the designed security systems—which were modified to increase the independence of the trains from the systems and increase their reliability, and (iii) more flexible reactor control—thanks to the use of control rods and the addition of control rods with less neutron absorption capacity.

Subsequently, it advanced to the plants of four primary circuits, which meant an increase in the generation capacity, reaching 1300 MWe. These new plants were called the P4 and P'4 series. The initial design of the plants named P4 was based on a Westinghouse license, of which 8 units were built throughout the 1980s. However, in the face of such an ambitious and protectionist national nuclear program, the Framatome company developed its own "Frenchified" version of Westinghouse's P4 series, called P′4, from which 12 units were built. The increase in power in these series P4 and P'4 was achieved by increasing the size of the reactor. To eliminate the increase in thermal power for the initial series CP0, CP1 and CP2, it was necessary to install an additional loop (thus changing from 3-loop for the CP0, CP1 and CP2 reactors from 900 MWe to 4-loop for the series P4 and P'4 of 1300 MWe). The components of each loop—mainly Reactor Coolant Pump and Generator Steam—are also larger than those of the previous series. Regarding the location of the buildings, the new series are single-unit plants, while the previous series were double-unit plants.

The designed security systems and auxiliary systems are located in specific buildings of each unit to improve the safety of its operation. Additionally, each containment vessel has a double concrete wall (one pre-stressed concrete interior wall and one reinforced concrete exterior wall) in place of the single steel-lined pre-stressed concrete wall in the 900 MWe reactors. New microprocessor-based control and instrumentation technologies using programmable memory are used. The P'4 series differs from the P4 series in that the installation of buildings and structures was optimized with the main objective of reducing costs. The result is a more complex plant design and smaller buildings and structures [32,33].

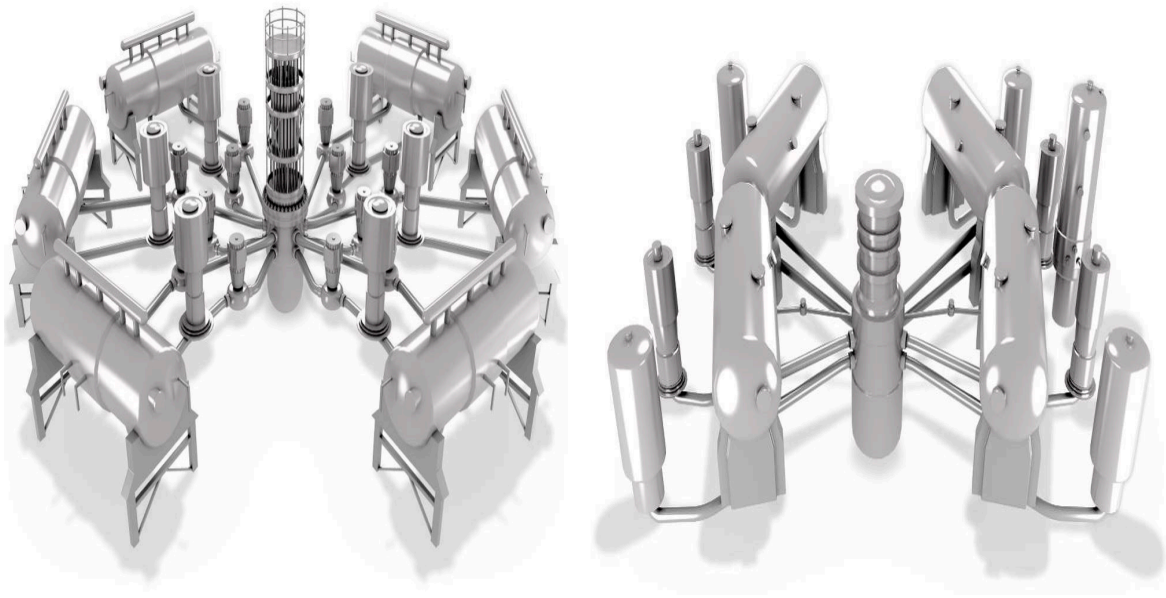
Finally, during the eighties, the Framatome company came to implement a French design for the PWR plant: the N4 design, four new plants were built with this N4 design: two new units in *Chooz* and another two units in *Civeaux*. With the help of advanced fuel and improvements to the main components of the secondary steam generation circuit, it offered a power of 1450 MWe with a 4-loop PWR. Currently, within Generation III, France continues to bet on the PWR design through the EPR (European Pressurized Reactor) design [34], with a generation capacity of 1600 MWe. The design of the Areva company—currently called Framatome—is based on the experience of the French N4 design and the Generation II German Konvoy design. Currently 2 EPR reactors are in operation in *Taishan* 1 and 2 (China) and meanwhile, the EPR *Olkiluoto-3* (Finland) and *Flamanville-3* (France) design nuclear power plants continue to be built. The United Kingdom is also betting on this design for the two units of the *Hinkley Point* nuclear power plant, that will be capable of generating 7% of the electrical energy consumed in the country from 2025 [35].

2.4. Russian PWR Evolution

In parallel with North American nuclear development, the former Soviet Union was also taking its first steps towards generating electric power from nuclear power. In 1954 the Soviet Union was able to start the operation of the world's first nuclear-powered nuclear reactor. It was the *Obninsk* nuclear power plant, based on the LWGR design, water-cooled, and moderated with graphite. This design, operational until 2002, had a generation capacity of 5 MWe. Soviet scientists and technicians went on to develop various designs of nuclear reactors with some success: LWGR, PWR and BWR. Finally, the communist regime opted for the development of the first two. As for the PWR design, the Soviet version was named *Water-Water Energetic Reactor* (WWER) [36,37], from the Russian *Vodo-Vodyanoi Energetichesky Reaktor* (VVER), which was developed by the company currently known as Rosatom. The main differences between the Soviet VVER design and the western PWR are [38]: (i) a hexagonal geometry of the fuel assemblies with the arrangement of the fuel rods in a triangular grid; (ii) the use of a zirconium-niobium alloy as a fuel rod clad material; (iii) the possibility of transporting all large equipment by rail, resulting in a limitation of the outside diameter of the reactor pressure vessel; and (iv) an original design of horizontal steam generators.

Within Generation I, the first two units of the *NovoVoronezh* nuclear power plant, named V-210 and V-365 based on their power generation capacity, served as prototypes of the VVER design. After the construction of these first two units, the construction of two units began at the *NovoVoronezh* nuclear power plant with the VVER-440 variant (Figure 10a). With minor changes from its predecessors, the VVER-440 design became the base design for the construction of more than twenty nuclear power plants around Europe: Slovakia, Hungary, the Czech Republic, Bulgaria, and Finland. The third stage of development of the VVER-440 design was the V-213 variant, which included as a design accident the severe breakage of the lines with the maximum diameter of the primary.

The continuous evolution of the VVER-440 design resulted in the VVER-1000 design (Figure 10b), first implemented in 1980 in Unit 5 of the *NovoVoronezh* nuclear power plant. While the VVER-440 reactor has six loops, the VVER-1000 design reduces the number of these to four [39]. This design was developed within Generation II and Generation III nuclear reactors (Figure 1). In this design, the reactor is located within a concrete containment. The number of fuel elements increased, and the number of control bars was reduced.



(**a**) (**b**)

Figure 10. Rosatom VVER designs: (**a**) VVER-440; (**b**) VVER-1000.

In the mid-2000s, began the development of a yet further modernized design: the VVER-1200. The new Russian reactor Generation III+ VVER-1200 represents the latest model currently offered for construction by Rosatom. It is an evolutionary development of the well-proven VVER-1000 with an increasing thermal power to about 3200 MWt and providing additional passive safety features [40].

2.5. Chinese PWR Evolution

The Chinese PWR nuclear reactor design program is based on the parallel development of three companies [41–43]: (i) *China General Nuclear Power Corporation* (CGN); (ii) *China National Nuclear Corporation* (CNNC); and (iii) *State Nuclear Power Technology Corporation* (SNPTC).

2.5.1. China General Nuclear Power Corporation PWR Design

The beginnings of the Chinese company CGN were based on French technology. The first 900 MWe units were exported by the Framatome company for the two units that were built at the Chinese *Daya Bay* and *Ling-AO* nuclear power plants respectively.

The design of these units ended up being called M310, which evolved in the following years to the CPR-1000 Generation II+ (Chinese PWR) design. The 3-loop CPR-1000 and 1086 MWe electrical output, has an operational cycle of 18 months. A major change from the original M310 design was the removal of the weld joint in the reactor pressure vessel, thus shortening component production time and eliminating the need to inspect the weld over the life of the reactor. The CPR-1000 has 157 fuel assemblies with UO_2 enrichment of 4.5%. The fuel assembly design is a 17 × 17.

The CPR-1000 has evolved to a more advanced variant, the Generation III ACPR1000 (advanced Chinese power reactor, based on PWR design). This design has several technical improvements such as: (i) greater generation capability; (ii) simplification of the chemical and volumetric control system; (iii) extension of its useful life; (iv) increased resistance to external events; (iv) greater length of fuel elements; (vi) increase in the heat transfer area of the steam generator; and (vii) increasing the capacity of the presser; and (viii) increased capability to withstand high concentrations of hydrogen thanks to the assembly of passive recombinants.

2.5.2. China National Nuclear Corporation PWR Design

The CNNC company began the development of its line of CNP reactors (CNP nuclear power reactor) in the 1970s, during the research and development project of a nuclear reactor for use in submarines. The result was the PWR design named CNP-300, 1-loop PWR, and 300 MWe electrical output. The Generation II CNP-300 design evolved to Generation II CNP-600, 2-loop PWR, and 650 MWe electrical output. Later, the CNNC, together with the companies Westinghouse and Framatome, developed a Generation III PWR variant with three loops and a generation capacity of 1000 MWe, called CNP-1000. Later, the CNP-1000 design evolved to another Generation III design called ACP-1000 (advanced Chinese power reactor). Recently, both companies, CGN, and CNNC, joined forces to merge their respective PWR designs: the ACPR1000 and ACP-1000, in a design called HPR1000 (called *Hualong one*).

2.5.3. State Nuclear Power Technology Corporation PWR Design

Although the Westinghouse AP1000 Generation III design is the main foundation of the Chinese Generation III nuclear program, the *State Nuclear Power Technology Corporation* (SNPTC) has developed the Chinese version of this design, called CAP1400, one of the sixteen National Science and Technology Major Projects in China. The CAP1400 is an enlarged version of the AP1000, a 2-loop PWR, and a 1500 MWe electrical output reactor. This design is the largest Generation III PWR. Ensuring its advanced nature from the very beginning; CAP1400 comprehensively inherits the philosophy of the passive concept and the simplification of AP1000 [44–46].

3. Discussion

This section aims to compare the different variants of the PWR design throughout history. To achieve this, a study is carried out on different aspects: (i) analysis of the technical evolution of the different variants; (ii) the *operating factor* (OF) of PWR nuclear power plants; (iii) the *under construction factor* (UCF), which represents the relative frequency of reactors under construction around the world; and (iv) simulation of the electrical capability of both operational and under construction PWR nuclear power plants in a scenario of life extension of 60 years.

3.1. Technical Aspect

If we analyze the different relationships throughout the evolution of American, French, Russian, and Chinese PWR designs (Figure 11), we observe the existence of different technical influences throughout history, which have given rise to a large number of variety of designs with different related technical aspects. The beginnings of the PWR design are found in the different Westinghouse versions, in which both the number of loops and the size of the main components (reactor vessel, steam generator, reactor coolant pump and fuel assemblies) increased as new reactors were redesigned. These changes mainly favored an increase in electricity generation capacity.

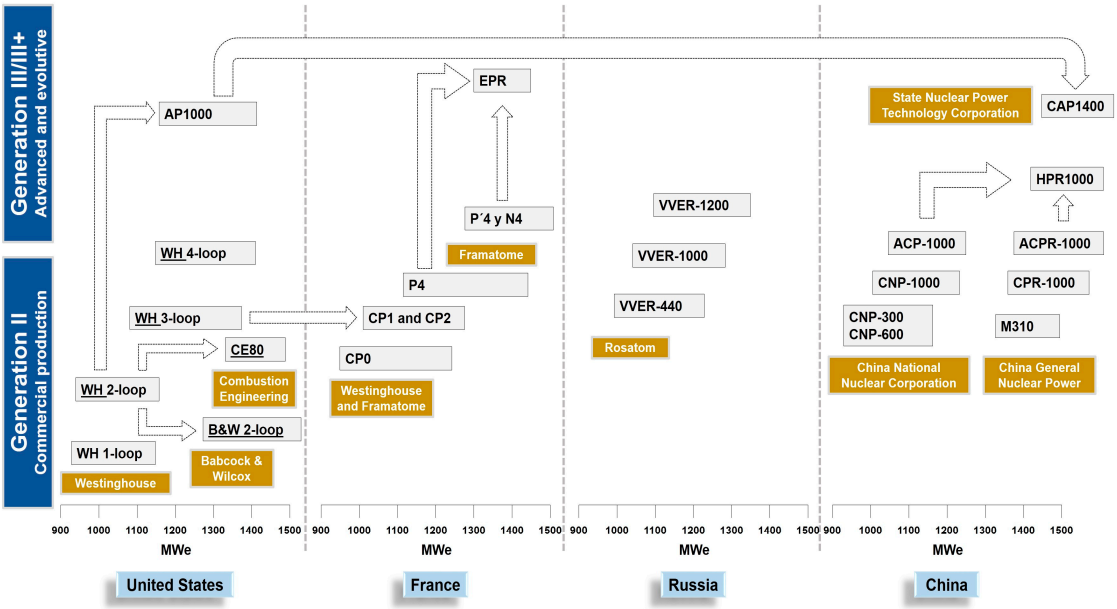


Figure 11. Evolution of PWR designs in the United States, France, Russia, and China.

As has already been shown, the 2-loop Westinghouse PWR was the reference for the development of two fundamental PWR designs in Generation II: Babcock & Wilcox and Combustion Engineering CE80. Subsequently, CE80 was the reference model for the development of the Korean design OPR1000. However, these designs have as a fundamental difference the incorporation of a second cold branch in each of the loops. Therefore, this technical modification involved the second RCP. In the case of Babcock & Wilcox, another fundamental modification of the original design was the addition of a once-through steam generator. All these modifications again meant an increase in power generation capacity.

Initially, Framatome opted for collaboration with Westinghouse to develop an entire nuclear industry around PWR design. Within Generation II, the French CP0 series features the 3-loop Westinghouse design, while the following CP1 and CP2 begin to include aspects typical of the French nuclear industry. These changes were further noted in the later P4 series—still in collaboration with Westinghouse—and on French P´4 and N4—100%. These new PWR series increase primary circuits and power generation capacity to 4, but also expanded design safety, for example, increasing the redundancies of safety systems or improving the strength of the containment building.

In the case of the Russian VVER versions, it is more difficult to find similarities with other, Western PWR versions, since these designs have characteristics and differentiating aspects: (i) the hexagonal geometry of their fuel elements; (ii) the horizontal steam generators; and (iii) the increase in the number of loops. Lastly, the Chinese nuclear industry has been able to join this technological race, despite being 20 years behind. Initially, it opted for collaboration with the great western powers to develop the first PWR Generation II designs, but nowadays it has been able to generate enough autonomy to develop its designs. To know more about this topic, the main parameters of the final Generation II designs are described in Table 2.

Table 2. Main parameters of United States, France, Russia, and China final PWR Generation II designs.

Design	nº loop/ Steam Generators	Fuel Assemblies	Trains Emergency Core Cooling System	Thermal Capacity (MWt)	Electrical Output (MWe)
WH 4-loop	4	193	2	3400	1200
B&W 2-loop	2 (OTSG)	205	2	2600–2800	900
CE80	2	241	2	2600–2800	900
N4	4	205	2	4250	1450
VVER-1000	4 (horizontal)	163	4	3000	1000
ACP-1000	3	177	3	3060	1100
ACPR-1000	3	177	3	3500	1150

In Generation III, the differences between the current PWR designs are maintained, although it is possible to establish certain relationships between the reference designs: AP1000, EPR, VVER-1200, HPR1000, and CAP1400 [46,47]. Thus, according to the data collected from [15,46,48], the main parameters of these designs are described in Table 3. Furthermore, in these PWR Generation III the core damage frequency considering the contribution from internal and external events is less than 10^{-5} events per reactor-year.

Westinghouse continues its commitment to the inherent safety—or passive safety—and the modular construction and simplicity of the AP1000 design. This AP1000 design is the reference for the Chinese PWR Generation III design, the CAP1400. The CAP1400 maintains the AP1000 design philosophy, increasing electrical generating capacity. Both designs, AP1000 and CAP1400 have a core-catcher; if there was a core meltdown, the core would be "caught" and prevented from entering the environment. In the case of the Russian VVER-1200, this design has technical aspects similar to the French EPR, e.g., 4 independent trains of emergency safeguards and double containment building. They are designs that bet on the increase in the number of trains in the safety systems, as well as their redundancies, moving away from the passive safety of the previous AP1000 and CAP1000 designs.

Table 3. Main parameters for United States, France, Russia, and China PWR Generation III designs.

Design	nº loop/ Steam Generators	Passive Safety	Core-catcher	Modular Construction	Efficiency	Electrical Output (MWe)	Core Damage Frequency (Events Reactor-Year)
AP1000	2	Yes	No	Yes	32%	1150	$<5 \times 10^{-7}$
EPR	4	Minimal	Yes	No	36%	1650	$<10^{-5}$
VVER-1200	4 (horizontal)	Minimal	Yes	No	33.9%	1200	$<7.37 \times 10^{-6}$
HPR1000	3	Minimal	No	No	36.6%	1150	$<10^{-6}$
CAP1400	2	Yes	No	Yes	34.5%	1500	$<10^{-5}$

Finally, the Chinese versions: ACPR-1000, ACP-1000, and HPR1000 maintain the number of loops of the first Generation II designs and the first French series. In these cases, the modular construction of the plant is not possible, and unlike the CAP1400, the ACPR-1000, and ACP-1000 designs do not have passive safety systems.

3.2. Operating PWR Nuclear Power Plants

Taking as a reference the 300 PWR nuclear reactors operating around the world in early 2020 [6], it is observed that the countries where this design has been mostly implemented are the United States, France, China, and Russia (Table 4). Besides, these countries are also the ones with the most operational nuclear reactors in their territory. According to Table 4, the PWR design is fully implemented in the cases of France and China. However, in the United States and Russia, there is greater diversification of technologies, since the PWR design accounts for approximately 60% of the operating nuclear reactors. This may be because in France and China they adapted nuclear technology later than in the United States or Russia, and consequently learned from the experience of predecessor countries in choosing their reactor design. Other countries outside the scope of this global PWR review, but with a high number of operating reactors in their territory, are Korea and Japan. On one hand, among the 24 operating reactors in Korea, 21 have PWR technology. On the other hand, Japan has a total of 33 operating reactors, and among them, 16 are PWR.

Table 4. PWR designs in United States, France, Russia, and China.

Country	Number of PWR	Number of Reactors	% PWR
USA	64	96	67%
FRANCE	58	58	100%
CHINA	45	48	94%
RUSSIA	23	38	61%

Table 5 analyzes various data from the PWR designs developed in the United States, France, Russia, and China, specifically: (i) Generation, (ii) Electrical output range; (iii) number of reactors; and (iv) the parameter OF.

To carry out the analysis comparing companies or countries, a new parameter is necessary. Thus, the *global operating factor* (GOF) is defined as the sum of the OF for a specific set of designs grouped: (i) by country, (ii) by design, or (iii) by company. Among the PWR designs are those developed by the American company Westinghouse: WH 2-loop, WH 3-loop, and WH 4-loop, as well as the different series of the French PWR design: CP1, CP2, N4 and P4 and the Russian variant VVER-1000, already in Generation II+. Thus, Table 5 shows that the VVER-1000 design is the most implemented around the world, with 37 operating units (OF = 12.33%). However, the different variants of the American Westinghouse are the most implanted around the world, with GOF upper than 25%.

In a second group would be the variants developed by the American companies Combustion Engineering and Babcock & Wilcox. These two variants of the PWR design achieve a GOF of 5%, assuming a GOF for American suppliers of the PWR design of over 30%. Lastly, regarding the Western versions, the first units of the Westinghouse AP1000 designs and Framatome EPR, within Generation III, as well as the Russian floating nuclear power plants KLT-40 [49,50], have started operations. As for the Chinese variants of the PWR design, the CNP-300 and CNP-600 designs stand out. Within this group of oriental variants, the 23 units of the Chinese CPR-1000 design already appear, within that of Generation II+ [51].

Taking into account the expansion mechanism, that is, how PWR design has been implemented in other countries, the result is different from that obtained by analyzing the number of operational reactors. In the case of the United States, Westinghouse maintains its operational designs in 9 different countries (Figure 12): (i) PWR 2-loop: 6 reactors operating in Switzerland, Belgium, Slovenia, and Brazil; (ii) PWR 3-loop: 18 reactors operating in Korea, Spain, Belgium, Taiwan, and Sweden; (iii)

PWR 4-loop: 1 reactor operating in the United Kingdom. In the United States, the Westinghouse company maintains 48 PWR reactors (GOF=34%), distributed as follows: (i) PWR 2-loops: 5 reactors, (ii) PWR 3-loop: 13 reactors; and (iii) PWR 4-loop: 30 reactors.

Table 5. PWR designs operating in the United States, France, Russia, and China.

Design/Overvall	Generation	Electrical Output Range (MWe)	Number of Reactors (*n*)	Operating Factor (%)
UNITED STATES				
Westinghouse				
WH 1-loop	Generation II	150	0	0.00
WH 2-loop	Generation II	500–900	11	3.67
WH 3-loop	Generation II	800–950	31	10.33
WH 4-loop	Generation II	800–1180	31	10.33
AP1000	Generation III	1150	4	1.33
Babcock & Wilcox				
B&W	Generation II	825–1000	5	1.67
Combustion Engineering				
CE80	Generation II	850–1200	11	3.67
FRANCE				
Framatome				
CP0	Generation II	900	7	2.33
CP1	Generation II	900	22	7.33
CP2	Generation II	900	10	3.33
P4	Generation II	1300	20	6.67
N4	Generation II	1500	4	1.33
EPR	Generation III	1650	2	0.67
RUSSIA				
Rosatom				
VVER-440	Generation II	440	22	7.33
VVER-1000	Generation II+	1000	37	12.33
VVER-1200	Generation III+	1200	3	1.00
CHINA				
China General Nuclear Power				
M-310	Generation II	900	4	1.33
CPR-1000	Generation II+	1080	23	7.67
ACPR-1000	Generation III	1150	1	0.33
China National Nuclear Corporation				
CNP-300	Generation II	300	5	1.67
CNP-600	Generation II	600	6	2.00

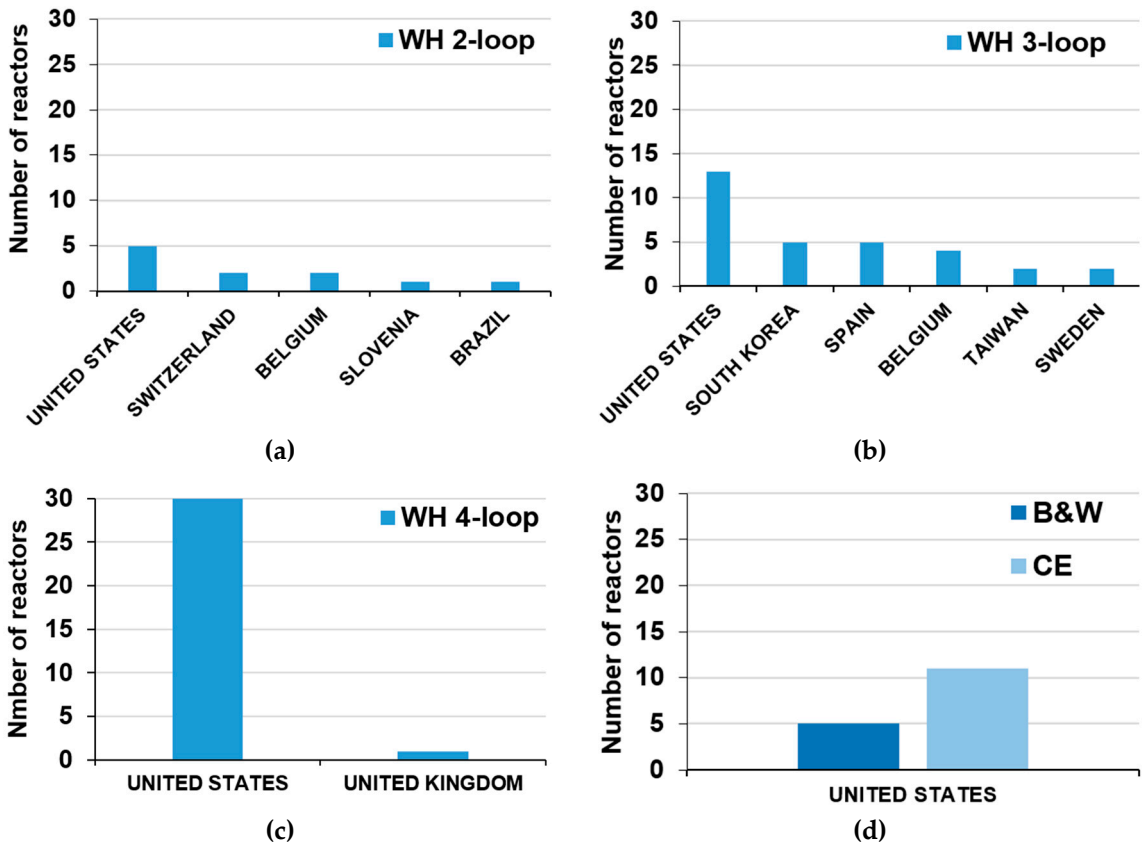


Figure 12. US PWRs operating worldwide: (**a**) WH 2-loop; **(b)** WH 3-loop; **(c)** WH 4-loop; **(d)** B&W and CE.

On the other hand, there would be four AP-1000 Generation III reactors operating in China. In the case of Babcock & Wilcox and Combustion Engineering, 100% of its operating reactors are located in the United States, with 5 and 11 PWR Generation II reactors operating, respectively.

In the case of France, the different variants of the PWR design developed throughout the past 20th century have had an expansion mechanism based on satisfying the demand of their national industry. Of the 58 nuclear reactors operating in France, 100% have a PWR design; however, several CP1 3-loop units supplied by Framatome continue to operate worldwide (Figure 13): two units in South Africa and another two units in Korea. The other variants: CP2 3-loop, P4 4-loop, and N4 4-loop have not been implemented outside of French territory. On the other hand, within Generation III there has been an export of the technology, and there are already two operating EPR reactors in China.

In the case of the Russian VVER designs, the expansion mechanism is different from that developed by the North American and French designs, since of the 22 VVER-440 reactors operating around the world, 77% have been implanted outside the country (Figure 14a): Slovakia, the Czech Republic, Hungary, Ukraine, Finland, Armenia. In the case of the Generation II + VEER-1000 design, the previous trend is maintained—specifically, 65% of these reactors remain operational outside their country of origin: Ukraine, China, India, the Czech Republic, Bulgaria and Iran (Figure 14b). In the case of Generation III and Generation III + of safe nuclear reactor designs, the Russian commitment to the VVER-1200 design is already operational at three national sites.

Finally, in the case of China, after years of expansion of nuclear technology in its territory, and especially of PWR design, there has been no international expansion. Its expansion mechanism bears certain similarities with the French case in the 1970s and 1980s. China encompasses 34 national Generation II and Generation II + PWR nuclear reactors (Figure 15): (i) 4 units M-310; (ii) 23 CPR-1000 units; (iii) 6 CNP-600 units, and (iv) 1 CNP-300 unit. These units should be added to the four CNP-300 reactors operating in Pakistan and the ACPR-1000 Generation III reactor operating in China.

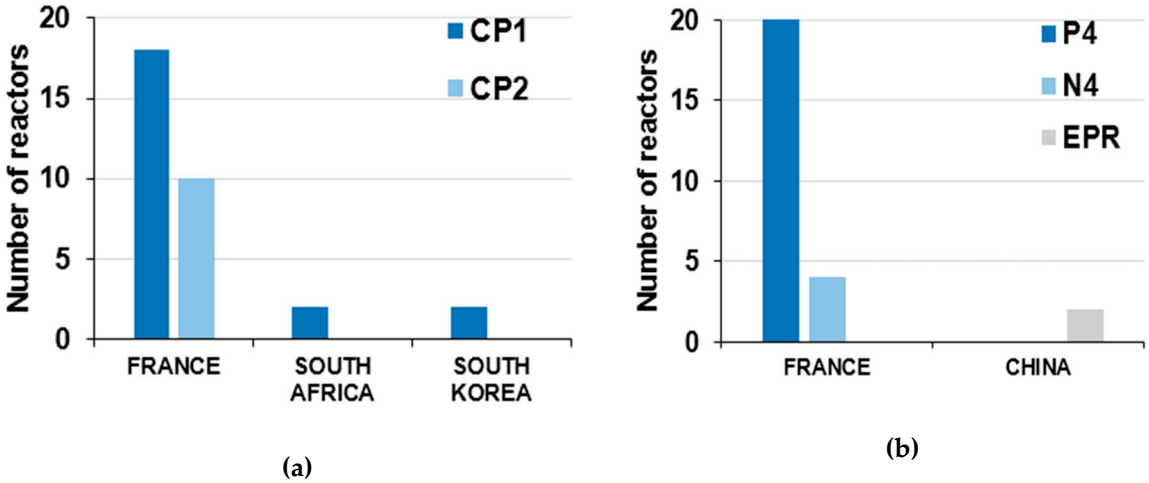


Figure 13. French PWRs operating worldwide: (**a**) CP1 and CP2; **(b)** P4, N4 and EPR.

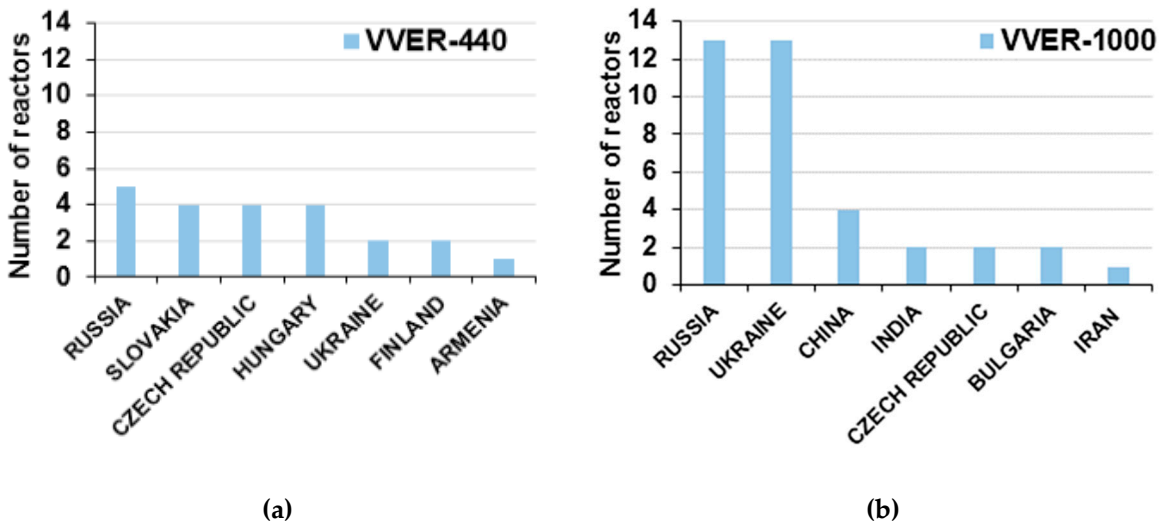


Figure 14. Russian PWRs operating worldwide: (**a**) VVER-440; **(b)** VVER-1000.

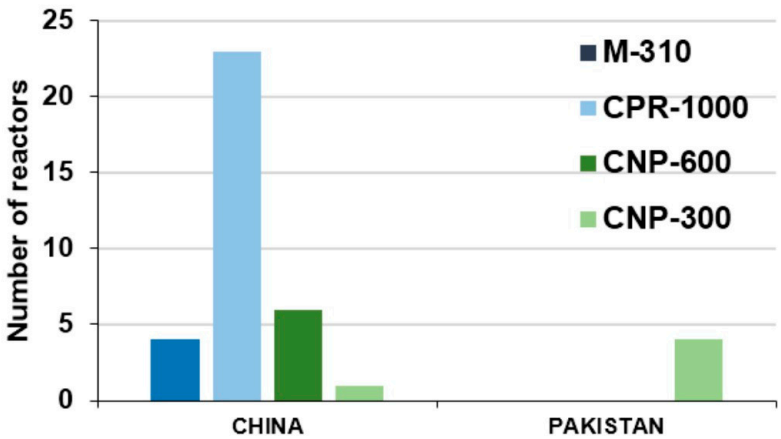


Figure 15. Chinese PWR (CGN and CNNC) operating in the world.

3.3. Under Construction PWR Nuclear Power Plants

After studying the current situation of the PWR design, it is convenient to analyze the international expansion plans of these four nuclear powers, studying different aspects of the future forecast of the PWR design: (i) Generation, (ii) Electrical output range; (iii) number of reactors; (iv) the parameter UCF (Table 6). To carry out the analysis comparing companies or countries, a new parameter is necessary. Thus, the *global under construction factor* (GUCF) is defined as the sum of the UCF for a specific set of designs grouped: (i) by country, (ii) by design or (iii) by company. Based on the GUCF parameter, of the 52 nuclear reactors currently under construction, 42 will have a PWR design, representing a GUCF of 80%. In the case of the countries where the PWR design has been implemented the most (United States, France, Russia and China), the GUCF is 63%. The only PWR construction projects with designs different from those of the four powers are: (i) APR-1400: four units in the United Arab Emirates and four units in Korea (country of origin of the design); and (ii) Konvoi: one unit in Brazil. Thus, the APR-1400 is, along with EPR, HPR1000 and VVER-1200, the most ambitious Generation III PWR design under construction.

Table 6. United States, France, Russia, and China PWR designs under construction.

Design/Overvall	Generation	Electrical Output (MWe)	Number of Reactors (*n*)	Under Construction Factor (%)
UNITED STATES				
Westinghouse				
AP1000	Generation III	1150	2	3.84
FRANCE				
Framatome				
EPR	Generation III	1650	4	7.69
CHINA				
China General Nuclear Power				
ACPR-1000	Generation III	1150	2	3.84
China National Nuclear Corporation				
CNP-1000	Generation III	1000	2	3.84
ACP-1000	Generation III	1000	2	3.84
HPR1000	Generation III	1150	5	9.61
RUSSIA				
Rosatom				
VVER-1000	Generation II+	1000	7	13.46
VVER-1200	Generation III+	1200	9	17.30

As previously seen in the evolution graph of the different PWR designs (Figure 11), the design evolves within Generation II+ and Generation III+ as a safer and more efficient design, developed in different variants: (i) AP1000; (ii) EPR; (iii) HPR1000 [52]; and (iv) VVER-1000 and VVER-1200. Based on the results obtained analyzing the situation of the PWR reactors under construction (Table 6), it

can be affirmed that the Russian variants are those that have UCF 13.46% in the case of the VVER-1000, and 17.30% in the case of the VVER-1200. This makes GUCF higher than 30%. Therefore, they maintain their international expansion mechanism, without neglecting the need to cover the internal demand for nuclear reactors.

In the case of the North American and French Generation III PWR designs, AP1000 and EPR, they have lost the relevant role that their predecessor designs (Figure 11) had during the 20th century, obtaining GUCF of 3.84% and 7.69%, respectively.

Finally, it is the different Chinese PWR design variants that undergo a fundamental change in their expansion mechanism. These variants go from having a GOF of over 10% in operational PWR reactors around the world today to having a GUCF of over 21% in operating nuclear reactors in the near future. The GUCF of the Russian and Chinese PWR designs under construction is close to 50%. Therefore, unlike what happened with PWR reactors in operation, 50% of PWR reactors under construction are of Asian origin.

Analyzing the expansion mechanism of the different PWR designs under construction around the world, a protectionist expansion mechanism is observed in Europe and the United States. Of the 42 PWRs under construction around the world, 12 are being built in Europe and the United States, accounting for 28% of the total. In the case of Europe, countries such as France, Finland, and the United Kingdom are committed to EPR design as nuclear generation technology, while, in the United States, the technology under construction is its own Generation III AP1000 design. On the other hand, in the case of the former countries of the Soviet Union: Belarus, Slovakia, and Ukraine, a technological dependence is shown towards the different Russian VVER versions (Figure 16).

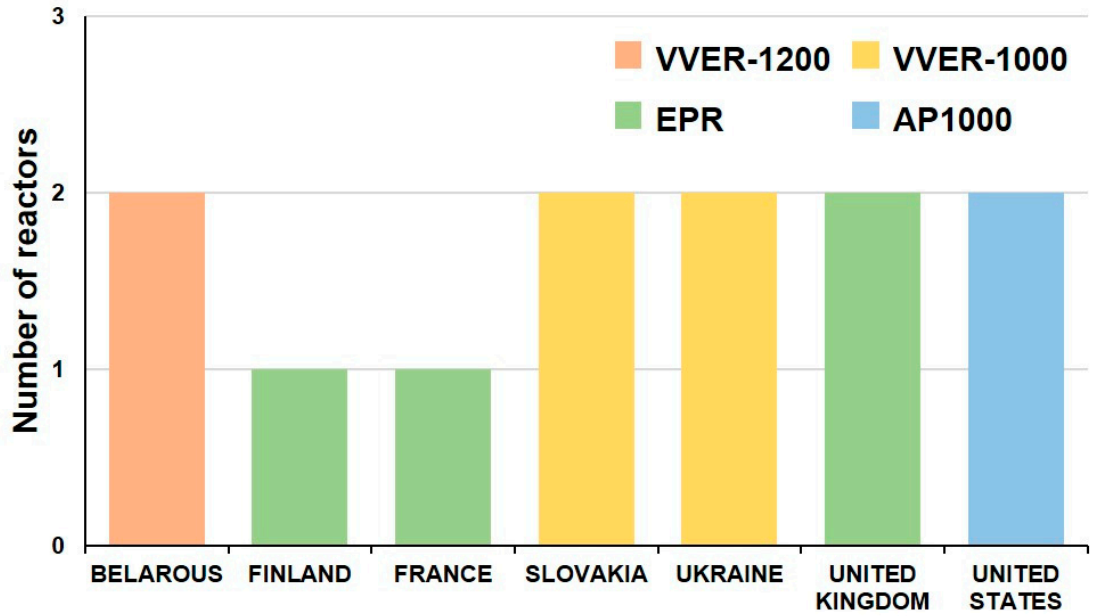


Figure 16. Number of PWR nuclear reactors under construction in Europe and United States.

In the case of construction PWRs in Asia (Figure 17), what is reflected in the GUCF study is maintained, where the Asian variants are the most widely implemented around the world, highlighting the implementation of the VVER-1000 and VVER-1200 designs. Regarding the expansion mechanism, 63% of the rectors under construction have Russian and Chinese PWR version. Russia, in addition to satisfying the national demand for nuclear reactors, exports its designs to countries such as Bangladesh, India, Iran, and Turkey. Like Russian designs, Chinese designs supply domestic demand with nine PWRs under construction (five HPR1000 reactors, two ACPR-1000 units, and two ACP-1000 units).

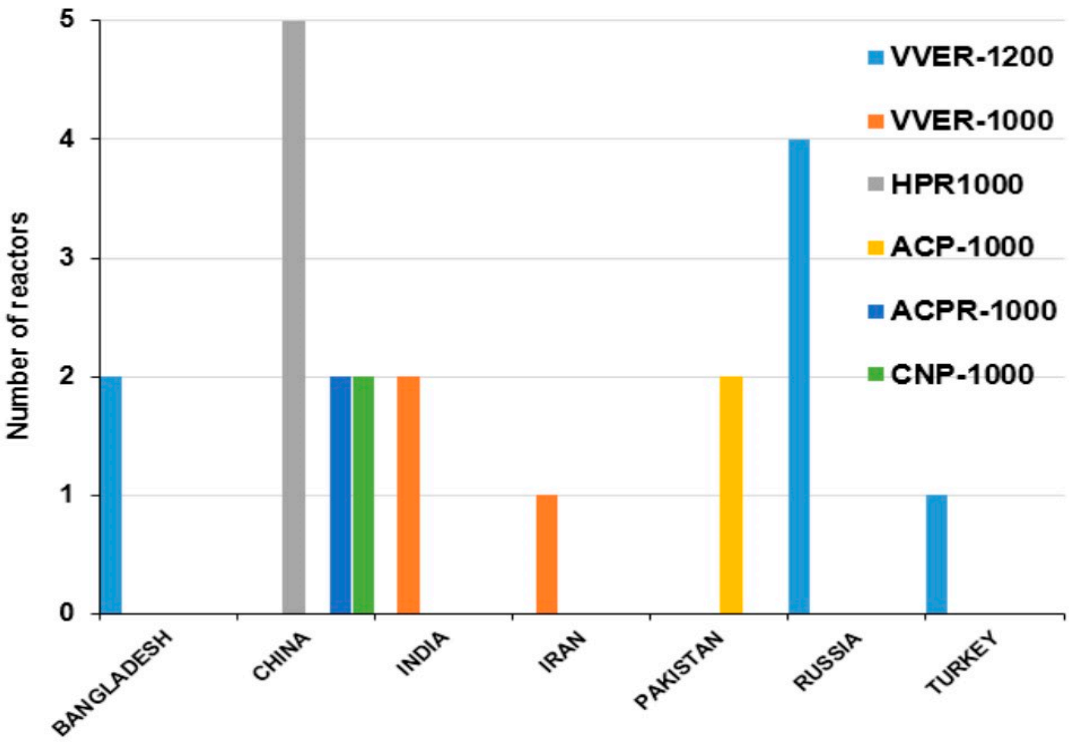


Figure 17. Number of PWR nuclear reactors under construction in Asia.

Bearing in mind that other Asian PWR designs such as the Korean APR-1400 or the Japanese APWR [48] should be added to this result, the trend reflected by the GUCF regarding the expansion of Asian versions of the PWR design is confirmed. The reason for not including these designs in the scope of this article is that they have a lower level of number of operational reactors than the great world powers. The great world powers that have promoted PWR design throughout the past 20th century, France and the United States, have given up their advantageous position in favor of the new Asian powers, China and Russia. This result confirms that the nuclear industry in Asia is in an advanced evolutionary stage, which is in agreement with previous studies [53].

Similarly to Figure 4, a new data group was collected from SCOPUS (Figure 18) with the number of articles that include the name of Generation III designs (AP1000, EPR, VVER-1200, HPR1000 and CAP1400) in the title, abstract or keyword. According to Figure 18, the total number of 971 papers in the SCOPUS database includes the denomination of the most important Generation III designs. Among this criterion, 646 of the total published papers (around 66%) include "AP1000", so this design gets the highest number of papers among the Generation III designs. Secondly, 225 of the published research papers (around 23%) are linked with "EPR". The rest of the Generation III designs consulted ("VVER-1200", "HPR1000" and "CAP1400") only add up to 100 of the published research papers (around 11%).

As shown in Figure 18, scientific interest in the AP1000 design increased markedly from 2011. This sudden interest in this design may have resulted from the accident at the Fukushima-Daiichi Japanese nuclear power plant, which occurred on 11 March 2011. Although all four units of this nuclear power plant had BWR reactors, the evolution and consequences of the accident may have influenced the increased scientific interest in the design and safety criteria of the AP1000 design. Similarly, in 2017 the scientific interest in PWR design suffered a decrease of approximately 20% (all the PWR designs exhibit a decrease in scientific production, as shown in Figure 18). This decrease could be a consequence of the financial crisis that the Westinghouse Company suffered in 2017.

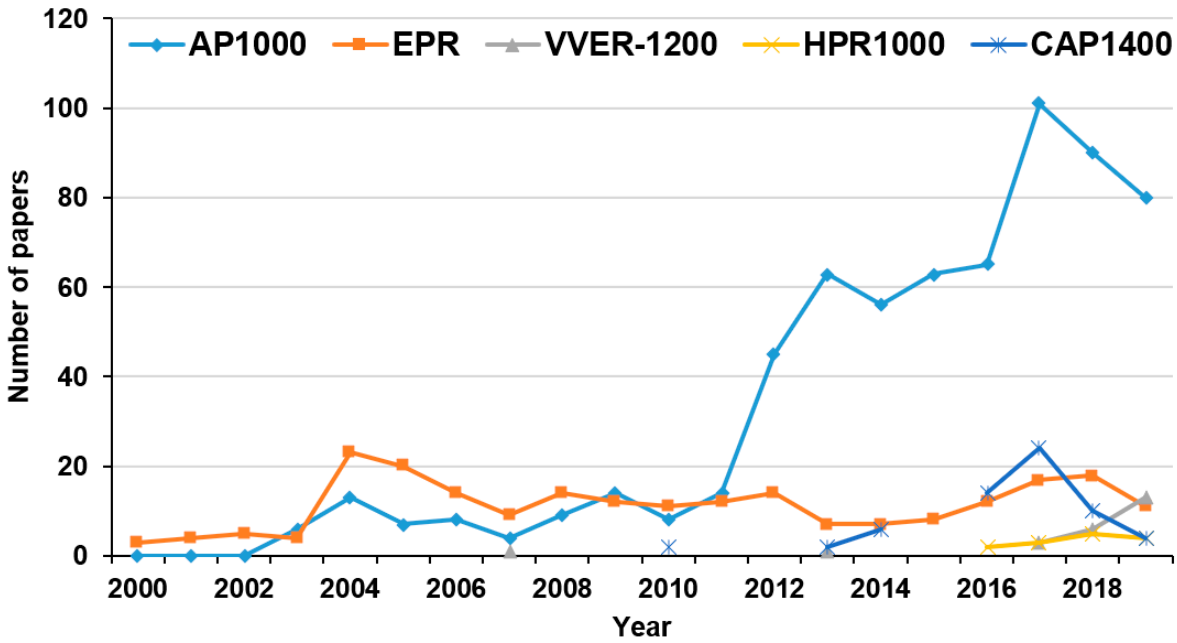


Figure 18. Number of research papers indexed in SCOPUS related with the Generation III designs (data collected on April 2020).

3.4. Simulation of the Life Extension of Operational PWR

The extension of the operating life of nuclear power plants is a solution to energy production—without carbon emissions—for a long time [54]. Due to the aging in the most important components—which implies a continuing time-dependent degradation of materials due to service conditions, including normal operation and transient conditions—the nuclear power plants are initially designed for a technical life of 40 years [55]. It is common experience that over long periods, there is a gradual damage in the properties of materials as a consequence of neutron radiation and the corrosion these components endure [56–58]. Thus, the reactor vessel materials of the PWR design are the components most affected by neutron radiation, thereby reducing its mechanical properties [59]. On the other hand, the SG is the component of PWR design suffering the most corrosion damage [28,60], being both stress corrosion cracking (SCC) and particle deposition the main degradation mechanisms. The degradation of steam generators tubes has involved costly modifications, inspections and even the replacement of SG in the most severe cases [61,62].

Although the technical life of 40 years is recommended in previous studies [56], other papers [63] consider that the 40-year term was based on economic and antitrust considerations rather than on technical limitations. In recent years, countries such as France or the United States have studied the lifetime extension significantly beyond 40 years: specifically, a lifetime extension up to 60 years [64]. The PWR Generation III designs were designed for a life of 60 years [65,66], and the United States is even planning a lifetime extension up to 80 years [67–71].

According to the IAEA, the half-life of operating nuclear reactors around the world is currently over 30 years [72] and in cases such as WH 2-loop, B&W, and CP0 (Generation II), the designs have already reached the initial life of 40 years [6]. In this situation, in order to provide information for making a decision about the life extension beyond the initial 40 years, this study presents a simulation of the electrical power generation capacity of operational PWR in a scenario of lifetime extension to 60 years, consequently placing a maximum time horizon in the year 2050. To do this, the progressive implementation of the PWRs that is currently under construction is also taken into account, estimating for this a construction and commissioning time of 68 months (approximately 6 years), according to previous studies [72].

The results shown in Figure 19, in a scenario of lengthening the useful life of PWR nuclear power plants to 60 years, are clear: (i) the B&W and French series CP0 will shut down in 2040 and (ii) Westinghouse 2-loop and 3-loop, Combustion Engineering CE80 and French series CP1 and CP2 will

shut down in 2050. In this way, the PWR design would go from having 259 operating in 2020 in the world to 81 nuclear reactors operative in 2050, which means 69% less operating reactors in 30 years (Figure 19). In addition, 178 PWR nuclear power plants would permanent shutdown in 30 years.

Even considering new PWR nuclear power plants that could be projected in the coming years, this technology will suffer a drastic reduction in the coming years. The possible increase in the useful life to 60 years of the current operational PWRs would mean that this design maintains its global impact for other designs during the period 2020–2030, in which only 24 reactors would go into shutdown and the power generation capacity would increase as new Generation III designs—with higher generating capacity—now under construction start operating. According to Figure 19, starting in 2040, the PWR nuclear power plants will notably reduce their electrical capacity. This situation is likely to influence decisions about future investment and operating costs [71], as well as prospects for the decommissioning and management of high-level radioactive waste at current nuclear power plants [72–77]. Lastly, if no advances are made in R&D of new designs or in the use of the actual nuclear power plants in cogeneration systems for the production of hydrogen [78,79], in 2050 this technology will decrease its generation capacity to 50%, keeping 127 GWe and the number of operating rectors at 70%. It is worth noting that these data are underestimated and, hence, this situation will likely occur earlier.

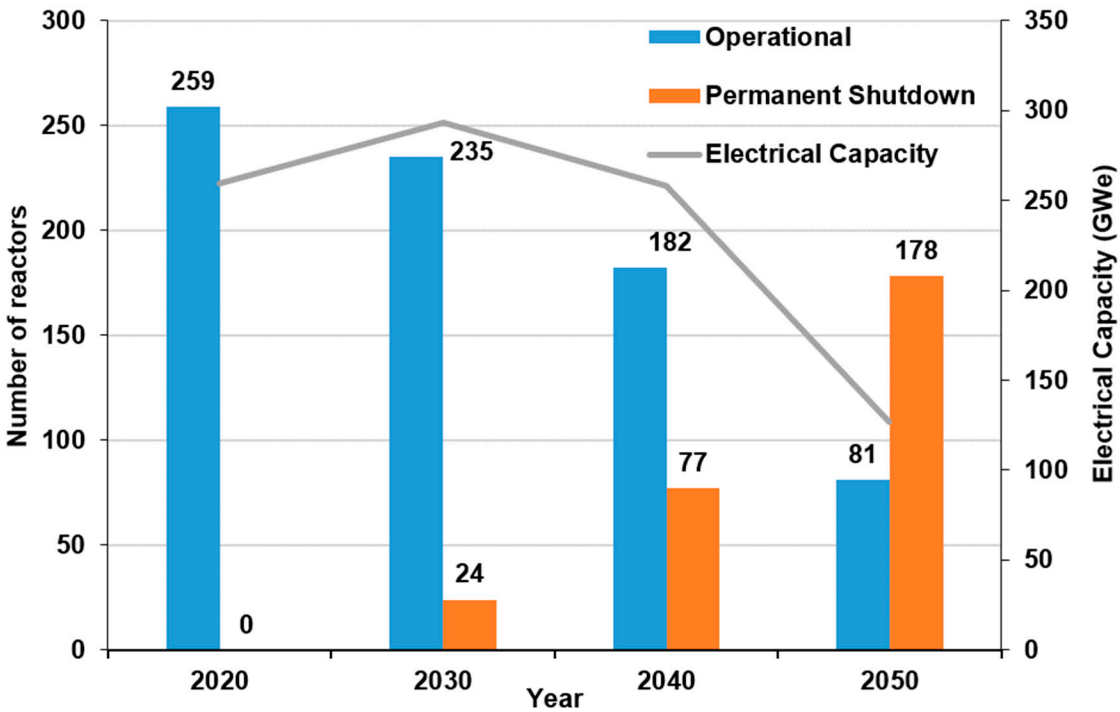


Figure 19. Scenario of life extension of PWR nuclear power plants to 60 years.

R&D advances of new PWR are reflected in the development of Small Modular Reactor (SMR) technology, still only under development, but not implemented in any nuclear power plant. The SMR technology has two strategic goals: firstly, reduce onsite construction cost and time; secondly, mass manufacturing will make up in economies of volume production what is lost in economies of scale [80]. To achieve this, its design is based on three principles: (i) reactors with a capacity below 300 MWe; (ii) small size and standardized main components; (iii) passive safety design [81]. Among the different projects related to the manufacture of SMR, those carried out by NuScale Power and the Korea Atomic Energy Research Institute (KAERI) stand out. The SMR designs of these companies are, respectively: (i) the NuScale and (ii) the SMART. The first one, NuScale is an integral pressurized water reactor (iPWR) with seven layers of barriers between fuel and environment. Its rated capacity was raised to 45 MWe of electrical power. On the other hand, the electrical output of SMART could be around 110 MWe and could be use as seawater desalination [80–83].

4. Conclusions

Nuclear energy is positioning itself as an alternative to climate change and the problem it poses to humanity. Of the 447 nuclear reactors operating in the world in January 2020, the pressurized water reactor (PWR) has been the most widely deployed nuclear reactor design throughout history, with an operating factor (OF) of 67%.

After years of expansion throughout the 20th century for PWR (Generation II) variants, 300 PWR reactors are currently operating worldwide. Based on the global operating factor (GOF), the North American (GOF = 31%) and French (GOF = 21%) versions stand out among PWRs. Taking them as a reference, during the 21st century, different oriental PWR designs have been developed. The PWR designs implanted within Generation II evolved to increase their generation capacity. To achieve this, the evolution of the different designs is based on the increase in the size of the main components, i.e., reactor vessel, steam generator and fuel assemblies, as well as the number of reactor coolant system.

Going forward, advances in new PWR designs developed within Generation III and Generation III+ will make these safer and more efficient. These designs, like the Generation IIs, have evolved, increasing both their effectiveness, availability, and generation capacity from a security point of view. This fundamental aspect, the improvement of security, is achieved through an increase in the number of redundancies and including passive security systems.

The under construction factor (UCF) allows us to identify the capacity of implementation of the different PWR designs. Thus, the UCF and expansion mechanism values shown in this article reflect that the Chinese and Russian versions of the PWR design are preferred in under construction nuclear reactors. The Russian and Chinese designs of nuclear reactors PWR, with a global under construction factor (GUCF) greater than 30% and 20%, respectively, have been characterized both by supplying the demand for nuclear reactors in their home countries, and by having implemented in other Asian countries with growing economies.

In a 60-year life extension scenario, the main Generation II designs will go into permanent shutdown starting in the year 2030. Starting in the year 2030, the start of operation of the Generation III PWR now under construction will mean maintaining capacity of current generation. In 2050, generation capacity will decrease to 127 GWe, a 50% decrease from current generation capacity. Until then, 178 PWRs will be on permanent shutdown and only 81 will be in operation.

The high interest shown throughout the 21st century in SMR technology shows that soon it will be a reality. Taking into account the results shown in this study, which set a 60-year life extension scenario for PWR nuclear power plants both operative and under construction, the development and commissioning of SMR nuclear power plants would mean maintaining the global impact of the PWR designs in the nuclear industry.

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