

Wealer, Ben; Bauer, Simon; Landry, Nicolas; Seiß, Hannah; von Hirschhausen, Christian R.

**Research Report**

## Nuclear power reactors worldwide: Technology developments, diffusion patterns, and country-by-country analysis of implementation (1951-2017)

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# Data Documentation

Deutsches Institut für Wirtschaftsforschung

2018

## Nuclear Power Reactors Worldwide – Technology Developments, Diffusion Patterns, and Country-by-Country Analysis of Implementation (1951-2017)

Ben Wealer, Simon Bauer, Nicolas Landry, Hannah Seiß and Christian von Hirschhausen

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## Data Documentation 93

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### **Nuclear Power Reactors Worldwide – Technology Developments, Diffusion Patterns, and Country-by-Country Analysis of Implementation (1951–2017)**

Berlin, April 2018

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## Executive Summary

Nuclear energy is among the most important innovations of the twentieth century, and it continues to play an important role in twenty-first century discussions. In particular, there is a debate about the potential contribution of nuclear power to policies of climate change mitigation and energy security in both, industrialized and emerging countries. In this context, many existing nuclear countries, and others considering entering the sector, are facing questions of how to structure organizational models for nuclear power, and what lessons to be learned from the past seven decades of civilian use of nuclear power.

The objective of this Data Documentation is to trace the development of nuclear power since its beginnings, by providing both a technological and a country-specific perspective, to allow a better understanding of issues on nuclear power going forward. Our hypothesis, based on the early literature on nuclear power post World War 2, e.g., the Acheson-Lilienthal Report (1946), Lovins and Lovins (1980) but also a more recent survey of the literature (Hirschhausen 2017), is that nuclear power is the “child of scientific research and the military” (François Lévêque 2014, 212), the development of which follows an “economies-of-scope”-logic: nuclear power is developed for military and civilian purposes (e.g., electricity, medical services), and thus obeys no simple economic logic that could be expressed, e.g., in simple business investment calculus (Davis 2012). Rather than searching for an economic rationale where there is none, it is therefore instructive to analyze specific diffusion patterns of nuclear power, based on stylized organizational models, and going back to the origins in the middle of the last century.

A certain understanding of nuclear reactor physical principles is useful to understand the link between different applications of nuclear power, and the inherent link between military and other uses. Nuclear fission was developed at industrial scale to produce the atomic bomb, in the Manhattan Project. All subsequent applications derive from the first large-scale military application, be it more sophisticated nuclear weaponry, electricity, medical uses, etc. Post-WW2 reactor technologies were developed with the scope-objectives, be it the graphite-moderated reactors in the U.K., France, and the Soviet Union, or the heavy-water reactors in Canada and Sweden; the light-water route, pursued by the U.S. thanks to a separate pluto-

nium facility, was also rooted in a military application, i.e. submarine propulsion. There is no purely “civil” (sometimes used “peaceful”) use of nuclear power.

A historical analysis of the emergence of nuclear power since 1945 suggests to distinguish four periods:

i/ Between 1945 and into the mid-1950s, four major countries had established independent, national pathways of nuclear technologies for military purposes and electricity generation: the U.S., the Soviet Union, the U.K., and France;

ii/ subsequent to the mid-1950s, and the failure of US attempts to control proliferation of nuclear material, mainly the “Atoms for Peace” program, lead to fierce competition between the two nuclear superpowers, the U.S. and the Soviet Union, for controlling technological diffusion. The US approach was much more “liberal”, by selling technology and licenses to adoption countries, like Japan, Korea, and Germany, whereas the Soviet Union kept the technology and only gave away turnkey reactors to satellite states. Some countries were able to develop their own nuclear pathway, such as India, Pakistan, and Israel;

iii/ starting in the mid-/late 1980s, China developed its nuclear sector, to become the third nuclear superpower, and the move from the first to the “second nuclear age” (Bracken, 2012), with ten or even more countries controlling the nuclear bomb, including North Korea and attempts in Iran;

iv/ Post-Fukushima (2011) is characterized by the implosion of nuclear power in Western capitalist market economies, and the closure of nuclear power plants, often before reaching technical lifetimes, due to economic reasons; many of the newbuild projects were abandoned, too. This leaves the development of nuclear power to “other”, non-market systems, where countries hang on to nuclear development, for political, military-strategic, or other reasons, mainly the nuclear superpowers China and Russia. “Nuclear diplomacy”, i.e. attempts to attract partner countries by providing them reactor technology more or less for free, is gaining ground in particular in China, Russia, and—to a lesser extent—the U.S.

The analysis of the diffusion of nuclear power on a country-by-country basis reveals different patterns: we distinguish “economies-of-scope” trajectories, recipient countries of nuclear technologies with and without subsequent indigenous technology catch-up, and “other”

countries; we also identify current trends in potential newcomer countries, such as Turkey, Bangladesh, and Sudan.

Initial hopes placed on “Generation IV” and/or small modular reactors (SMRs) have not been fulfilled. Although some Gen IV research reactors are developed, no technology has any perspective of becoming economically competitive, neither with current nuclear technologies, nor with conventional fossil or renewable generation in combination with storage. Most SMRs are based on designs that are several decades old, and none of them is close to attaining any sort of commercial availability.

The Data Documentation fills a research gap in the literature, in that it provides bottom-up, evidence-based proof that nuclear power follows no economic rationale, but some other logic linked to “science and warfare”. None of the 674 reactors analysed in the text and documented in the appendix, has been developed based on what is generally considered “economic” grounds, i.e. the decision of private investors in the context of a market-based, competitive economic system. Given current technical and economic trends in the global energy industry, there is no reason to believe that this rule will be broken in the near- or longer-term future.



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**Abbreviations and Acronyms**

ABR	Advanced boiling water reactor
APWR	Advanced pressurized water reactor
AEG	Allgemeine Elektrizitäts-Gesellschaft
AGR	Advanced gas-cooled reactor, evolution of MAGNOX
ATR	Advanced thermal reactor
B&W	Babcock and Wilcox
BBC	Brown, Boveri & Cie.
BWR	Boiling water reactor
CE	Combustion Engineering
CEA	Commissariat à l'énergie atomique et aux énergies alternatives, French Alternative Energies and Atomic Energy Commission
CGNPC	China Guangdong Nuclear
CNNC	China National Nuclear Corporation
EDF	Electricité de France
EPR	European Pressurized Reactor
FBR	Fast breeder reactor
FRG	Federal Republic of Germany
GCR	Gas cooled reactor
GE	General Electric
GFR	Gas-cooled fast reactor
HEU	Highly enriched uranium
HWR	Heavy water reactor
HTGR	High-temperature gas-cooled reactor
HTR	High temperature reactor
IAEA	International Atomic Energy Agency
JAEA	Japan Atomic Energy Agency
JAEC	Japan Atomic Energy Commission
JPDR	Japan Power Demonstration Reactor
KAERI	Korea Atomic Energy Research Institute
KEPCO	Korea Electric Power Corporation
KWU	Kraftwerke Union AG
LEU	Low enriched uranium
LFR	Lead-cooled fast reactor
LMR	Liquid metal-cooled Reactor
LWR	Light water reactor
LWGR	Light water cooled and graphite-moderated reactor
MAGNOX	First models of GCR developed by the U.K.
MHI	Mitsubishi Heavy Industry
MSR	Molten salt reactor
MW	Megawatt
MW <sub>e</sub>	Megawatt electric

MW <sub>th</sub>	Megawatt thermal
NPP	Nuclear power plant
NPT	Treaty on the Non-Proliferation of Nuclear Weapons
NRC	United States Nuclear Regulatory Commission
NSSS	Nuclear Steam supply system
PHWR	Pressurized heavy water reactor
PNC	Power Reactor and Nuclear Fuel Development Corporation
PRIS	Power Reactor Information System
Pu	Plutonium
PWR	Pressurized water reactor
RBMK	Graphite moderated family of Soviet reactors (Russian: Reaktor Bolschoi Moschtschnosti Kanalny)
RWE	Rheinisch-Westfälisches Elektrizitätswerk Aktiengesellschaft
SFR	Sodium-cooled fast reactor
SMR	Small modular reactor
SNERDI	Shanghai Nuclear Engineering Research and Design Institute
SNF	Spent nuclear fuel
SNTPC	State Nuclear Power Technology Company
TMI	Three Mile Island
U	Uranium
UAE	United Arab Emirates
U.K.	United Kingdom
UN	United Nations
UNGGs	Uranium Naturel Graphite Gaz (French GCRs)
U.S.	United States (of America)
USSR	Union of Soviet Socialist Republics, Soviet Union
VVER	Soviet/Russian model of PWR (Russian: Vodo-Vodjanoj Energetičeskij Reaktor)
WNISR	World Nuclear Industry Status Report
WW2	World War 2



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## 1 Introduction

Nuclear energy is among the most important innovations of the twentieth century, and it continues to play an important role in twenty-first century discussions. In particular, there is a debate about the potential contribution of nuclear power to policies of climate change mitigation and energy security in both, industrialized and emerging countries. In this context, many existing nuclear countries, and others considering entering the sector, are facing questions of how to structure organizational models for nuclear power, and what lessons to be learned from the past seven decades of civilian use of nuclear power.

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The analysis of historical trends enables us to understand how nuclear power spread across the planet, and why the technologies adapted differ between countries, mainly between the United States and the rest of the world. The country-specific analysis opens perspectives on trajectories that have been observed over the last decades. The Data Documentation also allows the reader to familiarize her- and himself with available statistical material, such as the PRIS database from the International Agency for Atomic Energy (IAEA), the material put together by the World Nuclear Industry Status Report (WNISR), the Bulletin of the Atomic Scientists, EURATOM, and yet others.

The Data Documentation is structured in the following way: The next section contains a brief, non-technical introduction to the principles of nuclear reactor technologies, spanning a broad range of reactor deployment since 1945. Section 3 describes the long-term nuclear power developments, by broad historical periods, whereas Section 4 traces the developments in the main nuclear countries on a country-specific level; Section 5 concludes. The annex contains more detailed statistical material, as well as a complete list of all nuclear reactors (except research reactors) ever built, by country.

## **2 Nuclear Reactor Physics Principles**

To understand choices and the subsequent diffusion of nuclear reactors, we provide in a first step a brief introduction into nuclear physics and the principles of nuclear reactor designs. Pioneers in the field of nuclear physics research were also involved in the building of the first nuclear reactors both for military and civil purpose in the middle of the twentieth century.

### **2.1 Nuclear physics**

A nuclear reactor is a system designed to convert the binding energy of some atoms into thermal energy and eventually, in a last step, into electrical energy. The binding energy contained in the nucleus of an atom is by several orders of magnitudes higher than any chemical reaction can release, meaning that a large quantity of energy can be converted with a relative small amount of material. This binding energy can be extracted using two different nuclear reactions:

- Nuclear fission: the splitting of the atom of heavy elements in smaller ones,
- Nuclear fusion: the fusion of small nucleuses (hydrogen, helium, et cetera)

The latter can be done with nuclear fusion reactors, which are currently still in an experimental stage, and will not be deployed anytime in the foreseeable future. Nuclear fission is, on the other hand, the process on which all subsequent nuclear reactors have been based on.

Milestones in the history of the development of nuclear power are among others the identification of uranium as the heaviest of all natural elements<sup>5</sup> by Rutherford in 1905, the discovery of radioactivity by Marie Curie-Sklodowska and Pierre Curie around the turn of the century and the relativity theory by Albert Einstein in 1905. In 1933, Leo Szilard published the first theory of a nuclear chain reaction and experiments indicating the described chain reaction of uranium were carried out and interpreted first by Otto Hahn and Fritz Strassmann (in Berlin) in collaboration with Lise Meitner (in Stockholm) five years later, in 1938. Otto Hahn discovered that a heavy nucleus can be split when bombarded by a beam of neutrons; i.e. when the nucleus of uranium<sub>235</sub> (U-235) atom is hit by a neutron, there is a non-null probability that it splits into two smaller nucleuses and releases two to three neutrons during this process. These released neutrons can then be used to split other nucleuses of U-235, creating what is known as a chain reaction. Enrico Fermi and his team succeeded the first sustained chain reaction (0.5 W) at the University of Chicago, in 1942. The first large-scale experiment of nuclear power succeeded on July 16<sup>th</sup>, 1945, with the “Trinity Test” in the South-West U.S., followed by the first (and until today only) use of nuclear bombs on the cities of Hiroshima and Nagasaki, on August 6<sup>th</sup> and 9<sup>th</sup>, 1945, respectively.

The nuclear fission process produces several new chemical products, radioactivity (alpha-, beta- and gamma-rays), plus a large amount of energy (heat). However, the probability of a fission of U-235 when hit by a neutron depends on the speed of the neutron; the probability decreases greatly when the emitted neutrons from the fission of U-235 are too fast. In order to maintain a chain reaction, the neutrons must be slowed down by a *moderator*—a chemical element that captures a certain amount of the neutrons. The moderator must be a light element; i.e. having a small nucleus to slow the neutrons effectively down and not capture them. Therefore, only a few moderators are compatible with nuclear fission of U-235, e.g., hydrogen (found in water H<sub>2</sub>O), deuterium (heavy water D<sub>2</sub>O), beryllium, or carbon (graphite). A reactor which uses slowed down neutrons is called a thermal reactor.

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<sup>5</sup> Elements containing more than 92 protons, called “transuranic”, must be assembled through transformation.

The released heat from the fission process must be extracted from the reactor core; this is the purpose of the *coolant*. A coolant should have properties compatible with the nuclear reaction process: large thermal capacity, non-corrosive, stable when exposed to radiation, and a low absorption rate of neutrons. It can be air, water, heavy water, CO<sub>2</sub>, or several liquid metals like sodium. An important parameter is the absorption rate of neutrons. To obtain a sustainable chain reaction, a significant proportion of neutrons emitted during one split should not be absorbed. This criterion has a profound impact on the choice of structural materials as well as on the fuel. Natural uranium is mainly composed of two isotopes of uranium: U-238—which represents 99.2% of the naturally occurring uranium—and U-235, representing only 0.7%. U-235 is *fissile*, meaning that it can easily be split by a neutron, whereas U-238 absorbs neutrons.

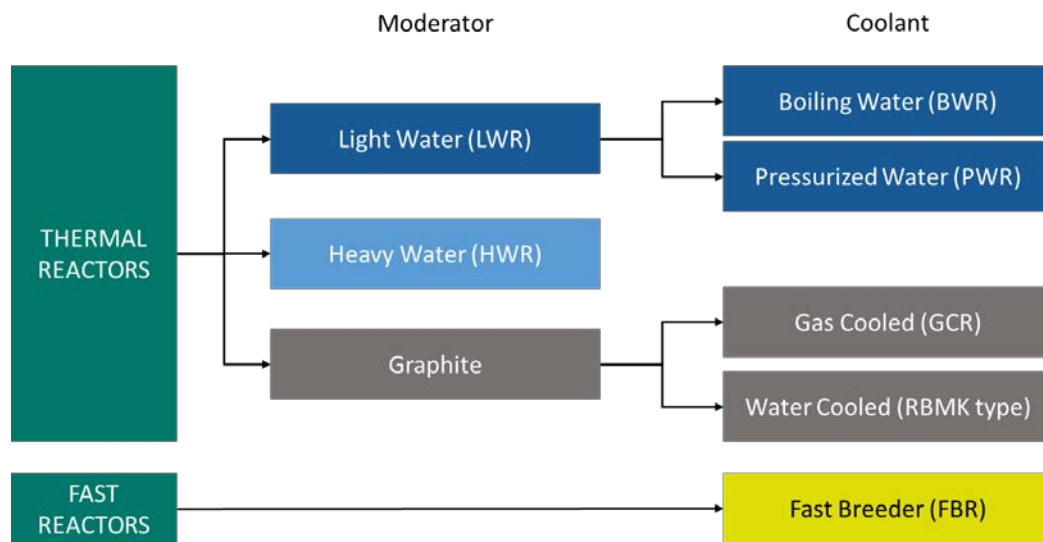
A sustainable chain reaction can be obtained with natural uranium only using deuterium (heavy water) as a moderator, since it has the smallest absorption rate. Otherwise, the share of U-235 has to be increased artificially to lower the impact of the absorption of U-238. This artificial increase is called enrichment. Low enriched uranium (LEU)—used in thermal reactors—corresponds to uranium enriched up to 20%, and highly enriched uranium (HEU) more than 20%. The two most important enrichment technologies in use today are the modern gaseous diffusion and gas centrifuge plants.

Another chemical element that can be split is plutonium<sub>239</sub> (Pu-239), which is not a natural element and has to be created artificially. When U-238 absorbs a neutron, it becomes an unstable form of uranium (U-239) and decays rapidly into neptunium<sub>239</sub>. The latter will decay in a few days into the fissile Pu-239. As U-238 can produce fissile material, it is called *fertile*. Contrary to U-235, Pu-239 can be used without a moderator, since it releases more neutrons on average than U-235 (U-235 can be used without moderator too, but as HEU only). This type of reactor—which can regenerate their own fuel—is called fast reactor. If some U-238 is exposed to neutrons emitted by the core of the reactor, it is partially converted into Pu-239, which can later be used as a fuel again. Fast reactors using this principle are called fast breeder reactors (FBR).

The spent nuclear fuel (SNF) contains a large part of unused fuel: U-238, U-235, Pu-239, Pu-240, and other products such as barium, strontium, and caesium. Some of these products can be treated chemically (“reprocessing”), and all of them need to be stored safely, for at least a million years, due to the continued radioactive emissions, posing threats to human health, animals, and nature.

## 2.2 Overview of reactor types

As mentioned above, nuclear reactor types can be distinguished according to their moderator, fuel, and coolant. Figure 1 provides an overview over the major reactor types.



**Figure 1: Major reactor types and used moderator and coolant**

Source: Own depiction.

### 2.2.1 Thermal reactors

The choice of reactors implies different capabilities to combine the generation of energy and weapons-grade material, as in the case of plutonium and electricity generation. Roughly, one can distinguish reactor types with which it is relatively easy to combine the two, which are graphite- and heavy water-moderated reactors, and those where the combination is more complicated (although still possible), for instance, light water reactors.



### 2.2.1.1 Graphite-moderated reactors

In this setting, the neutron flow is moderated by graphite, and the reactor is composed of a large number of steel pipes (“channels”) in which gas (e.g., helium) captures and transports the heat. Alternatively, light water can be used as a coolant (as in the Soviet-type RBMK reactors, see the case study on the former USSR). The reaction of the graphite with the uranium neutrons rapidly produces—among other things—a large quantity of plutonium<sub>239</sub>. Graphite moderated reactors can be run with natural uranium, and are constructed such that the scope economies of nuclear power, that is, the production of military weaponry (here: plutonium) and electricity, can be carried out easily. The reactor is not under high pressure (as is a pressurized light water reactor, for example), so that the fuel rods containing the uranium elements can be shifted and loaded or unloaded in continuous mode. This facilitates the outtake of plutonium in real time and at the desired densities. The graphite moderated and gas-cooled reactors have a better neutron economy, i.e. lower fuel cycle cost but higher capital costs, being much larger than the compact LWR (Weinberg 1959, 134).

### 2.2.1.2 Heavy water reactors

In the early 1940s, the first tests of larger-scale nuclear power were carried out in a “heavy water” reactor; heavy water is used as a moderator and usually also as a coolant.<sup>6</sup> Due to the moderation with a low neutron absorption rate, the HWR is able to use natural uranium oxide as a fuel. As with the graphite-moderated reactor, the heavy water reactor can also produce an element for use in nuclear bombs: Tritium, which is radioactive and can also be used to produce nuclear bomb material. Tritium is  $^3\text{H}$  produced when the deuterium ( $^2\text{H}$ ) captures an additional hydrogen neutron. A heavy water reactor requires significantly more space and material, and thus has higher capital costs.

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<sup>6</sup> Heavy water is also called “deuterium”,  $\text{D}_2\text{O}$ . This corresponds to  $\text{H}_2\text{O}$  plus an additional neutron,  $2\text{H}_2\text{O}$ ; heavy water contains the hydrogen isotope deuterium (D, or  $^2\text{H}$ ), with the mass-number of 2 (H: 1).

### 2.2.1.3 Light water reactors

Today, by far the most widely deployed reactor design is the light water reactor (LWR), using water both as moderator and as coolant. Two types of LWRs must be distinguished. First, the boiling water reactor (BWR) has only one circuit that transports the steam from the reactor core into the turbine, and then back, which spreads radioactivity to the thermodynamic process, and requires more protection; the BWR is less capital-intensive, but more complex to manage in operations. Second, in pressurized water reactors (PWR) two water circuits are employed, in the first one the water is heated by pumping it through the core, the heat is then passed through steam generators on to a secondary circuit, where steam is generated to be later on expanded in the turbine; reactor coolant pumps are employed to circulate the water back into the primary circuit. The water in the first circuit—the coolant system—must be kept under high pressure to keep it under its boiling point; this is the function of the pressurizer system. PWRs come in different “loop configurations” for different power outputs, e.g., the three standardized French PWRs: 3-Loop 900 MW<sub>e</sub>, 4-Loop 1,300/1,450 MW<sub>e</sub> reactor types. The number of loops stands for the number of steam generators and reactor coolant pumps.

Note that initially, light water reactors were not part of the technology set of the late 1940s/early 1950s, because they require enriched uranium (U<sub>235</sub>, at least 3-5%), which is complicated and very expensive to produce and was not readily available in the 1940/1950s. With Project Manhattan, the United States developed the first large-scale enrichment facility in Oak Ridge (Tennessee). Few other countries have been able to take that route up to today. The extraction of plutonium from light water reactors is more complicated: it is possible in batch mode only, and it requires premature extraction of Pu<sub>239</sub> from the process before it converts to Pu<sub>240</sub>, which prevents the plutonium from being used in bombs due to the danger of self-ignition. LWRs have a poorer neutron economy, i.e. higher fuel cycle cost but lower capital costs, due to being more compact (Weinberg 1959, 134).

### 2.2.2 Fast breeder reactors

Reactors that do not use a moderator are called fast breeder reactors (FBR). These reactors can either be based on the thorium-U-233 cycle or on the uranium-plutonium cycle (in the

first, thorium is the raw material, in the latter uranium). FBRs can regenerate their own fuel, e.g., if some (fertile) U-238, in the uranium-plutonium cycle, is exposed to neutron bombardment, it is partially converted into Pu-239, which can later be used as a fuel again. All large scale FBRs use liquid metal as coolant, in most cases sodium. Sodium has a high melting point (98°C), therefore the pipes containing the coolant must be heated electrically and be thermally insulated to prevent freezing. Another difficulty of sodium consists in the danger, which stems from the contact between sodium and water or air, which would result in a serious fire.<sup>7</sup>

FBRs have been considered by many countries as the ideal future nuclear technology, due to their better fuel economy (Weinberg 1959). The rationale for FBRs was based on the following key assumptions: uranium<sub>235</sub> is scarce; breeders would become quickly competitive with LWRs; the reactors could be “as safe and reliable” as LWRs; and the proliferation risks and the closed fuel cycle could be managed. However, these assumptions all proved to be wrong. Especially the proliferation risks pose serious threats, FBRs are de facto plutonium production facilities and require the reprocessing of plutonium—making it more accessible for military purposes.<sup>8</sup> Many research reactors started up, but nearly all projects were abandoned. The majority of large-scale FBRs are shut down too, e.g., Superphénix in France or Monju in Japan. Today, Russia operates two large-scale FBRs (BN-600, BN-800), while India is currently constructing a scaled-up version of its unsuccessful prototype FBR (See Cochran et al. (2010) for a comprehensive overview of the different national FBR programs, Cochran et al. (2010) and Lovins (1973) for a detailed assessment of the risks of FBRs).

### 2.2.3 Reactor generations

Overall, the development of nuclear power technologies can be clustered into four generation types, depending on the date of their construction and the employed design: Gen I, Gen II, Gen III, Gen III<sup>+</sup>, and Gen IV reactors, but there are no clear definitions of what determines

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<sup>7</sup> To prevent such an event, a heat exchanger is installed between the radioactive primary sodium and the secondary sodium (Murray and Holbert 2015, 465).

<sup>8</sup> Cochran et al. (2010, 53).

what generation a given reactor fits into (Schneider et al. 2015, 56). Gen I or early prototype reactors are all shut down today, e.g., the demonstration reactors Shippingport, Dresden, and Fermi I in the U.S.; the Magnox GCRs in the U.K., and the UNGG GCRs in France. Gen II reactors constitute the major part of today's installed nuclear capacity, e.g., the major part of the LWRs, Canadian CANDU reactors and the Soviet PWRs VVER and the RBMK reactors, all widely deployed since the mid-1960s. Gen II reactors are still being built today, e.g., in China, India, Russia, and Slovakia.

Gen III designs (considered as advanced LWRs) began to emerge from the mid-1980s onwards, learning from the Three Mile Island accident; while Gen III<sup>+</sup> were significantly developed after the Chernobyl disaster—the latter were seen as transitional technologies until Gen IV reactors would become available but also as the last chance for the LWR technology (Schneider et al. 2015, 56). The World Nuclear Association (WNA) claims, that Gen III reactors have among others a simpler, more standardized design, a longer operating life (60 years), a further reduced possibility of core melt accidents; Gen III<sup>+</sup> (considered as evolutionary designs) now also include added requirements to withstand aircraft impact /resulting after the 9/11 attack.<sup>9</sup> Another difference between Gen III and III<sup>+</sup> reactors, is that the latter are said to rely more on natural processes and passive systems. The only operational Gen III reactor technology are the Advanced Boiling Water Reactor (ABWR) in Japan built by Hitachi and Toshiba under US license. Since then no ABWR has finished construction and only two are currently being constructed—also in Japan. Gen III<sup>+</sup> reactors currently being built are AP-1000 PWRs—in China and the US, as well as the European Pressurized Water Reactor or Evolutionary Pressurized Water Reactor for the US market (EPR) in Finland, France, and China. In 2016, the first Gen III<sup>+</sup> reactor was connected to the grid in Russia, Novovoronezh-6 (Rosatom VVER1200; 1,114 MW), two years behind schedule.

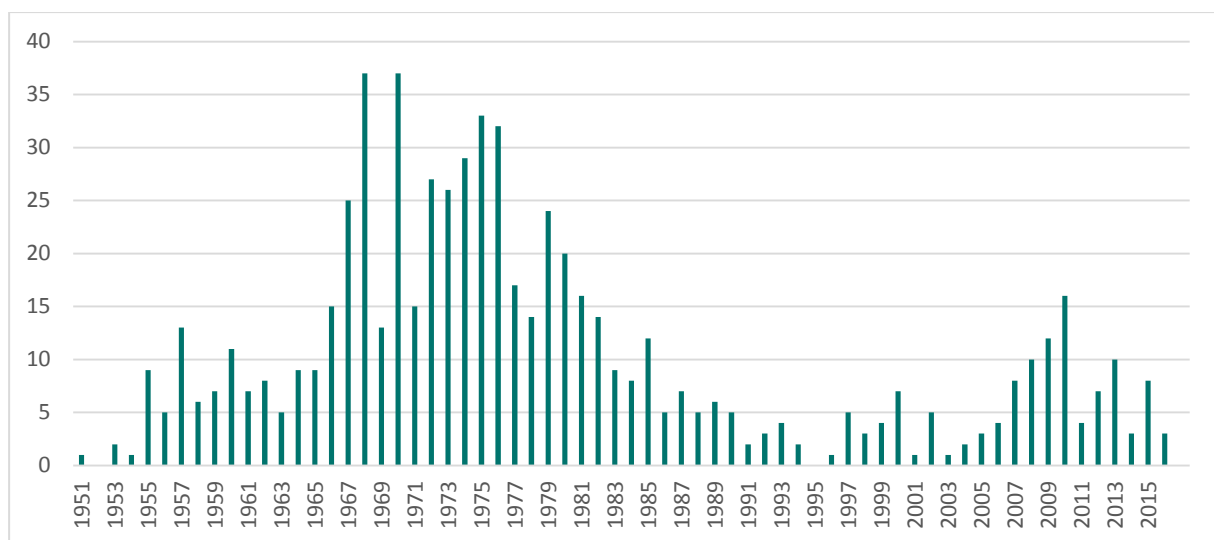
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<sup>9</sup> World Nuclear Association. 2017. "Advanced Nuclear Power Reactors." April 23, 2018. <http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/advanced-nuclear-power-reactors.aspx>

### 3 Diffusion Patterns of Nuclear Power Technologies (1945–2017)

#### 3.1 Overview and methodology

In this section we provide a full-scale account of the diffusion of nuclear power technologies, going back to the 1940s and including an outlook in the medium-term future. Nuclear power plants evolved all along the second part of the 20<sup>th</sup> century to finally arrive to the present-day situation. To understand the contemporary era, it is necessary to analyze the development of the nuclear industry from scratch and thus detect the major events and long-term trends that shaped the development of nuclear technology. In this section we thus cover all nuclear reactors at scale ever built (for research reactors see below), a total of 674 NPPs. Figure 2 depicts the construction starts of nuclear power plants since 1951 (for a depiction of the cumulative net generation capacity (operational) by reactor type for the period 1954–2016, see Figure 13).



**Figure 2: Construction starts of nuclear power plants, 1951-2016**

Source: Own depiction based on IAEA PRIS Database (2017).<sup>10</sup>

<sup>10</sup> IAEA PRIS Database. 2017. "Power Reactor Information System." April 23, 2018. <https://www.iaea.org/PRIS/home.aspx>

The analysis is mainly based on data from the IAEA PRIS Database, the annually updated World Nuclear Status Report (WNISR), and nuclear steam supply system (NSSS) supplier information from IAEA (2017): *The Nuclear Power Reactors in the World*, which is published annually. In addition, we use different sources on the country of origin of the respective reactor, the country which built it, and patterns that explain the long-term diffusion trends. Correlating this data with the country where the power plant was built, we identified three ways to develop a reactor:

- Indigenous origin: the country which builds the reactor is the designer and constructor;
- Cooperative transfer: the country where the reactor is constructed cooperates with a foreign country to acquire the technology; later on, it may be able to build power plants by itself (under license or as indigenized technology);
- Turnkey transfer: the country that orders the reactor is not (or only little) involved in the construction.<sup>11</sup>

We were then able to retrace the chronological dispersion of the civil nuclear technologies worldwide. This analysis allows us to highlight major trends in their development and deployment. It should also be noted that we cover only commercial nuclear power reactors at scale; consequently, collaboration on research reactors hardly appears.

### **3.2 The child of science and warfare (1945–1957)**

The first nuclear power plants—the so-called “Generation I” (Gen I) reactors—emerged just after the Second World War (WW2) and were based on technology invented for military applications during the war. Nearly all the early builders of NPPs for electricity production were among the winners of the Second World War: the United States of America, the United Kingdom, France, and the Soviet Union (USSR). In 1951, the Soviet Union started the worldwide first construction project of a “civil” reactor for electricity production (AM1). Two years

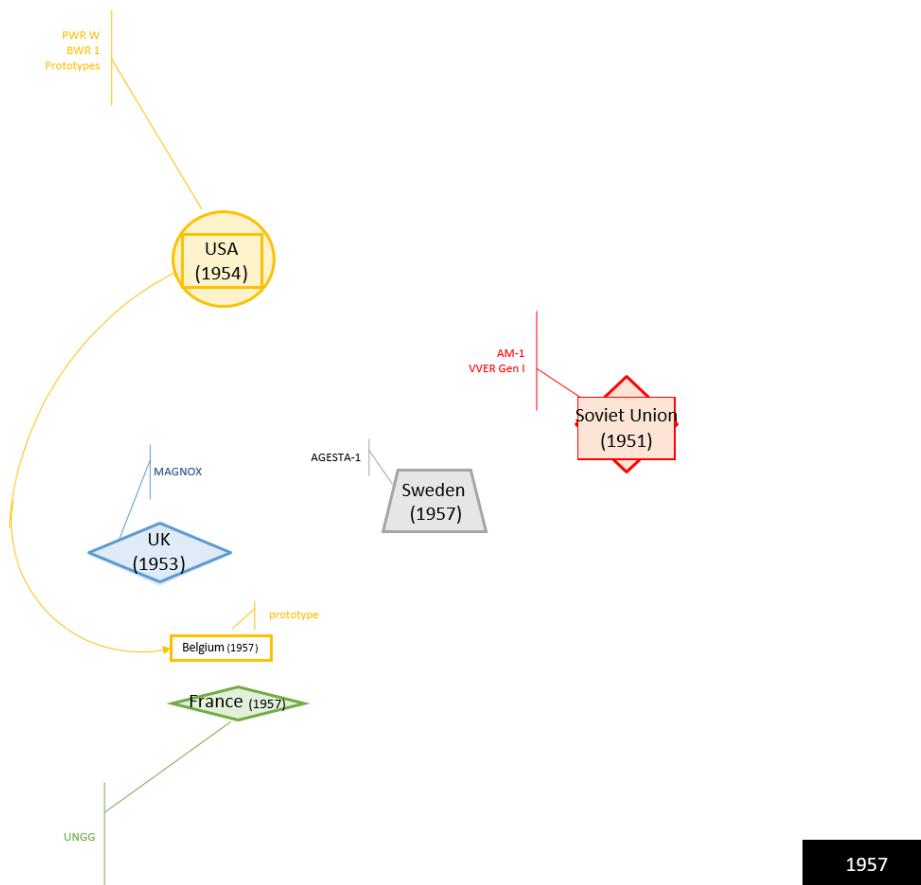
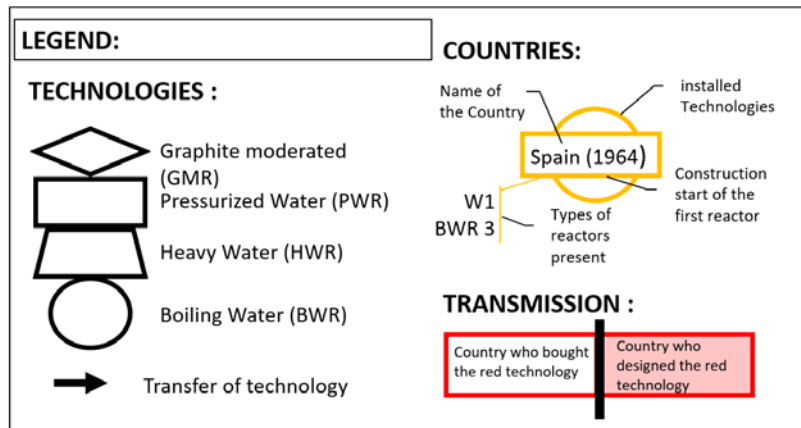
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<sup>11</sup> We call this a “turnkey plant”, it is not to confound with a “turnkey contract”, i.e. where the price of the contract is fixed.

later, the U.K. started on their part with the construction of Calder Hall and the U.S. joined them in 1954 with the construction start of the demonstration reactor Shippingport (Pennsylvania). France brought the first reactor online in 1957, in Marcoule. These four countries were naturally involved in the research and development of nuclear energy for military purposes at that time and were familiar with nuclear physics and engineering since they actively participated during the war in the development of the first nuclear bomb: the Manhattan project for the U.S. and the U.K., and the development of the bomb in 1949 for the USSR. These early prototype and demonstration reactors were based on military technology—mainly plutonium production and submarine propulsion—and reflected the advancement of each country at that time.

As part of this Data Documentation, we trace the origins of each large-scale nuclear reactor, and also the diffusion of the reactor type. Box 1 describes the approach of this exercise, which allows tracing not only the origin of each individual reactor, but also the interlinkages between technologies, the regional diffusion, and the political sponsorship of nuclear power. Figure 3 provides the first output of the exercise, for the period 1951–1957: One observes already quite divergent paths between the four nuclear countries, in particular between the light water reactors being used in the United States, and the graphite-moderated ones in the U.K., France, and the Soviet Union.

**Box 1: Description of technological analysis**



**Figure 3: Early national developments of nuclear power plants in 1957**

Source: Own depiction based on IAEA PRIS Database (2017), IAEA (2017), and cited literature in the case studies.

The major post-WW2 trends that shaped the development of reactor technologies still shape the nature of the nuclear industry to this day. During the war, the U.S. developed the worldwide first site for plutonium production, in Hanford (Washington State), where pluto-



Plutonium was mainly produced by gas-cooled and graphite-moderated reactors (GCR), which was one (of the two) simple ways to produce plutonium with natural uranium. In addition, the first large-scale enrichment facility in Oak Ridge (Tennessee) was developed, making the U.S. the sole owner of enriched uranium. This put them in a unique position and is one of the major reasons, why the development of the employed technology differs from the other countries. Although, the heavy support for the deployment of LWR technology was also caused by the already strong involvement of General Electric (GE) and Westinghouse in the military industry, e.g., the development of nuclear submarine propulsion technology.

The U.K., France and the USSR (LWGR - light water cooled and graphite moderator reactor) reactor employed mainly GCRs; both using natural uranium as fuel and built in such a way, that it is relatively easy to extract plutonium. These were “dual-use” reactors, i.e. these reactors allow the combination of weapon-grade material generation, e.g., plutonium (or tritium in the case of HWR) and electricity generation. It should be remarked that, due to this direct link between the first NPPs, WW2, and military purposes, the development of early civil reactors was a national affair and no cooperation between countries appeared—except for Belgium.<sup>12</sup> This segregation explains an initial heterogeneity.

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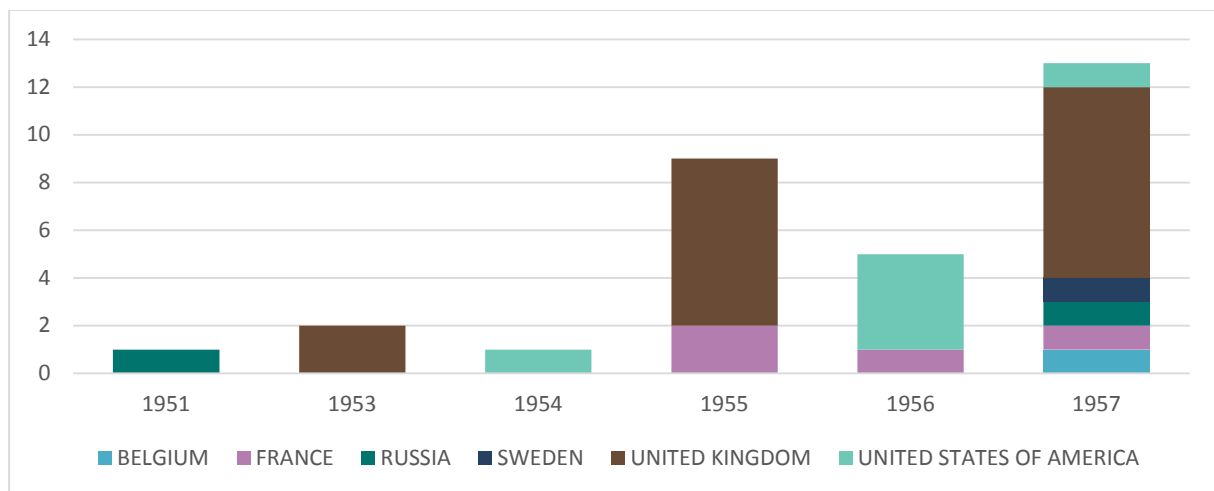
<sup>12</sup> Belgium is among the first nuclear countries, as they provided uranium ore to the U.S. from its Congo colony in the early days of the Manhattan Project, it was thus entitled to preferential treatment. With the import of a Westinghouse reactor and nuclear grade graphite from the U.K. Belgium started a prototype reactor fueled by enriched uranium (BR-2, operational from 1962-1966) (Gueron 1970, 63).

Country	Construction CAP MW <sub>e</sub> (NPP)	Technologies	Supplier
Belgium	10 (1)	PWR	Westinghouse
France	154 (4)	GCR	France
USSR	202 (2)	LWGR, PWR	USSR
Sweden	10 (1)	PHWR	ABB Sweden
United Kingdom	1,691(17)	GCR (16), FBR	United Kingdom
United States of America	766 (6)	BWR (2), PWR (3), FBR	U.S. / B&W (1), GE (2), Westing- house (2)
	<b>2,833 (31)</b>		

**Table 1: Nuclear capacity under construction, 1951–1957**

Source: Own depiction based on IAEA PRIS Database (2017) and Thomas (2010a).

By 1957, 31 prototype and demonstration reactors were under construction, with a total rating of 2.8 GW<sub>e</sub> electricity (Table 1). The largest amount was under way in the U.K. (1,7 GW<sub>e</sub> in 17 mainly Magnox reactors), followed by the U.S. (~ 800 MW in 6 reactors). Except for Belgium, all nuclear countries were “indigenous home suppliers”, with three main companies providing reactor technology in the United States (Westinghouse, GE, and B&W), and one, respectively, in the other countries. This early period of reactor deployment is characterized a national affair and in state-hands. At that time, only in the U.S. the first private companies enter the reactor market: GE, Westinghouse, and Babcock & Wilcock (B&W), but all three were naturally involved in the development of military technologies. The late 1950s also see the first reactor export from the U.S.: a Westinghouse PWR is supplied to Belgium. The reactors under construction by 1957 went online latest by 1965. Table 1 shows the capacity under construction for the period 1951–1957 and Figure 4 depicts the construction starts of nuclear power plants for this period.



**Figure 4: Construction starts worldwide, 1951–1957**

Source: Own depiction based on IAEA PRIS Database (2017).

This first period of nuclear deployment was mostly, with the exception of Belgium, characterized by nations interested in gaining access to nuclear weapons. Four of these succeeded: the USSR carried out the first nuclear weapons test in 1949, the U.K. in 1952, and France in 1960 and all four countries are still in possession of nuclear weapons technology in 2017. Sweden constitutes an interesting case, as the main purpose of the natural uranium fuelled PHWR Agesta 1 was to produce plutonium, in case the decision to produce nuclear weapons was made. Initial Swedish plans also foresaw a large reprocessing facility, but the military ambitions were dropped later on and Sweden switched to the LWR technology.

### 3.3 Proliferation accelerates (1958–1984)

#### 3.3.1 “Atoms for peace”

Contrary to the idea of a controlled diffusion of nuclear technology, expressed in the “Atoms for peace” program of the United States after 1953, nuclear technologies spread wildly after the initial period. This proliferation process was carried out mainly, but not fully controlled, by the first two nuclear superpowers, the United States and the Soviet Union, in an attempt to spread “their” respective technologies among follower countries, but also the aspiration of other countries to become nuclear powers, such as India and Pakistan.

The United States had attempted to control the diffusion of nuclear technology and to contain new nuclear countries to limited civilian use of nuclear power. The “Atoms for peace” program, presented by US President Dwight Eisenhower to the UN General Assembly in New York on December 8<sup>th</sup>, 1953, called for the declassification of nuclear technology.<sup>13</sup> The program proposed to support countries desiring to deploy nuclear technologies for peaceful means by providing assistance, equipment, and information for the development of a civil nuclear industry. Former general director of research and development for EURATOM and the first director of the CEA's nuclear research centre Jules Guéron (1970) highlights three main points for countries interested in nuclear power after the secrecy was lifted:

- First, now it would be possible to obtain moderately enriched uranium (LEU) and scarce materials as heavy water from the U.S.;
- second, the UN would be entrusted with supply and safeguard functions. To promote these safeguards and to promote the civil use of nuclear technology, the *International Atomic Energy Agency* (IAEA) was founded in 1957. The autonomous organization reports to both the United Nations General Assembly as well as the Security Council;
- third, a great amount of technical and scientific data would be generated, and be made publicly available. The first large-scale event to this behalf was the Geneva I conference, held in 1955, followed by similar conventions in the 1950s.<sup>14</sup>

As an instrument of the “Atoms for peace” program, the United States lowered the prices for low-enriched uranium in the end of the 1950s, i.e. reducing the fuel costs to run LWRs. The light water technology was also promoted as more reliable than the heavy water system. This enabled private companies to start developing light water technology, since they did not have the burden of developing methods for enriching or processing uranium themselves.<sup>15</sup>

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<sup>13</sup> Eisenhower (1953).

<sup>14</sup> The conference lasted two full weeks and even included an industrial exhibit, where a small swimming pool reactor was publicly displayed, see Gueron (1970, 64).

<sup>15</sup> Jonter (2010, 71).

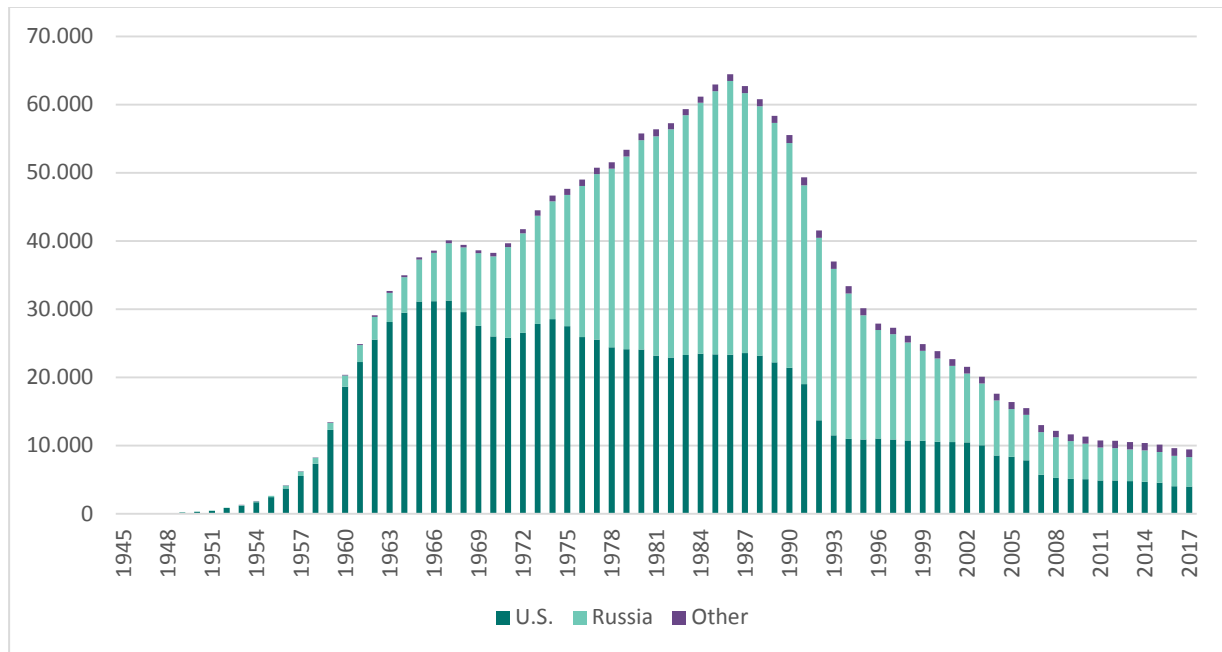
The U.S. trained (or funded the training) of many nuclear scientists in countries that eventually became of proliferation concern, e.g., Turkey (the first country to sign an agreement), Israel (the second country to sign an agreement), India. Today, there is a consensus that the “Atoms for peace” program accelerated the proliferation of nuclear weapons by helping some nations achieve more advanced nuclear arsenals than they would have otherwise been able to.<sup>16</sup> Figure 5 shows, that the proliferation of nuclear weapons accelerated after the mid-1950s and peaked in 1986, although the bulk of the nuclear weapons were part of the US and Soviet arsenal. This accelerated proliferation of nuclear weapons is exactly what the Acheson-Lilienthal report<sup>17</sup> meant when it spoke of states being tempted to consider making nuclear weapons if they had a national nuclear energy program due to the fact (as the report emphasized), that the development of atomic energy for peaceful purposes and the development of atomic energy for bombs are in much of their course interchangeable and interdependent.<sup>18</sup>

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<sup>16</sup> Weiss (2003, 41–44).

<sup>17</sup> The report included former scientific director of the Manhattan Project Robert Oppenheimer, former head of the Tennessee Valley Authority David Lilienthal; the committee also included among others Lieutenant General Leslie Groves, the director of the Manhattan project.

<sup>18</sup> Acheson-Lilienthal Report (1946, 10).



**Figure 5: Development of the nuclear arsenals in the world, 1945-2017**

Source: Own depiction based on the Bulletin of the Atomic Scientists (2018).<sup>19</sup>

### 3.3.2 The U.S.-EURATOM program (1958)

For Western Europe, the “Atoms for peace” program was particularly significant, as it allowed not only the U.K. and France (and in addition Belgium and Sweden), but also other European countries to access nuclear technology at very favourable economic conditions.

The U.S.-Euratom program, launched in 1958, was based on the following rationale (Guéron, 1970): power in Europe was in that time due to the increasing import of conventional fuel more expensive than in the U.S.; therefore, nuclear power could eventually become more competitive earlier in Europe, and Europe could benefit technologically and economically from being a testing ground for U.S. nuclear technology. The program initially foresaw 5,000 MW<sub>e</sub> of reactor capacity by 1965 and provided amongst others low interest loans from the U.S. Export-Import Bank, the lease of fuel by the U.S. Atomic Energy Commission on the same terms as in the U.S. home market, guarantees on fuel performance and fissile material

<sup>19</sup> Bulletin of the Atomic Scientists. 2018. “Nuclear Notebook. Nuclear Arsenals in the World.” April 24, 2018. <https://thebulletin.org/nuclear-notebook-multimedia>.

supply during the whole life of the reactors; and more importantly the U.S. agreed to Euratom control instead of its own. The U.S. would also benefit from this constellation, as a major vendor of technology and securing “dependence” from U.S. technology.<sup>20</sup> The U.K. and France tried to stay abreast the U.S.-technology domination, but with the GCR-technology never working as expected, they eventually also had to surrender (1946) to the U.S. technological supremacy and LWRs (France started in 1962 with Chooz-A under Westinghouse license, the U.K. (only) in 1988 with Sizewell B, a Westinghouse PWR).

The Atoms for Peace period corresponds to a new stream of development based on cooperation. Even if the main part of built NPPs were “indigenous constructions”, cooperative and turnkey designs were also developed. By enhancing the international exchange of knowledge, material, and designs had three main impacts on the evolution of nuclear reactors:

- Some countries adapted foreign technology to modify it later-on and create their own technology with the acquisition of licenses (See the case of Japan, Germany, or India).
- Countries, which already developed a nuclear program were influenced by the access to foreign resources (the case of France and Sweden).
- Some countries bought turnkey reactors but did not develop their own technology later (the cases of Italy, Spain, Belgium, Brazil, all countries of the former Soviet satellite states).

The U.S. provided enriched uranium and research facilities to several countries<sup>21</sup> and after Belgium the Federal Republic of Germany was next in line to receive NPPs from the U.S. In 1958, Italy bought a turnkey Magnox reactor from the U.K. Canada also entered its nuclear age in 1958 with the deployment of the CANDU reactor, fuelled by natural uranium and

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<sup>20</sup> Gueron (1970, 65–66).

<sup>21</sup> Fuhrmann (2012).

heavy water. Sweden abandoned its nuclear program and switched to the LWR technology, but with Swedish BWRs (the first non-U.S. LWR) and US PWRs.

### 3.3.3 Soviet technology spreads to satellites

The second global nuclear superpower the Soviet Union—fearful that the U.S. wanted to perceive economic and industrial advantages of its East European Allies—also pursued an early form of “nuclear diplomacy” in signing agreements to provide nuclear power to Czechoslovakia, Poland, and East Germany. Although in a different form: all nuclear technologies developed in the Soviet Union were exported to non-Russian Republics (Ukraine, Kazakhstan, Armenia) and the satellite countries, but on “turnkey” terms only, i.e. without a large-scale technology transfer. For example, after having developed the PWR “VVER” technology in 1957, the Soviet Union provided such a reactor to Slovakia one year later, followed by similar exports to the GDR and Bulgaria.<sup>22</sup> Also among the earliest recipients of Soviet nuclear expertise was China, but in form of research reactors, technical support, and scarce materials.

### 3.3.4 Oyster Creek: the first “commercial” order for a nuclear power plant

In 1964, for the first time a US operator placed a “commercial” order for the construction of a nuclear power plant, as it was the cheapest available option—cheaper than coal. In the following three years, a total of 20 orders for LWRs were placed under a turnkey contract in the U.S., but as the vendors realized that fixed-price contracts were a substantial risk, some offers were withdrawn. It is generally acknowledged, that both GE and Westinghouse subsidized the offers strategically and suffered substantial losses on the turnkey contracts. Nevertheless, this “commercial” order in combination with the availability of enriched uranium at lowered prices heavily influenced the roll-out of the LWR technology around the globe, e.g., to Spain, Switzerland, Italy, the Netherlands, Japan. In some cases, this even led to the abandonment of different national nuclear deployment plans, e.g., Germany and Sweden dropping the natural uranium technology. Figure 6 shows the number of construction starts of

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<sup>22</sup> As well as to „neutral“ Finland.



the Gen II reactors in the period 1958–1984 by country. After the first commercial orders in the U.S., the number of construction starts increased more than three-fold from 1965 to 1968, especially in the U.S. proliferation really accelerated.

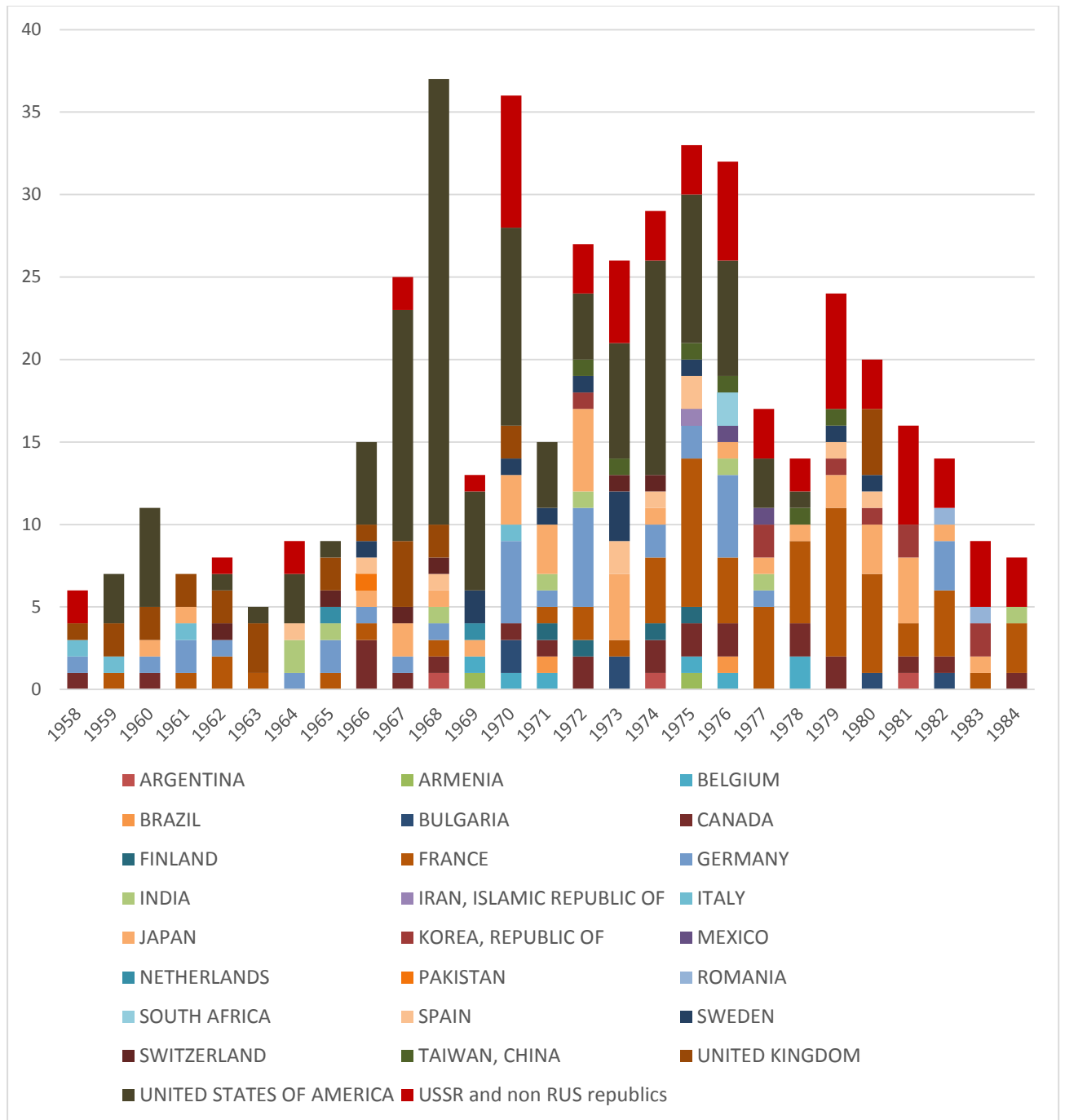


Figure 6: Construction starts worldwide, 1958–1984<sup>23</sup>

Source: Own depiction based on IAEA PRIS Database (2017).

<sup>23</sup> Non-Russian Republics (Ukraine, Kazakhstan, Armenia) and the satellite countries are grouped together in the cluster “USSR and non Rus Republics.”

### 3.3.5 Graphical representation

Figure 7 indicates how nuclear reactor technology had spread by 1973, and that the controlled proliferation of only civilian technology under the control of the United States had not worked out as sketched out by the “Atoms for peace” program. One clearly distinguishes two spheres of influence: i/ the US LWR route spread to its allies, mainly in Europe, Japan, Korea, and Taiwan (in yellow); and ii/ the Soviet Union’ LWR-route (called VVER), spread to their respective satellites (in red).

The graph also suggests peculiar developments that obeyed neither of the two superpowers’ logic. Thus, India and Pakistan were supplied by Canada and the U.S., with heavy water and light water technology, but they also went ahead with their own nuclear bomb technology, ignoring previous treaties on the transfers and of civilian technology only.<sup>24</sup> France supplied both Israel and South Africa with civilian and military technology, allowing a joint nuclear test off the South African coast in 1979. Some re-selling of technology also developed, e.g., Germany exporting a PHWR to Argentina, a PWR to Switzerland and the Netherlands.

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<sup>24</sup> Bracken (2012).

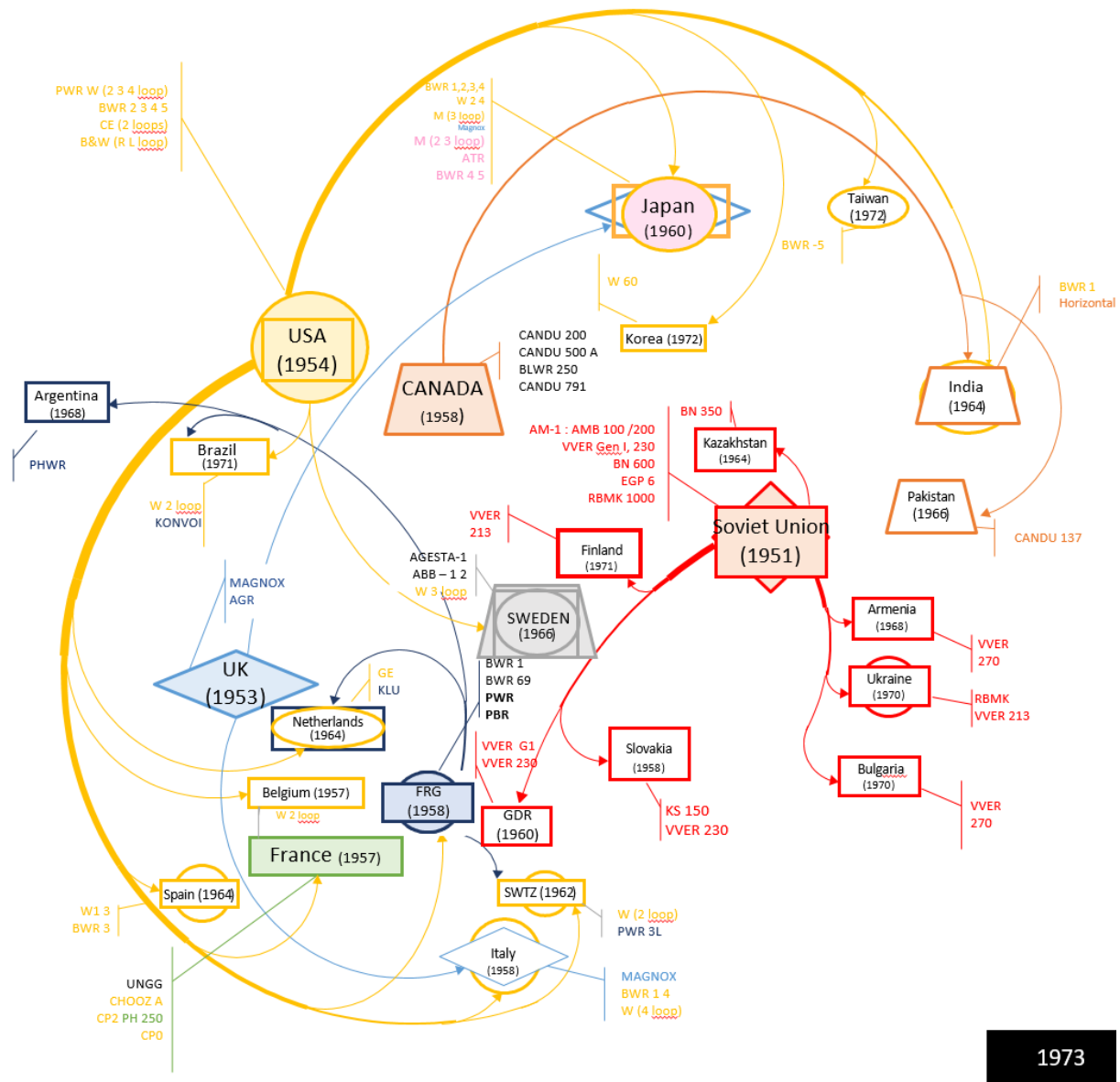


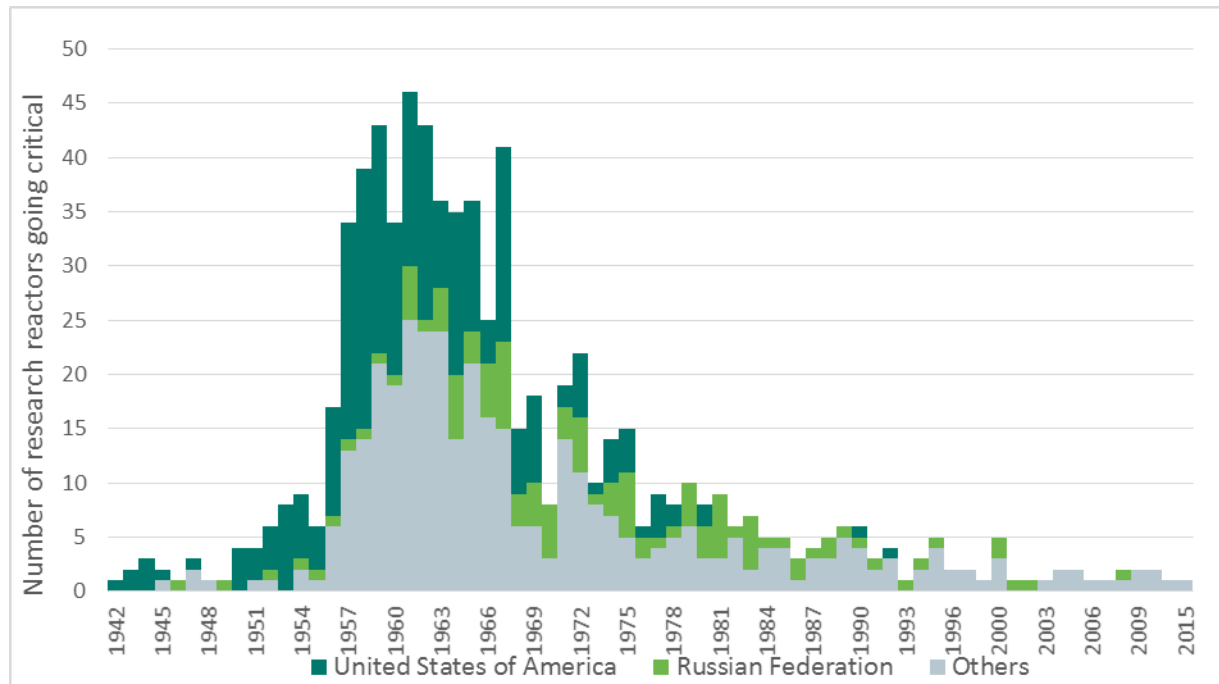
Figure 7: Nuclear technology in 1973: The effect of “Atoms for Peace”

Source: Own depiction based on IAEA PRIS Database (2017), IAEA (2017), and cited literature in the case studies.

### 3.3.6 Research reactors

The late 1950s and early 1960s also saw—after the “Atoms for peace speech”—a significant spread of research and experimental reactors (See Figure 8). Much more scrutiny should be paid to these facilities, as they produced in most cases the fissile material for weapons pro-

duction (See the cases of India, Pakistan, South Africa, and North Korea).<sup>25</sup> In most cases, the gained experiences in operating and installing research reactors led later on to the deployment of large scale reactors. There are two countries in 2017, which do not run commercial nuclear reactors but are in possession of nuclear weapons: Israel and North Korea.



**Figure 8: Grid connections of research and experimental reactors**

Source: Own depiction based on IAEA Research Reactor Database (2017).

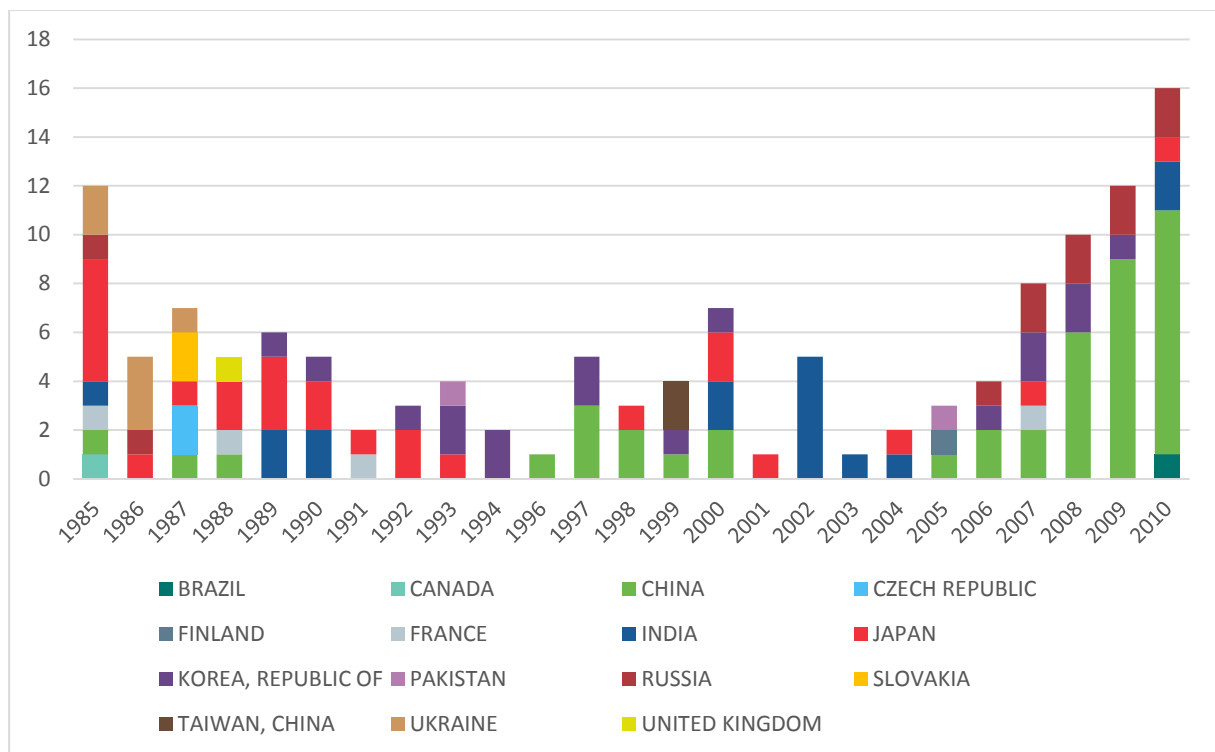
### 3.4 China emerges as key player (1985–2011)

Having practiced economies-of-scope strategies themselves, the two big nuclear superpowers of the time also contributed, directly and indirectly, to the establishment of smaller nuclear powers. Thus, the United States and Canada had equipped India and Pakistan with nuclear technology; disrespecting their initial promises to keep the use of nuclear in the civilian space, both countries then developed their respective military apparatus, and proceeded with testing nuclear bombs (India: 1974; Pakistan: 1998). Canada withdrew from the

<sup>25</sup> Lévêque (2014, 15).

cooperation with India, and the United States put severe restrictions on the export of equipment. Reacting to this, India went ahead with the development of its own nuclear industry and turned to Russia for reactor imports. Pakistan, that had initially also imported the Canadian CANDU PHWR, later turned to China for imports, first the CNP-300 (1980s) and—more recently—it became the first country worldwide to import the Chinese self-made Hualong HPR-1000.

Davis (2012, 52) observes that by 1990, construction had moved to Eastern Europe and in particular Russia and Ukraine. The increase in construction 2008–2010 comes primarily from China, which today has more reactors under construction than any other country (See Figure 9). The key date leading to this was 1985, the year when China entered the sector with its first large-scale reactor, the CNP 300. The Chinese activities in military and civilian applications had started in 1957 already; in fact, China had been the only permanent member of the UN Security council not to have become a nuclear power since the 1940s (France tested nuclear weapons in 1960). Eager to develop nuclear weaponry itself, China had sought technical support from the Soviet Union that had supplied a heavy water reactor. Soviet experts also helped China to assemble an enrichment facility (also imported from the USSR), and plutonium production facilities in Jiuquan. When political relations between the two became strained, in the early 1960s, China went on to develop its nuclear bomb by itself, and successfully tested it in 1964 (see the case study on China for more details).



**Figure 9: Construction starts worldwide, 1985–2010**

Source: Own depiction based on IAEA PRIS Database (2017).

China turned to reactors also generating electricity in the late 1970s, having only worked on research reactors thus far. Following the US example in the late 1940s, China transformed a PWR for submarines into an NPP in 1985, the CNP 300: The pressurized vessel was bought from Mitsubishi (Erickson et al. 2012) and came from a submarine developed by Westinghouse in the 50s (Biello 2011). From then on, China pursued a consequent strategy of importing foreign technology, and then tailoring its own design from a multitude of imported equipment. Thus, China used elements from imported reactors from France, Canada, the U.S., and the Soviet Union, in the 1980s: China imported a M310 (equivalent of N4) from France in 1988, a CANDU from Canada in 1998, and a VVER from Russia in 1999. The French design was then “indigenized”: components and procedures of the French technology served as model for both the CPR-1000 and the CNP-600.<sup>26</sup> In 2013, the Chinese government re-

<sup>26</sup> Ramana and Saikawa (2011, 6785).

quired the two major nuclear companies CGN and CNNC to “merge” the two Gen III designs ACPR-1000 and ACP-1000, which resulted in the Hualong One design (HPR-1000). In parallel, China keeps localizing foreign nuclear technologies, such as enrichment facilities (Zhang 2015), the French EPR and the American AP1000.<sup>27</sup>

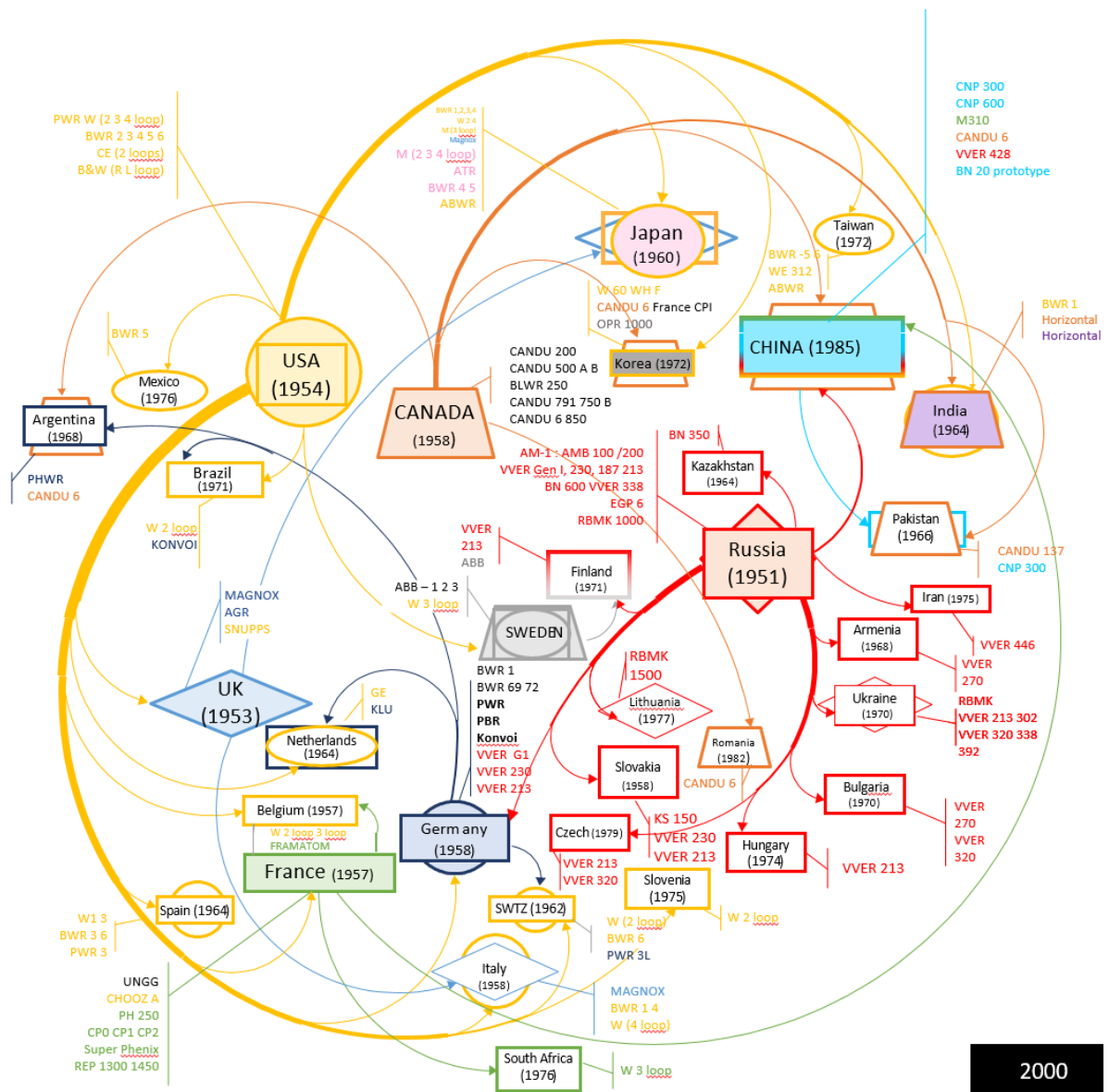
Based on this learning, China has also developed its own, specific design, e.g., for a fast breeder reactor. China is also active in research on designs for small modular reactors (SMRs, see below). The German model of the pebble-bed reactor (PBR) was adapted in 1992 into a research reactor, the HTR-10. A scaled-up version, the HTR-PM was constructed in 2012, making China the only country to develop this model. Moreover, China plans to build several molten salt reactors. Based on its consequent nuclear policy, China has established itself firmly among the three global nuclear superpowers, alongside or even leading the United States and Russia. It started exporting its CNP 300 reactor to Pakistan, in 1993, and has been successful in its nuclear diplomacy recently, providing the Hualong HPR to countries like Pakistan, probably Sudan, and—under negotiation—the U.K.<sup>28</sup> Figure 10 indicates how nuclear reactor technology had spread by 2000, and shows China’s unique position as a buyer and seller of nuclear technologies.

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<sup>27</sup> In 2008, China ordered four units from Westinghouse, apart from this Westinghouse only had one other order in the previous 25 years (Thomas 2010a, 20).

<sup>28</sup> By end 2013, the three Chinese reactor vendors had target export markets: CGN was competing in U.K., Romania and Kenya; CNNC was competing in Argentina, Algeria and Sudan; and SPIC was competing in Turkey and South Africa. This export drive is backed by Chinese financial institutions. The China Development Bank (CDB) and the Export and Import Bank of China are supporting state-backed companies, with CDB offering government-to-government low interest loans to Argentina and Algeria for their nuclear programmes as well as loans to CGN for the U.K.’s Hinkley Point project. The Industrial and Commercial Bank of China has agreed to offer loans of €10 billion to support CGN’s nuclear project in Romania (See Yu (2015) in Thomas (2017, 685)).





**Figure 10:** Current developments: China has a unique position as buyer and seller.

Source: Own depiction based on IAEA PRIS Database (2017), IAEA (2017), and cited literature in the case studies.

### 3.5 Current trends: 2011 going forward

This section summarizes the status quo of construction projects in 2017 as well as current trends ongoing in nuclear reactor technology, most of which have been around for several decades (e.g., Gen III) or even since the very early days of nuclear power (SMRs).

### 3.5.1 Status Quo: Construction projects in 2017 (Gen III/III<sup>+</sup>)

In 2017, there are 54 NPPs or around 52 GW<sub>e</sub> of capacity in construction in 13 countries worldwide, with roughly 85 percent of the projects clustered in two major geographical regions: Asia (33 NPPs or ~ 65 percent, 19 alone in in China) and Russia and the former USSR states (9 NPPs or ~ 20 percent). Only four reactors are currently being built in the EU and two in the U.S.<sup>29</sup> There are still 7 or around 5 GW<sub>e</sub> of Gen II reactors being constructed in China, India, Russia and Slovakia. The major part of the construction projects are Gen III reactors (27 NPPs, ~ 28 GW<sub>e</sub>) and Gen III<sup>+</sup> reactors (16 NPPs, ~ 21 GW<sub>e</sub>). Table 2 gives an overview of the current worldwide construction projects in 2017.

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<sup>29</sup> In 2017, the construction of two AP1000 units for the V.C. Summer nuclear project were cancelled. The project was estimated to be 40% completed and the costs were around 9 billion USD. The abandonment came after Westinghouse filed for Chapter 11 bankruptcy protection in the U.S.

Reactor designs	China	India	Russia	UAE	Korea	U.S.	Belarus	Slovakia	Pakistan	Japan	France	Finland	Argentina	Total
<b>Gen II</b>														<b>7</b>
PHWR-700		4												4
VVER V-320			1											1
VVER V-213								2						2
<b>Gen III</b>														<b>27</b>
ACP-1000	6													6
HPR-1000 (Hualong One)	4													4
ACP-1000 (Hualong One)									2					2
HTR-PM	1													1
VVER V-428M	2	1												3
ABWR										2				2
APR-1400				4	5									9
<b>Gen III<sup>+</sup></b>														<b>16</b>
AP1000	4					2								6
EPR/ EPR-1750	2										1	1		4
VVER V-392M			1											1
VVER V-491			3				2							5
<b>Other</b>														<b>4</b>
		1	2										1	4
<b>Total</b>	<b>19</b>	<b>6</b>	<b>7</b>	<b>4</b>	<b>5</b>	<b>2</b>	<b>2</b>	<b>2</b>	<b>2</b>	<b>2</b>	<b>1</b>	<b>1</b>	<b>1</b>	<b>54</b>

**Table 2: NPP construction projects in 2017 by country and reactor design, worldwide**

Source: Own depiction based on Thomas (2010a, 2017), Schneider et al. (2017), IAEA (2017), and Goldberg and Rosner (2011).

### 3.5.1.1 Construction projects in Europe

The last construction project that started in the EU prior to the EPR projects was a Gen II reactor for the Civeaux-II station in France, in 1991 (connected to the grid in 1999). In 2017, four NPPs are under construction in three countries: France, Finland, and Slovakia. In Slovakia, two Gen II VVERs (Mochovce-3 and -4, two times 440 MW<sub>e</sub>) are expected to enter operations in 2018/19, although construction already started in 1985 but was halted and officially restarted in 2009. The costs for completion were estimated to be around 5.1 billion EUR in 2016 (Schneider et al. 2017, 231).

If there is a near-term future deployment of NPPs in Europe, it will consist of Gen III/III<sup>+</sup> reactors, e.g., the EPR (European Pressurized Reactor) by Areva (now Framatome) or the AP1000 by Westinghouse. Initially the development of Gen III/III<sup>+</sup> reactors were thought to be cheaper, safer, and easier to build, which are key elements for a possible nuclear renaissance. But, especially the EPR (European Pressurized Reactor) could never meet its high expectations and won until today only two tenders: For the Flamanville station in France and the Olkiluoto station in Finland (see below).

In 2003 (one year before the French regulator approved the EPR), TVO (Teollisuuden Voima Oyj) a Finnish nuclear utility signed a turnkey deal (fixed price) with Framatome for 3 billion 2003 EUR (or 2,250–2,475 2004 USD/kW).<sup>30</sup> In 2005, EDF ordered its first EPR for the Flamanville site with expected costs of 3.3 billion 2004 EUR. Contrary to TVO, EDF did not seek a turnkey contract, but chose to be the contract manager (Thomas 2010b, 9–11). The latest cost estimate for both Flamanville-3 and Olkiluoto-3 was around €10.5 bn (~6,500 €/kW) in 2015.<sup>31</sup> Today, the EPR as well as its vendor are both in a financial crisis. The two European EPRS are well behind schedule and are now expected to enter operations in 2018/2019—with commissioning initially planned for Olkiluoto-3 for 2009 and 2012 for Flamanville-3.

### 3.5.1.2 Construction projects in the United States of America

In the U.S, no Gen III/III<sup>+</sup> has finished construction too. Only in 2013, 35 years after the last construction start, orders for new nuclear power plants were placed at Westinghouse; four AP100s reactors started construction in 2013: the V.C. Summers project in South Carolina and Vogtle in Georgia, with Westinghouse as the primary contractor in both projects.

The V.C. Summer project was cancelled in 2017—with a completion rate of 33.7% at that time—after Westinghouse filed for Chapter 11 bankruptcy protection in the U.S. The construction project in Georgia was only 36% complete in 2016 and the latest estimate for

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<sup>30</sup> Including interest during construction and two fuel charges reducing the OC somewhat—well over the industry target from the 1990s.

<sup>31</sup> Schneider et al. (2017, 47).

commissioning of the two reactors is set to 2023, although this remains very speculative and the risk of further delays is likely. The construction costs of the two Vogtle AP1000 reactors have escalated from initially 14 billion USD (~6,200 USD/kW) in 2013 to estimated 29 billion USD in 2017 (~9,400 USD/kW).<sup>32</sup>

### 3.5.1.3 Construction projects in Asia

Asia has been the centre of nuclear newbuild since 1985 (See Figure 9) and still is in 2017 with around 65 percent of construction projects situated in this region. Of the 33 NPPs under construction in Asia, 19 are in China—the majority of them Gen III (13) reactors and six Gen III<sup>+</sup> reactors. Since 2009/2010 the first four Westinghouse APR-1000s (Sanmen and Haiyang), worldwide, are under construction, this was the first reactor order for Westinghouse since the 1970s. Sanmen was thought to enter operations in 2013, the latest expectation is 2018.<sup>33</sup> In 2007, the largest ever nuclear deal estimated to be around USD 12 billion for two EPRs was signed. The deal was signed without any international bidding, but the French government offered a convincing financing package with EDF taking a 30% stake in the project and the French finally agreeing to the Chinese demand for technology transfer.<sup>34</sup> Construction of the two EPRs for the Taishan site started in 2009/2010, but the project has gone bad and is already several years late. After the Fukushima disaster, the Chinese State Council terminated the approval of new-build projects, this changed in February of 2015 as projects gained restart under the impetus of new policies. If China wants to expand nuclear power, inland sites will have to be developed, but there is significant opposition to this, in addition the Chinese government prohibited this after Fukushima.<sup>35</sup>

India is also expanding its nuclear fleet with six construction projects in 2016, with the majority (4) being Gen II Indian PWRs, Pakistan imported two Gen III Hualong One reactors from China. Korea and Japan, also build new power plants, all Gen III reactors (Korea five

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<sup>32</sup> Schneider et al. (2017, 94–95).

<sup>33</sup> Schneider et al (2017, 200).

<sup>34</sup> Ramana and Saikawa (2011, 6785).

<sup>35</sup> Thomas (2017, 685).

APR-1400s, Japan two ABWRs). The Korean Shin-Kori-3, also an APR1400 was connected to the grid in 2016. In Japan, Ohma is projected to be completed in 2024. In addition, Korea is for the first time constructing nuclear power plants outside of their home country, in the United Arab Emirates.

#### **3.5.1.4 Construction projects in Russia**

In Russia and the former USSR, a total of 9 NPPs are under construction. In 2017, the first Gen III<sup>+</sup> reactor went online: Novovoronezh 2-1. Three more Gen III<sup>+</sup> are under construction (VVER-1000), but also one Gen II NPP is still under construction since 2010 (Rostov-4, VVER V-320). In addition, Atomstroyexport builds two Gen III<sup>+</sup> reactors in Belarus.

#### **3.5.2 Graphical representation**

Figure 11 shows the status quo of sixty years of nuclear deployment and indicates how nuclear reactor technology had spread by 2015. Figure 12 shows the number of construction starts in the period 2011– 2016. Figure 13 shows the cumulated operational net generation capacity (in MW<sub>e</sub>) from 1954 to 2016. Construction peaked in 2013 with ten newbuild projects, only a third of the major rollouts of the 1960 and 1970s, respectively. China, too, has significantly reduced the speed of its nuclear deployment after the Fukushima incident. The last five years also see the construction start of a nuclear power plant in the Middle East: The United Arab Emirates import turnkey APR1400 technology from Korea—the first time that KEPCO builds outside of its home country.

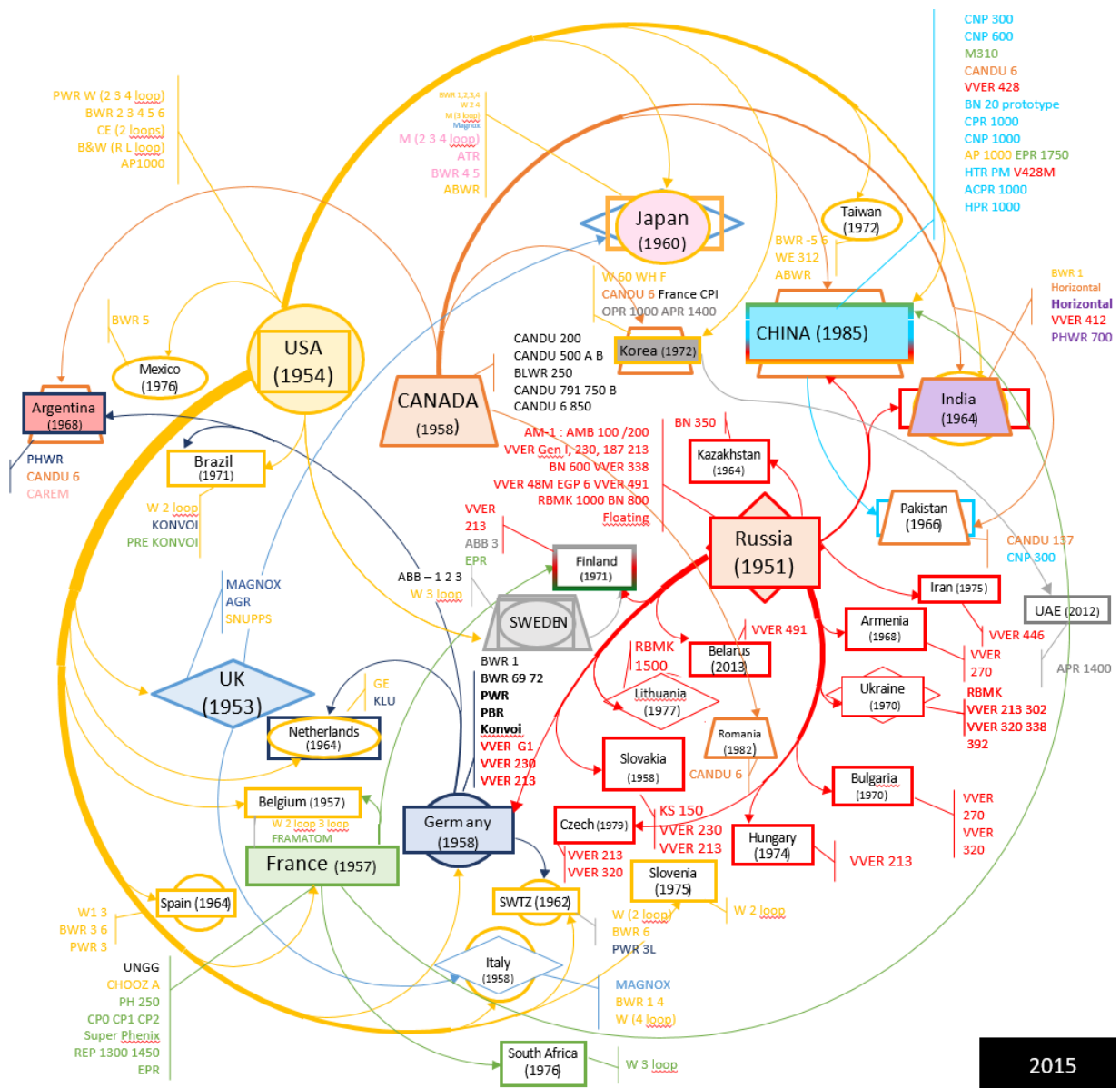


Figure 11: Status quo in 2015

Source: Own depiction based on IAEA PRIS Database (2017), IAEA (2017), and cited literature in the case studies.

Diffusion Patterns of Nuclear Power Technologies (1945–2017)

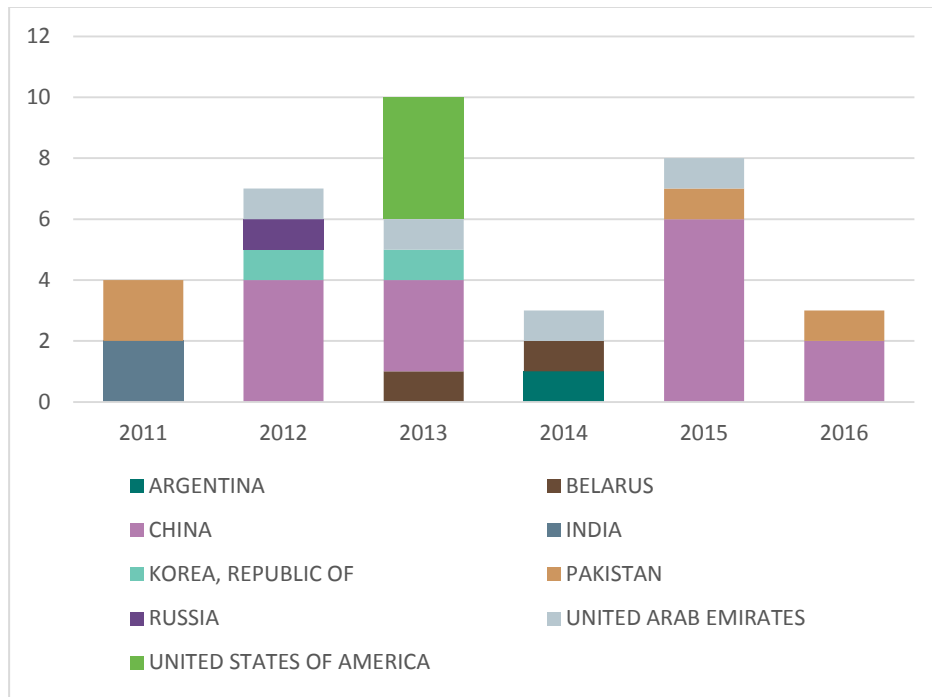


Figure 12: Construction starts worldwide, 2011–2016

Source: Own depiction based on IAEA PRIS Database (2017).

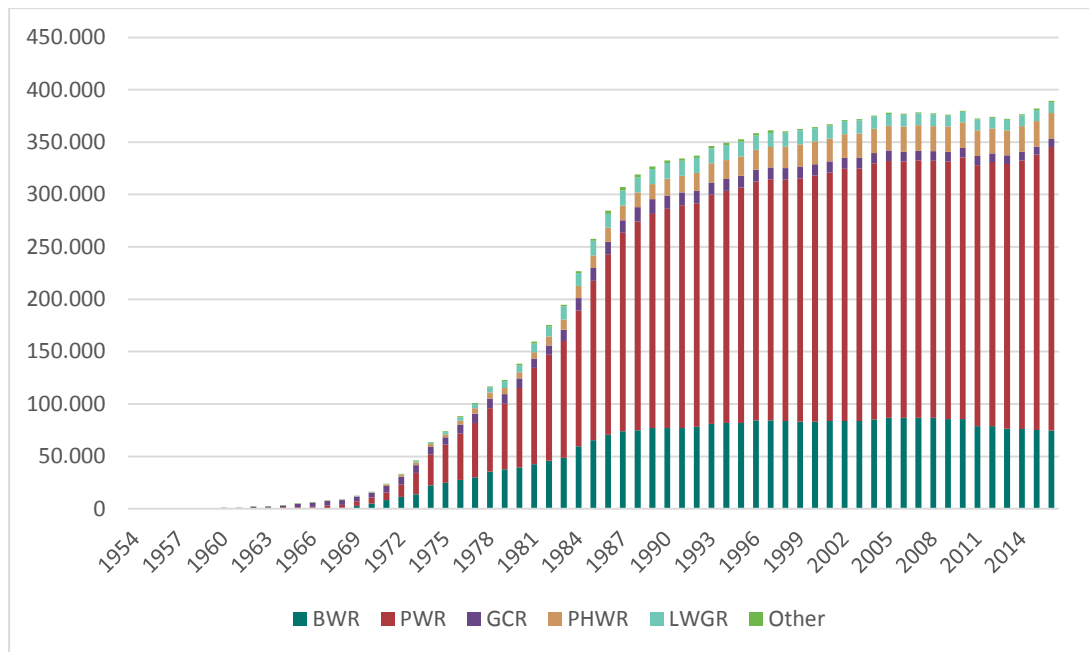


Figure 13: Operational net generation capacity in MW<sub>e</sub>, 1954 - 2016

Source: Own depiction based on IAEA PRIS Database (2017).



Looking forward, as Figure 13 shows nuclear power deployment (the deployment takes the form a classic s-curve) has seemed to have long reached its maturity. The few construction starts, that took place, have nearly all moved from the West to the East, while two of the constructions starts in the West have been abandoned in the U.S., even after a lot of money had been spent. China has rapidly decreased its expenditure speed, too. Although, the Middle East has seen its first construction start since Buser in Iran in the late 1970s, with UAE buying reactor technology from Korea, the near-term future for nuclear power deployment seems bleak at the moment. Especially, if one considers, that the much-promised future reactor technologies, like Gen III/III<sup>+</sup> reactors are in technological troubles with no finished construction project in the U.S. nor Europe, in addition, its traditional vendors are in financial turmoil, with Framatome being bailed out and split up by the French state and the filing for bankruptcy of Westinghouse in the U.S.

### **3.5.3 Possible future reactor technologies: Gen IV and SMR**

#### **3.5.3.1 Small modular reactor (SMR)**

Small modular reactors (SMR) are often presented as nuclear newcomers and praised as a potential technology that could help the nuclear industry to overcome the failed nuclear renaissance. As large NPPs face increasing construction cost and construction time, SMRs are presented as one possible solution; in addition, they are proclaimed as being more flexible, e.g., providing additional features such as district heating. Even if some SMRs are based on large reactor designs, they generally incorporate improvements, such as passive safety systems or integrated vessels (e.g., the steam generators are installed inside of the reactor pressure vessel) that reduce the complexity of the reactor by removing extra components.<sup>36</sup> The IAEA provides on its website ARIS (Advanced Reactor Information System) a list containing all available SMR technology; however diverse documents show that the term SMR is ambiguous and is used for small modular reactors as well as small and medium sized reac-

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<sup>36</sup> Passive safety systems use natural forces to operate the reactor in terms of cooling and safety for example (IAEA 2009). The NuScale SMR for example uses a pool as a passive cooling system that is able to cool the reactor via natural convective movements.

tors. Following the official definitions of the IAEA, small reactors are reactors with an equivalent electric power less than 300 MW<sub>e</sub> (IAEA 2007). SMRs are a sub-branch of small reactors defined as *“advanced reactors that produce electric power up to 300 MW(e), designed to be built in factories and shipped to utilities for installation as demand arises”*.<sup>37</sup> Therefore, only some of the small and medium sized reactors can be considered as SMRs, if these attributes (mass produced, transported to the site, and assembled in a decentralized way) are applied.

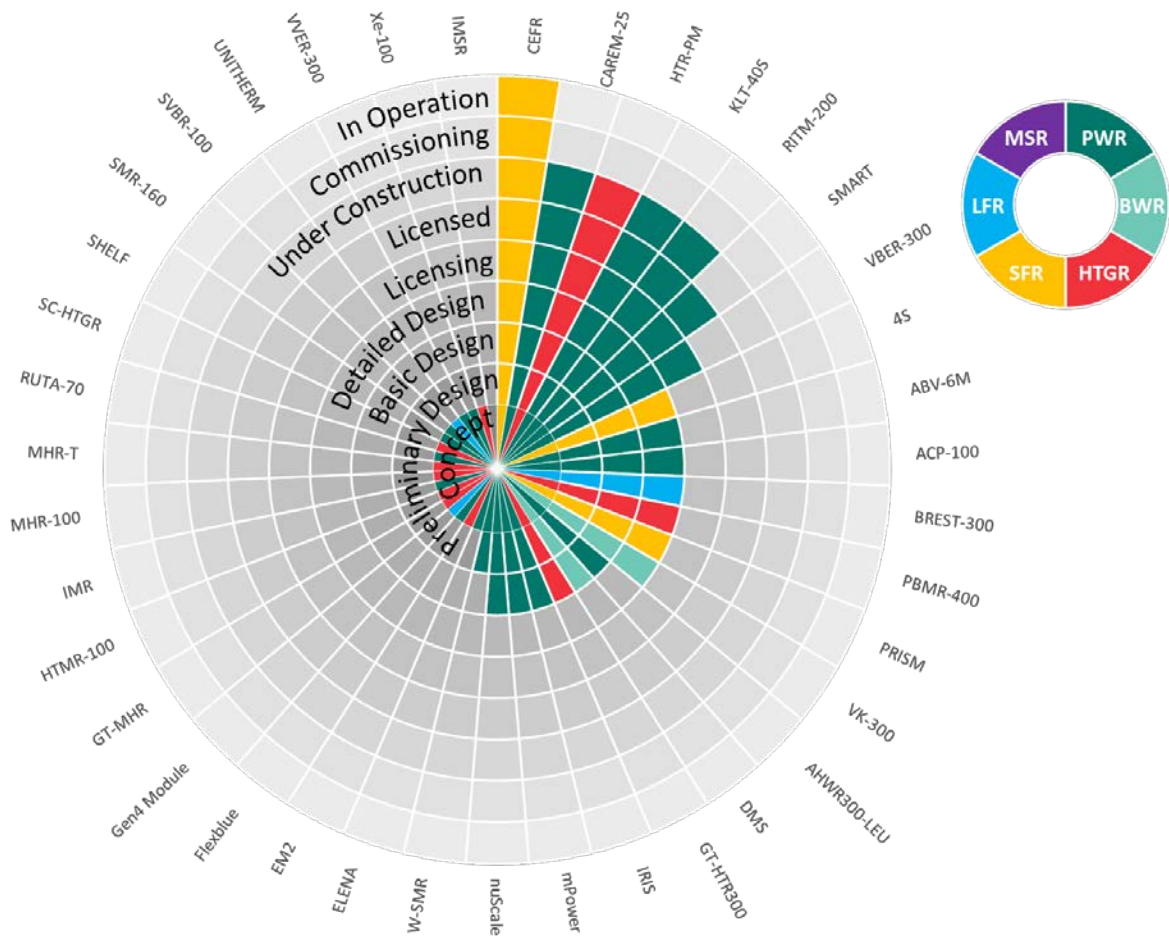
#### 3.5.3.1.1 Current most advanced SMRs<sup>38</sup>

There are several SMR projects currently in different stages of development (in 2017). Almost half of the projects listed by the IAEA are currently only at the conceptual level, while only seven reached the licensing step: the Russian KLT-40S and RITM-200, the Korean SMART; the Chinese HTR-PM and CEFR; and the Argentinian CAREM-25 (See Figure 14).

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<sup>37</sup> IAEA. 2016. “SMR - Nuclear Power.” December 12, 2016. <https://www.iaea.org/NuclearPower/SMR/>.

<sup>38</sup> For a detailed analysis of SMRs see the special sections “Small Modular Reactors” in Schneider et al. (2015, 2017) on which the following description of the current SMR projects is largely based.



**Figure 14: Advancement of SMRs design development in 2017.**

Source: Own depiction.

**CHINA**

China has already pursued different SMR designs<sup>39</sup> with the Chinese HTR-PM (high temperature gas-cooled pebble bed reactor, which is not a new concept, as it has been developed in Germany, U.K., and the U.S.) being the most advanced reactor. China first developed a prototype (HTR-10), and launched in 2001 the construction of the demonstration twin-reactor HTR-PM (210 MW<sub>e</sub>). The design is modular, since several modules can be connected to a single turbine, e.g., the HTR-600 configuration foresees up to 6 modules connected together.

<sup>39</sup> The Chinese experimental fast reactor (CEFR) was the first and only small reactor operating in 2014, but the reactor is not modular as it is a single pool-type reactor with components assembled on-site. Finally, it is only the first step of the Chinese nuclear program to master fast reactors, and the Chinese successor prototype fast reactor (CPFR) will have an output of 600 MW<sub>e</sub>.

The construction of the first unit started in 2012 at the Shidaowan site. The initial plans for further 18 units seem to have been dropped and commissioning of the first unit is delayed to 2018. One reason seems to be the high generation costs (reported to be significantly higher than for Gen III reactors)—one of the key challenges for the Chinese HTGR program. In recent years, some new SMR designs have been promoted: ACPR50 and ACPR100 by China General Nuclear (CGN) and ACP100 from China National Nuclear Corporation (CNNC), although no construction project has yet started (in 2017). The main motivation for China seems to be the construction of maritime nuclear power platforms in the South China Sea—the recent conflicts in this area have accelerated the development in the recent years.

#### ***RUSSIA***

It is remarkable that among reactors which reached the licensing stage, the majority comes from Russia. These Russian PWRs are not new concepts, and find their origin in the Russian military nuclear ship fleet. Based on the KLT-40 reactor—a PWR built to propel icebreakers used since 1957—two reactors were designed: the KLT-40S and the RITM-200. The purpose of the latter is to replace the KLT-40 reactor for the next generation of nuclear icebreakers (the three first ships are under construction). The KLT-40S is going to be used on a floating nuclear power station, the Akademik Lomonosov. Construction started in 2007 and is expected after several serious delays to be completed in 2019. Associated with the construction time increases are also large cost increases, initial cost estimates of around 140 million USD in 2006 have escalated to 740 million USD in 2015 (Schneider et al. 2015, 73). Another reactor is the VBER-300—a hybrid model descending from both VVERs and naval reactors. It could be used on land or on a ship to provide energy for electricity, district heating and desalination (IAEA 2011).

#### ***ARGENTINA***

The Argentinian concept of CAREM was already presented in 1984 but with a power output of 15 MW<sub>e</sub> by the CNEA (Comisión Nacional de Energía Atómica) with construction estimated to begin in 2001. Construction of CAREM-25 (27 MW<sub>e</sub>) started in 2014 with cold commissioning estimated to be carried out in 2016. Only in 2016, 15 years after the presentation of the SMR concept, a contract was signed with Trecna for the design, engineering, the whole

construction, and commissioning of the reactor; the estimated commissioning start was set to 2019.

#### ***SOUTH KOREA***

The South Korean SMART (System-Integrated Modular Advanced Reactor) design has been in development for two decades—the project was launched by KAERI (Korea Atomic Energy Research Institute). The small (90 MW<sub>e</sub>) PWR has received extensive government support and licensing was thought to be completed by 2004 based on the close cooperation between the industry (e.g., KEPCO) and the regulator. Only in 2012, a standard design approval was issued, making the SMART design the first licensed land based SMR of LWR design (not including the early 1950s/60s designs). Even if a license was issued, there are no plans to construct this SMR in South Korea, especially with the new administration under President Moon, which foresees the elimination of all newbuild plans. This leaves only the export market for KAERI, e.g., a memorandum of understanding was signed with Saudi Arabia and negotiations with Indonesia have been underway.

#### ***INDIA***

India has been working since the 1990s on a SMR design—the Advanced Heavy Water Reactor (AHWR)—of which the potential to use thorium and plutonium as a fuel (see the case on India for more details on India’s nuclear program) has been marketed the most. The AHWR has been repeatedly delayed but in 2016 the Department of Atomic Energy stated the SMR has “in principle” received approval for construction at the Tarapur site. As the Indian SMR concept is not proliferation resistant, India has announced (in 2009) that it will develop an export model, which is thought to be fueled by LEU.

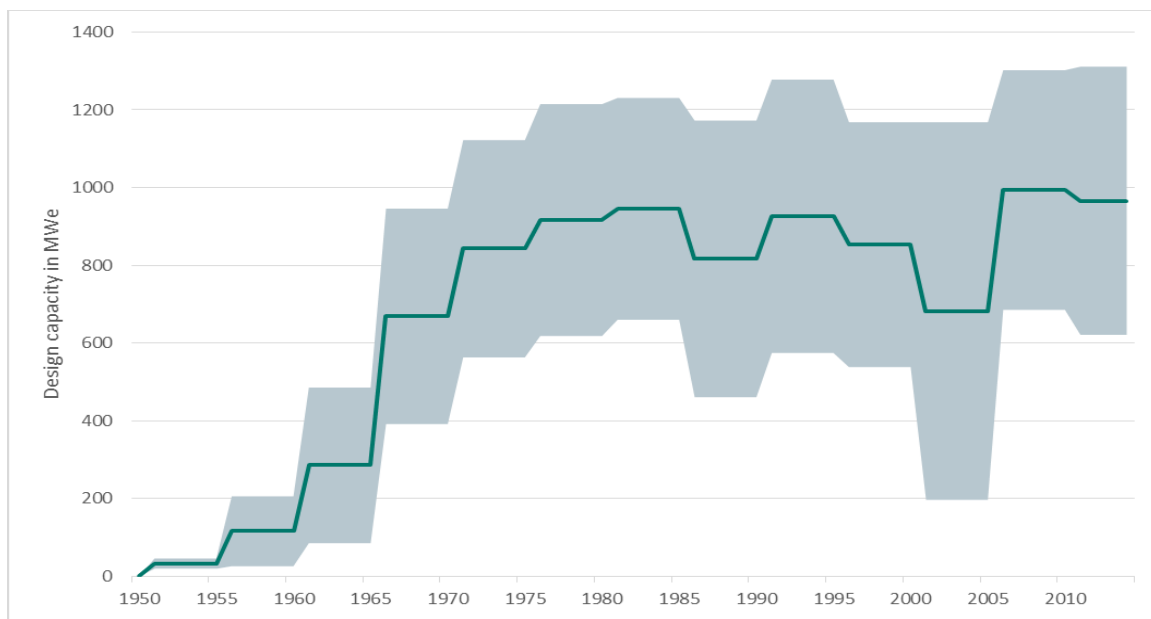
#### ***THE UNITED STATES OF AMERICA***

The United States of America has also been funding the development of SMR designs since the 1990s and in 2012, the Department of Energy selected two designs for further funding: mPower (developed by Babcock & Wilcox) and NuScale (developed by NuScale Power, one investor is Fluor Corporation). The two designs are integral LWRs, where the steam generators are located in the reactor pressure vessel. Due to missing investors or even finding customers willing to order an SMR, B&W seem to have dropped the whole SMR effort. NuScale on the other hand keeps pushing its SMR development ahead and the DOE’s support has

extended to siting and the administration entered into agreement with the public power utility Utah Associated Municipal Power Systems to evaluate various sites within the Idaho National Laboratory to construct the first NuScale SMR. NuScale is optimistic and is targeting operations to commence in 2024. A third reactor vendor that applied for DOE funding was Westinghouse, which has been developing SMRs in parallel with the AP600 and AP1000 reactor designs: the International Reactor Innovative and Secure (IRIS) design. The design was dropped by Westinghouse and in 2011, the Westinghouse SMR (225 MW<sub>e</sub>) was introduced—a downsized IRIS design but Westinghouse decided at that time to prioritize the development of the AP1000. In 2017, after the filing for bankruptcy, Westinghouse—as Babcock & Wilcox—seems to have dropped the whole SMR effort too.

#### **3.5.3.1.2 The prospects for SMRs**

As a balance to the increasing number of SMR designs, several recent studies (Cooper (2014), Sovacool and Ramana (2015), and Ramana et al. (2013)) point out crucial issues that SMRs need to address before being deployed. One of the main issues addressed to SMR designs are capital costs. The principle of economy of scale states that costs decrease with respect to the increasing size of the reactor. This is the main reason why the capacity of reactors has steadily increased since the construction of the first npp in the 1950s (see Figure 15).



**Figure 15: Average design capacity of new built reactors (solid line) and standard deviation, aggregated each 5 years**

Source: Own depiction based on IAEA (2017).

Locatelli et al. (2014) evoke, that capital cost of SMRs cannot be simply compared to a large reactor, as their designs are different (even for LWRs) and SMRs do not reap economies of scale but rather “economics of multiples”: multiple units at a single site, faster learning due to more units built, shorter construction schedule, and a simplification of the reactor design. Modularity—the notion of multiple units—is an important component of the evaluation of the profitability of SMRs. The construction cost of a second (or nth) reactor are not the same as for the first, e.g., machines and organization can be re-used with few modifications. Moreover, workers and companies learn the process, leading to efficiency gains. This idea is mainly driven by the principle of standardization. However, to benefit from this standardization, multiple units have to be built and they have to be built sequentially in order to reap economical advantages. Currently (in 2017), only the Russian KLT-40S has received real orders in series, with three units being under construction. Other reactors have only plans for scaling-up (CAREM, HTR-PM) or are under negotiation, like SMART.

SMR designs diverge from large reactors, however to reach the construction stage, they still need to comply with national regulations but licensing procedures are not yet tailored to

SMRs. In most regulated markets, a nuclear power plant requires two licenses to operate: one for the reactor design and another for the construction and operation of the reactor. The first one is issued prior to construction and is related to one technology—it is licensed only one time. The operating license has to be issued for each new power plant. Both processes are time-consuming. If SMRs were manufactured, the issuing of the operating license will extend the construction duration in the factory, leading to a reduced advantage in building SMRs. Yamashita (2015) estimates that it “*could extend construction time of SMRs beyond the pure technical schedule undermining the overall economics*”. Then, a necessary condition to export a standardized model of reactor across borders is to have common licensing and regulations in different countries. This is hardly the case nowadays, i.e. reactors need new licenses and design modifications for each country. Since standardization of reactors is a key parameter in SMRs manufacturing, regulations have to be harmonized. Nevertheless, regarding the diversity of institutions, Sainati et al. (2015) consider that “*it is difficult to make significant progress in this direction in the short-medium term*”.

Multiplying SMRs around the globe can thus only happen if a common regulatory framework is designed. This should lead to the centralization of the building of SMRs in a restricted amount of factories. However, manufacturing defaults occur even under strict monitoring conditions. Manufacturing defaults concern the nuclear industry too, as it is currently the case in France: Le Creusot, which is part of the Areva Group since 2006, has been in hot water in recent times and is currently being investigated due to irregularities in quality-control documentation and manufacturing defects of forged pieces produced for the EPR as well as the operational reactors, leading to multiple shutdowns in 2016.<sup>40</sup> More generally, one can say, the higher the number of products, the higher the risk that one of them has a default. SMRs cannot avoid this rule.

In sum, the concept of small reactors has been around since the dawn of the nuclear age and no SMR has ever been operated, and current projects—if they are not abandoned (South African PBMR-400)—suffer from serious delays both in terms of construction (KLT-40S) and

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<sup>40</sup> See Massemin (2017a, 2017b, 2017c) and Schneider et al. (2017) for a detailed report on the scandal.



design (Toshiba 4S). Not one SMR has even finished the construction stage. Due to the escalating construction costs of nuclear power plants, utilities and vendors alike called for large-scale reactors, for which economies of scale were highly expected but never reaped. Nowadays, nearly seven decades later, nuclear proponents call for smaller (and modular) reactors but for the same reason: to address construction cost explosions. In sum, the economic viability of SMRs is not clear, and they are no option any private investor would seek; while potential scale economies in production and assembly must be weighed against technical risks (e.g., failure of one mass-produced piece) and higher proliferation risks.<sup>41</sup>

### 3.5.3.2 Advanced large scale reactor designs

As mentioned above, Gen III/III<sup>+</sup> reactors are seen as an intermediate step before deploying Gen IV reactors, which are considered to be revolutionary, as they are partly based on fundamentally different technological concepts (e.g., use of alternative fuels). They are thought to provide enhanced safety through proliferation-resistance and minimal waste production. Gen IV reactors comprise among others the following technologies: the gas-cooled fast reactor (GFR), the lead-cooled fast reactor (LFR), the sodium-cooled fast reactor (SFR), the molten salt reactor (MSR), the super-critical water reactor (SCWR), and the very high temperature gas reactor (VHTR). Research is currently being coordinated within two multilateral frameworks: the U.S.-led Generation IV International Forum (GIF) and the IAEA-led International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO).<sup>42</sup>

#### 3.5.3.2.1 Sodium-cooled fast reactor (SFR)

The SFR is not a new technology (see above for a description of the functionality of a FBR) and much of the basic technology for the SFR has been established in former fast reactor programmes, e.g., Phénix and Astrid in France, the BN-600 and BN-800 in Russia, the Chinese Experimental Fast Reactor. Three future options are considered within the Generation IV Forum: a large sized (600-1,500 MWe) loop-type reactor with mixed uranium-plutonium fuel

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<sup>41</sup> Hirschhausen (2017, 13).

<sup>42</sup> Acton (2009, 50). The description of the Gen IV reactor designs is largely based on the system reports from the Annual Report 2016 of the Generation IV Forum (See GIF (2016, 45–143)).

and potentially minor actinides; an intermediate-to-large size (300-1,500 MWe) pool-type reactor with oxide or metal fuel; and a small size (50-150 MWe) modular-type.

#### **3.5.3.2.2 Gas-cooled fast reactor (GFR)**

The GFR is proposed as an alternative to the sodium-cooled fast reactors. The reference concept is a 2,400 MWth plant; the reactor core would be cooled with helium, which has the advantage of not becoming activated and not reacting with air or water. In 2013, the “V4G4 Centre of Excellence”—a legal body set up by research institutes in the Czech Republic, Hungary, and Slovakia Republic (also registered in Slovakia)—was formed with the goal of developing a 75 MWth demonstration reactor (ALLEGRO project) to be hosted in Slovakia. The project is funded by national resources of the involved countries, EURATOM Framework Programmes, and EU Structural Funds.

#### **3.5.3.2.3 Lead-cooled fast reactor (LFR)**

The LFR is also a proposed alternative for the sodium-cooled fast reactors and is conceptualized to be cooled by molten lead, which does not react with water or air. The reactor could be used as a burner of minor actinides, both self-generated and from reprocessing of spent nuclear fuel from LWRs and as a burner/breeder of thorium. There are currently three concepts: a 600 MWe (ELFR) as a centralized power generation station; a 3,000 MWe (BREST) in Russia; and a small transportable system of 10-100 MWe (SSTAR) in the U.S. For the Russian demonstration reactor licensing is underway and operation is expected to start in 2022. The LFR concept is also studied in Japan; here the use of plutonium from LWR SNF is considered.

#### **3.5.3.2.4 Molten salt reactor (MSR)**

MSRs are fast or thermal (with graphite as a moderator) reactors cooled by molten salts. In MSRs the fuel is liquid and dispersed in the coolant. One of the main advantages are—among others—that this MSR does not need fuel fabrication, increased safety through a lower mass of fissile materials and the option to entirely remove the nuclear fuel from the core in accidental situations. Molten salt fast reactors use a mixture of fluorides of thorium and uranium dispersed in lithium fluoride molten salt. Research is currently conducted in

France on a 1,400 MWe reactor (MSFR, the program predicts construction of a prototype by 2020) and in Russia on a 1,000 MWe reactor (MOSART). The Safety Assessment of the MSFR project (SAMOFAR) is one of the major research projects in the Horizon 2020 Euratom research program, carried out by Dutch, French, German, Italian, Mexican, and Swiss research partners. China has also accelerated research on liquid fuel molten salt reactors thought to be fuelled by thorium. A nearer-term concept for molten salt thermal reactors is the pebble bed - advanced high temperature reactor—a reactor moderated by graphite, cooled by molten salt and fuelled by pebble-type elements.<sup>43</sup>

#### **3.5.3.2.5 Super-critical water reactor (SWCR)**

The super-critical water reactor is a high-pressure, high-temperature, water-cooled reactor operating above the thermodynamic critical point of water (374°C). There are two main design categories: pressure vessel and pressure tube concepts. SWCR based on pressure vessel concepts was first proposed by Japan. The Japanese Super LWR project foresees the construction of a demonstration facility by 2020; a European project is the High Performance LWR (HPLWR). Canada is working on a pressure tube concept, the CANDU-SCWR cooled by super-critical water and moderated by heavy water; the deployment time frame of the CANDU-SWCR is between 2025-2080, but a prototype reactor is still missing. The main advantages of super-critical reactors are the desired improved economics gained through higher thermodynamic efficiency.<sup>44</sup>

#### **3.5.3.2.6 Very high temperature reactor (VHTR)**

The very high temperature reactors are based on the HTRs developed in the 1970/80s, e.g., Peach Bottom and Fort St. Vrain in the U.S., the German AVR and THTR, or more recently the Chinese HTR-10. VHTRs are thermal reactors moderated by graphite and cooled by helium. The use of helium as coolant and ceramics as core structure material allows operation temperature at core outlet as high as 1,000°C allowing for application as hydrogen production.

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<sup>43</sup> Locatelli et al. (2013, 1509–10).

<sup>44</sup> Locatelli et al. (2013, 1507).

The technology is being advanced through near- and medium-term projects in China, the U.S., Korea, and Japan. Construction of a HTR-PM started in 2012 (see above).

#### 3.5.3.2.7 Prospects for Gen IV reactors

The Gen IV reactors are only partly based on fundamentally different technological concepts, e.g., HTRs have been around for at least half a decade, the concepts of FBRs and thorium reactors even since the 1950s (See Weinberg (1959)). The different possible applications are—like the SMR—more than electricity generation (e.g., district heating, desalination, hydrogen production). At the moment, deployment for commercial construction seems far from certain; many experts believe that Gen IV reactor types are unlikely to be readily available and competitive anytime soon due to even higher capital costs than Gen III<sup>+</sup> reactors. Another plea for future nuclear technologies is proliferation resistance. This is certainly not the case for fast breeders (see above) and not the case if one looks at the fuel cycle, which is supposed to be closed for the above technologies, i.e. reprocessing (See Acton (2009), Kang and von Hippel (2005), and Kang and Feiveson (2001) for more details on the limited proliferation resistance and Lovins (1979) for the issues of proliferation and thorium cycles). Figure 16 gives an overview over the different Gen IV reactor designs and projects.

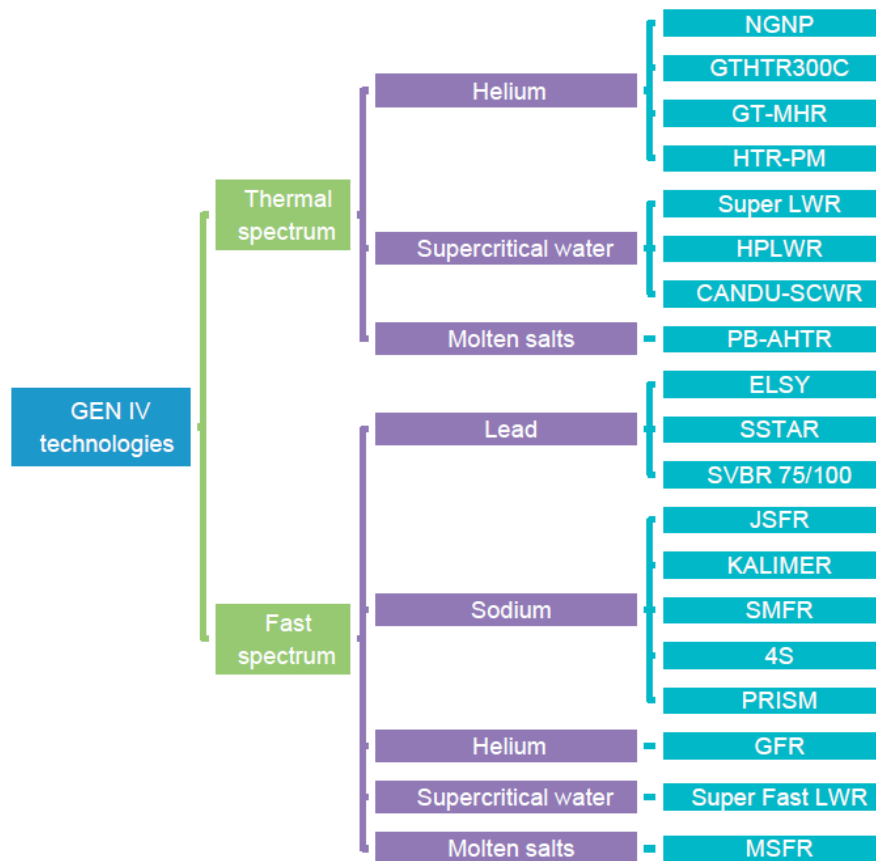


Figure 16: The different Gen IV technologies and designs (neutron spectrum, coolant, design)

Source: Locatelli et al. (2013, 1510).

#### 4 Country-specific Analysis

After the description of the main trends of nuclear power developments in the previous section, this section provides a country-by-country analysis about the emergence, the diffusion, the current state, and, in some cases, the perspectives of nuclear power. In the context of this Data Documentation, the most interesting individual aspect is how each country introduced nuclear technology in the first place, and what ideal types of diffusion patterns followed suit.

The country-specific analysis is structured along the classification introduced in the beginning of this study: it starts with the traditional and follow-up nuclear countries that have deployed an “economies of scope” approach right from the beginning, i.e. countries with

both, nuclear power as well as nuclear weapons programs. The next subsection includes countries with a major nuclear industry that have not sought economies of scope, i.e. a critical military nuclear arsenal. Subsection 3 describes countries that use nuclear power to generate electricity but have not developed a national industry themselves. Subsection 4 covers countries that do not correspond to any of the previous categories; last but not least, subsection 5 provides a brief overview of newcomers and potential newcomers to the sector.

#### **4.1 Countries with initial military deployment of nuclear power (“economies of scope”-countries”)**

##### **4.1.1 United States of America**

The United States opened up the “first nuclear age” (as Bracken (2012) calls it) with the Manhattan project, in 1941, a large-scale program to develop nuclear bombs, in the context of WW2. Two types of nuclear bombs were developed, i.e. one using highly enriched uranium (HEU), and the other one based on plutonium. HEU was developed at the Oak Ridge (TN) facility, whereas plutonium isolation took place at the Hanford nuclear reservation (south-eastern Washington State, 45,000 workers). The first test of the plutonium bomb succeeded on July 16<sup>th</sup>, 1945, near Alamogordo (New Mexico), in what is called the "Trinity-Test". A month later, August 6<sup>th</sup>, 1945, "Little Boy", a bomb mainly consisting of uranium U-235, was dropped on Hiroshima. Three days later, the Pu-239 bomb “Fat man” was released over Nagasaki. Post WW2, the Hanford site continued to be used for plutonium separation, whereas a civilian industry was launched, in parallel, based on the light water technology using enriched uranium. Today, the United States have the largest NPP fleet in the world: 99 (in 2017).

##### **4.1.1.1 Prototypes and demonstration reactors**

In 1946, the McMahon-Douglas Bill was passed as the Atomic Energy Act, with the intention to open up nuclear energy to the public sector through the United States Atomic Energy Commission (AEC), although the development of nuclear technologies was restricted to

government agencies.<sup>45</sup> Although the AEC's priority was making weapons, Lilienthal (the first chairman of the AEC) appointed an Industrial Advisory Group and the AEC began a nuclear power research program and Los Alamos, Oak Ridge, and Argonne Laboratories started research on test reactors for both, nuclear weapons and power (Weiss 2003, 38).

As the U.S. had already installed a large plutonium production centre at Hanford, they could experiment and develop new reactor designs, e.g., the first experimental reactor to generate nuclear power, the so-called Experimental Breeder Reactor I (EBR-I), in Arco (Idaho), four times 200 W. EBR-I was a liquid metal fast breeder reactor and was started in December 1951. Two years later, the US constructor Westinghouse Electric Corporation installed a PWR (designed by Alvin Weinberg and Eugene Wigner) for the first U.S.'s nuclear submarine. The first Mark 1 prototype naval reactor started up in Idaho and the first nuclear-powered submarine—*USS Nautilus*—was launched one year later, in 1954.<sup>46</sup> After this, the future four major reactor vendors General Electric (GE), Westinghouse, Babcock and Wilcox (B&W), and Combustion Engineering (CE) all built PWRs for the navy.<sup>47</sup>

In 1954, one year after Eisenhower's "Atoms for peace" speech, a new Atomic Energy Act was passed, allowing private companies to own nuclear facilities and the AEC to give grants to private companies for research and development of prototype plants—although not for commercial activities.<sup>48</sup> The major effort of the AEC was the launch of the Power Reactor Demonstration Program (PRDP) under which demonstration reactors were financed by the government. As the first LWRs were installed in the U.S. mainly due to the already existing submarine propulsion technology and because there was no need for the dual-purpose of the GCRs, this period was also characterized by the construction of experimental reactors to test further reactor technologies.<sup>49</sup> Nonetheless, it is interesting to note, that the head of

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<sup>45</sup> Thomas (1988, 68).

<sup>46</sup> The other first nuclear submarine was *USS Sea Wolf*, which was propelled by a GE PWR, also fuelled by HEU but cooled with sodium.

<sup>47</sup> Rippon (1984, 259).

<sup>48</sup> Thomas (1988, 69).

<sup>49</sup> Under the PRDP LWRs and various other types of demonstration reactors were built, e.g., FBR (Fermi-1), GCR (Hallam), superheater BWR (Bonus).

the AEC at that time was Admiral Rickover, who was—as a naval engineer—also in charge of the development program for submarine propulsion systems and hence in favour of LWRs. In the same year, in 1954, Westinghouse supplied a reactor for the first demonstration plant Shippingport in Pennsylvania; connected to the grid in 1957 (the station was shut down in 1982).<sup>50</sup> The first core of the PWR was fuelled by highly enriched uranium (93%), only later on the fuel was changed to LEU.<sup>51</sup> After Shippingport, Westinghouse consequently adapted the PWR technology to enter the large-scale reactor production. Already in the same year, in 1957, a second demonstration PWR was supplied to the Yankee Nuclear Power Station (or Yankee Rowe) in Maine. The net capacity was increased to 167 MW<sub>e</sub> and the station produced electricity from 1960 until 1991.

In 1956, two new companies entered the emerging nuclear power market: GE with the worldwide first BWR design and Babcock & Wilcox (B&W) with a second PWR design, but similar to the Westinghouse design. The first GE prototype (the NPP VBWR (Vallecitos Boiling Water Reactor, 24 MW<sub>e</sub>)) was commissioned in 1957 in California. The reactor was the basis for GE's "first generation" reactor line: the BWR-1, which was supplied in 1957 to the demonstration plant Dresden-1 (IL, 197 MW<sub>e</sub>, 1960–1978). The conceptualization of the BWR design was motivated by achieving a greater design simplicity leading to a higher thermal efficiency—by using a single circuit and by generating steam within the reactor core, in the hope that greater design simplicity would lead to lower construction costs.<sup>52</sup> In the same year, B&W supplied their first reactor to the Indian Point-1 station (NY, 197 MW<sub>e</sub>, 1962–1974). The time that followed Eisenhower's speech was mainly characterized by the construction of Gen I reactors and as the nuclear age lay just ahead, US companies were eager to obtain a share of the nuclear market and to coin the future nuclear rollout with their respective reactor technology. In 1959, Allis Chalmers entered the BWR market, but the company only supplied three demonstration reactors: Elk River NPP (MN, 25 MW<sub>e</sub>, 1964–1968),

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<sup>50</sup> After eight years of operation, Shippingport was temporarily shut down, in 1965, and transformed into a pressurized light-water breeder reactor (PLWBR), to demonstrate the feasibility of breeding fissile U-233 from thorium (Clayton 1993, 3–5).

<sup>51</sup> Weinberg (1959, 133).

<sup>52</sup> Hirsch et al. (2005, 22).



Pathfinder (SD, 59 MW<sub>e</sub>), and Lacrosse (WI, 58 MW<sub>e</sub>, 1968–1987). While the Pathfinder station never produced electricity and Elk River was already shut down five years after its commissioning, Lacrosse was the only Allis Chalmers reactor to produce electricity for a significant amount of time.

Burness et al. (1980) highlight that in the early 1960s the LWR emerged as the leading AEC candidate for commercialization. However, the problem with the LWR built under the PRDP was that capital costs of these small reactors were so high that capital charges more than offset the fuel cost. Reactor vendors and utilities alike pressed US Congress for an expansion of the AEC development program to include the subsidization of large scale reactors (400 MW<sub>e</sub> and larger), where economies of scale were expected. In 1962, the AEC responded with appropriating funds earmarking 20 million USD to be used for large-scale LWRs. Two NPPs were financed under this program: Connecticut Yankee (CT, 560 MW<sub>e</sub>, 1964–1984) and San Onofre-1. The latter was the launch of Westinghouse’s “first generation” PWRs called “W” which came with different loop configurations for different power outputs (two, three and four-loop configurations). San Onofre-1, a W (3-Loop) reactor with 436 MW<sub>e</sub> net capacity, started operations in 1967 and was shut down in 1992.<sup>53</sup> Both Westinghouse reactors were contracted under turnkey terms of 153 USD/kW (~ 1,240 2017 USD) and 180 USD/kW (~ 1,440 2017 USD). These two plants were the first two reactors built under turnkey conditions, i.e. the contractor takes on the responsibilities of design, construction, and testing as well as meeting the regulatory guidelines at a guaranteed fixed price. Even with AEC subsidies these two turnkey plants were not competitive with coal plants at that time.<sup>54</sup>

The reactor vendors Westinghouse and GE went on to dominate the reactor technology—both companies have been in the nuclear development since the 1940s and had already in the late 1950s early 1960s built up strong links in Europe and Japan. The AEC had put substantial amounts of money in the research laboratories of both companies and both were

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<sup>53</sup> The W (2-Loop) reactor for the Ginna station (NY, 580 MW<sub>e</sub>) was connected to the grid in 1969. Westinghouse installed a total of five W (2-Loop) PWRs in the U.S., the construction lasted in general between four and five years and except for Kewaunee all W (2-Loop) reactors are still operational (in 2017), well over 40 years after their grid connection.

<sup>54</sup> Burness et al. (1980, 189–90).

able to win the major part of the subsidized orders from the Power Reactor Demonstration Program set up by the AEC.<sup>55</sup> Table 3 summarizes the LWR demonstration reactors build under the PRDP, a total of 5 LWRs were built by Westinghouse (and one PHWR prototype CVTR), and four by GE (GE also constructed different prototypes, e.g., sodium cooled graphite moderated reactors, an organically cooled reactor).

Vendor	Construction Capacity in MW <sub>e</sub> (NPP)	Reactor Technology	Stations	Construction period <sup>56</sup>
Westinghouse	1,226 (5)	PWR	Shippingport, Yankee Rowe, Saxton, Connecticut Yankee, San Onofre-1	1954–1967
General Electric	351 (4)	BWR	GE Vallecitos, Dresden-1, Big Rock Point-1, Humboldt Bay	1956–1963
Babcock & Wilcox	257 (1)	PWR	Indian Point-1	1956–1962
Allis Chalmers	129 (3)	BWR	Elk River, Pathfinder, Lacrosse	1959–1968
	<b>1,963 (13)</b>			

**Table 3: US LWR demonstration reactors constructed under PRDP, clustered by reactor vendor**

Source: Own depiction based on IAEA PRIS Database (2017) and IAEA (2017).

#### 4.1.1.2 The turnkey reactors

In 1964, GE supplied the first BWR-2—of which only two were built in the U.S.—nearly a decade after the launch of its first-generation reactors to the Oyster Creek station (NJ, 650 MW<sub>e</sub>) and the Nine Mile Point-1 station (NY, 620 MW<sub>e</sub>). The order for Oyster Creek one year prior, in 1963, was the first “commercial” order of a nuclear reactor, i.e. for the first time an operator—Jersey Central Power and Light (now Exelon)—had ordered the construction of a nuclear power plant because it was expected to eventually become the cheapest available

<sup>55</sup> Thomas (1988, 69).

<sup>56</sup> Construction start of the first reactor and grid connection of the last reactor.

option. However, Oyster Creek was no exception to the rule; the reactor was ordered by a cost-of-service regulated public utility that could roll over all costs into its customer’s rate base. In the three years, that followed Oyster Creek, a total of 20 orders for LWRs on a turn-key basis were placed (until 1966), but as the vendors realized that fixed-price contracts were a substantial risk, some offers were withdrawn. The existence of substantial economies of scale was largely unquestioned and six of the 20 orders placed in 1966 were for units larger than 1,000 MW<sub>e</sub>—two years before a unit of half that size even entered operations. Oyster Creek marked the end of explicit government financial support for LWR construction and government money has from then on been channelled into high-temperature and breeder reactors.<sup>57</sup> A total of thirteen turnkey orders were placed, for which the vendor guaranteed the price of the plant to the utility allowing for inflation (see Table 4).

It is generally acknowledged that both GE and Westinghouse subsidized the offers strategically, in order to kick-start the rollout of commercial plants. Westinghouse and GE clearly dominated reactor sales and although GE was offering the BWR at a slightly cheaper price than Westinghouse its PWR, they won roughly the equal number of shares (See Table 4). The economies of scale that were strongly expected by moving from 600 to 1,000 MW<sub>e</sub> or “learning effects” never materialized and costs rose sharply. Both companies, GE and Westinghouse, underestimated the costs for large units and both companies suffered substantial losses on the turnkey contracts, resulting in Westinghouse and GE dropping the turnkey contracts in mid-1966.<sup>58</sup> Only then, B&W and CE entered the market for “commercial” reactors. The two companies were shy of turnkey contracts and were until then still the main suppliers of conventional boilers and they could share the success with the supply of major components to GE and to Westinghouse, notably the reactor pressure vessel.<sup>59</sup>

Station	Capacity in MW <sub>e</sub> (NPP)	Reactor Design	Construction time <sup>60</sup>	Permanent Shutdown
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<sup>57</sup> Thomas (1988, 68–73).

<sup>58</sup> Burness et al. (1980, 194).

<sup>59</sup> Rippon (1984, 261).

<sup>60</sup> Construction start of the first reactor and grid connection of the last reactor.

Station	Capacity in MW <sub>e</sub> (NPP)	Reactor Design	Construction time <sup>60</sup>	Permanent Shutdown
<b>General Electric</b>				
Oyster Creek	619	BWR-2	1964–1968	
Dresden 2,3	1,773 (2)	BWR-3	1966–1970/71	
Millstone	641	BWR	1966–1970	01.07.1998
Quad Cities 1,2	1,819 (2)	BWR-3	1967–1973	
Monticello	647	BWR-3	1967–1971	
<b>Westinghouse</b>				
Ginna	580	W (2-Loop)	1966–1970	
Robinson	741	W (3-Loop)	1967–1971	
Point Beach 1,2	1,182 (2)	W (2-Loop)	1967/68–1970/72	
Connecticut Yankee	560	Yankee	1964–1968	05.12.1996
	<b>8,562 (13)</b>			

**Table 4: Nuclear power plants built under turnkey contracts in the U.S.**

Source: Own depiction based on IAEA PRIS Database (2017) and Burness et al. (1980).

#### 4.1.1.3 The rollout of the “commercial” nuclear power plants

Nonetheless, after the kick-start with turnkey contracts, the rollout of Gen II NPPs accelerated and, in one only year (from 1966 to 1967) the number of construction projects nearly tripled from five to 14 projects. Construction starts peaked in 1968 with a total of 27 NPPs or around 24 GW<sub>e</sub> (Figure 17). In 1966, GE already introduced the BWR-3 design, of which the company supplied a total of six units in the U.S.—four in Illinois alone. Quad Cities 1-2 (IL) was the first twin-reactor construction project. The construction periods of the six BWR-3 reactors lasted around 4.5 years and the reactors—all commissioned between 1970 and 1973—are still operational in 2017.

In 1967, Westinghouse supplied the first PWR W (3-loop) to the Robinson-2 station (SC, 741 MW<sub>e</sub>). Between 1967 and 1978, 14 more W (3- Loop) PWRs were constructed with an average construction time of around 7.1 years, except for Farley-2, where construction lasted nearly 11 years. In 1966, construction of the Indian Point-2 station (NY) started, for which Westinghouse supplied the first W (4-Loop) PWR. With four loops, the reactor nearly dou-

bled its capacity to 1,020 MW<sub>e</sub> and was the first reactor worldwide that reached over one GW<sub>e</sub> of capacity. Indian Point-2 (likewise still operational in 2017) started electricity production in 1973, seven years after construction started. Westinghouse supplied in total 33 W (4-Loop) PWRs, making it the most installed reactor type in the U.S. The latest grid connections were the two units of Watts Bar (TN) in 1996 and 2016—over 40 years after the construction start in 1973.<sup>61</sup>

In the late 1960s, the BWR vendor market was again dominated by the GE, after three rather unsuccessful demonstration reactors by Allis Chalmers. The PWR market—on the other hand—was in the late 1960s more diverse and, in 1967, Combustion Engineering Co. (CE) supplied its first reactor, the 805 MW<sub>e</sub> CE 2-Loop reactor, to the Palisades station. CE supplied a total of nine stations with this design. Another design was the Comb CE reactor; the reactor was first supplied to Millstone-2 (CT, 869 MW<sub>e</sub>) and St. Lucie-1 (FL, 982 MW<sub>e</sub>), commissioned in 1975/76 (still operational in 2017). St. Lucie was the last reactor to be supplied in the U.S. by the company. In 2000, Combustion Engineering (PWR) was sold to Westinghouse. Based on the Indian Point-1 reactor, Babcock and Wilcox designed its second generation of PWRs: The B&W L-Loop (“lowered Loop”) model. In 1967, construction of the Oconee NPP (SC) started and Babcock supplied three reactors—around 850 MW<sub>e</sub> each—for its three units. The three reactors started producing electricity in 1973/74 and are still operational in 2017. In 1968, B&W supplied five more L-Loop reactors: two for the units of Three Mile Island (PA, 819/880 MW<sub>e</sub>), Anco-1 (AR, 836 MW<sub>e</sub>), Crystal River-3 (FL, 860 MW<sub>e</sub>); and Rancho Seco-1 (CA, 873 MW<sub>e</sub>); and one R-Loop reactor to Davis Besse-1 (OH, 894 MW<sub>e</sub>). Rancho Seco-1 was shut down in 1989 after 14 years of operation, and Crystal River-3 in 2013, 36 years after the grid connection. Davis Besse-1 was the last reactor to be designed by B&W.

In 1967, GE introduced its fourth generation of reactors: the BWR-4 design and supplied the 1,100 MW<sub>e</sub> reactors—the first BWR-4 reactors with over 1 GW<sub>e</sub> of electrical output—for

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<sup>61</sup> See Schneider et al. (2016, 126–27) for a report on the construction of the Watts Bar plant.

Browns Ferry 1-2 (AL).<sup>62</sup> Between 1967 and 1970, GE designed twelve BWR-4 reactors with an increased mean construction time of 7.9 years. In 1972, GE supplied the first BWR-5 reactor for the Columbia station (WA), the 1,107 MW<sub>e</sub> reactor was connected to the grid—12 years later—in 1984. GE designed a total of eight BWR-5s worldwide—five of them in the U.S. In 1976, construction started at the Grand Gulf-1 station (MS), the NPP should be supplied with the first BWR-6 reactor by GE. The reactor had a net capacity of 1,419 MW<sub>e</sub> and started producing electricity in 1985. GE installed a total of eight units worldwide and four units in the U.S.

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<sup>62</sup> In 1975, the most serious accident—before TMI—took place in the Browns Ferry units, where a fire broke out, caused by an electrician, who accidentally set fire to a cable tray with a lighted candle which he was using to carry out a leakage test. The fire disabled the safety systems for the two units and both units had to be taken out for 18 months (Thomas 1988, 76).

Vendor	Construction capacity in MW <sub>e</sub> (NPP)	Construction period <sup>63</sup>	Mean construction time
<b>Westinghouse</b>	<b>53,173 (53)</b>		
PWR W (2-Loop)	3,368 (6)	1966–1974	4.6 years
PWR W (3-Loop)	11,829 (14)	1964–1987	7.1 years
PWR W (4-Loop)	37,976 (33)	1966–2016	12.2 years
<b>General Electric</b>	<b>35,245 (38)</b>		
BWR-1	327 (3)	1956–1963	3 years
BWR-2	1,232 (2)	1964–1969	4.7 years
BWR-3	4,916 (6)	1966–1972	4.5 years
BWR-4	19,402 (19)	1967–1989	7.9 years
BWR-5	4,661 (4)	1972–1987	10.9 years
BWR-6	4,707 (4)	1974–1987	10.7 years
<b>Combustion Engineering</b>	<b>14,089 (14)</b>		
CE (2-Loop)	8,625 (9)	1967–1985	8.1 years
COMB CE	5,464 (5)	1969–1988	7.9 years
<b>Babcock &amp; Wilcox</b>	<b>7,972 (10)</b>		
B&W (L-Loop)	6,821 (8)	1967–1978	6.6 years
B&W (R-Loop)	894 (1)	<b>1970–1977</b>	7 years
	<b>110,479 (115)</b>		

**Table 5: Installed large-scale NPPs in the U.S., clustered by reactor vendor**

Source: Own depiction based on IAEA PRIS Database (2017) and IAEA (2017).

With an increasing reactor capacity and hence complexity, construction time increased steadily with each new reactor design (see Table 5). The evolving regulatory demands also impacted the construction time of the plants under construction in the 1970s. But the plants did not only keep taking longer to be built, they also kept getting more expensive. The average overnight construction costs escalated from around 2,000 2010 USD/kW in the 1970s up to around 8,000 2010 USD/kW for the Shoreham plant in 1989.<sup>64</sup>

<sup>63</sup> Construction start of the first reactor and grid connection of the last reactor.

<sup>64</sup> Davis (2012, 53).

#### 4.1.1.4 The creation of the NRC and post-TMI

Thomas (1988) highlights two regulatory changes in the 1970s that influenced the future deployment of nuclear power: the 1971 Calvert Cliffs decision and the creation of the regulatory body NRC (Nuclear Regulatory Commission) three years later. The conflict opposed environmental protection to the nuclear industry: the licensing of the Calvert Cliffs station in Maryland was challenged and in 1971, a judgement was won: the AEC was no exempt from the provisions of the National Environmental Protection Act. This and the rise of a standardization debate for emergency core cooling systems resulted in a requirement that all license applicants must produce an Environmental Impact Statement, and, in 1973, the AEC finally began to actively encourage standardized plants. It was thought that this would reduce the increasing heavy licensing work. In addition, the AEC limited the possible unit size to 1,300 MWe and 3,800 MW<sub>th</sub>.

In 1974, in order to avoid regulatory capture, the promoting and regulating role of the AEC was split up and the regulatory agency NRC was created. Although, there was quite optimism concerning nuclear, due to rising oil prices (and consequently gas and coal) in the 1970s and the grid connection of a large number of reactors supplying an increasing part of the power, 1974 marked the end of nuclear ordering in the U.S, as all orders after 1974 were cancelled.<sup>65</sup> From the 197 reactors on order by 1974, less than half were ever completed, some were even cancelled after a billion of dollars had been spent on them.<sup>66</sup> The growth of the nuclear industry was thus already in decline before the unit 2 of the Three Mile Island station (TMI) in Pennsylvania suffered a partial core meltdown on March 28<sup>th</sup>, 1978.<sup>67</sup> Figure 17 shows the number of reactor start-ups and construction starts in the U.S.

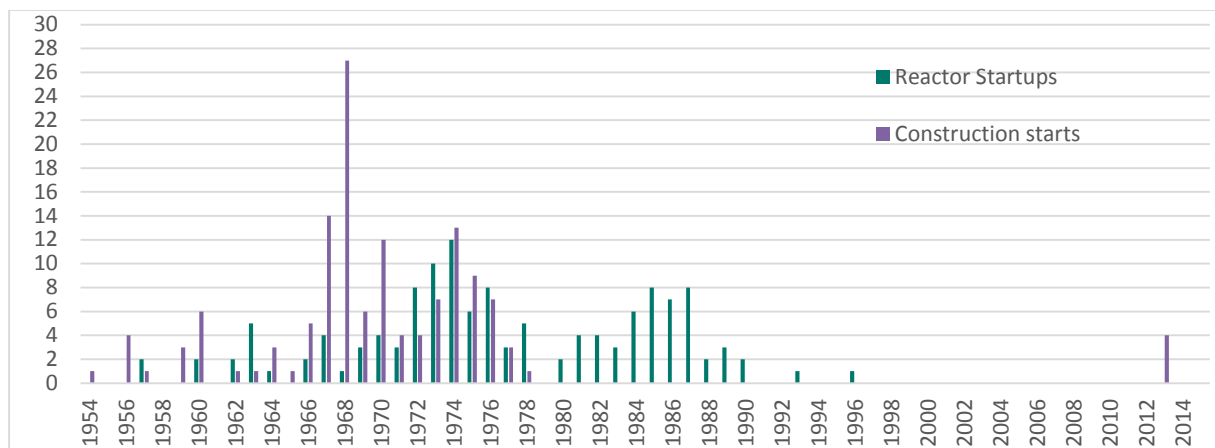
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<sup>65</sup> Thomas (1988, 74–75).

<sup>66</sup> Davis (2012, 50) and Bradford (2013, 13).

<sup>67</sup> See Walker (2005) for a detailed account of the nuclear accident at Three Mile Island-1.





**Figure 17: Number of reactor start-ups and construction starts in the U.S., 1954–2016.**

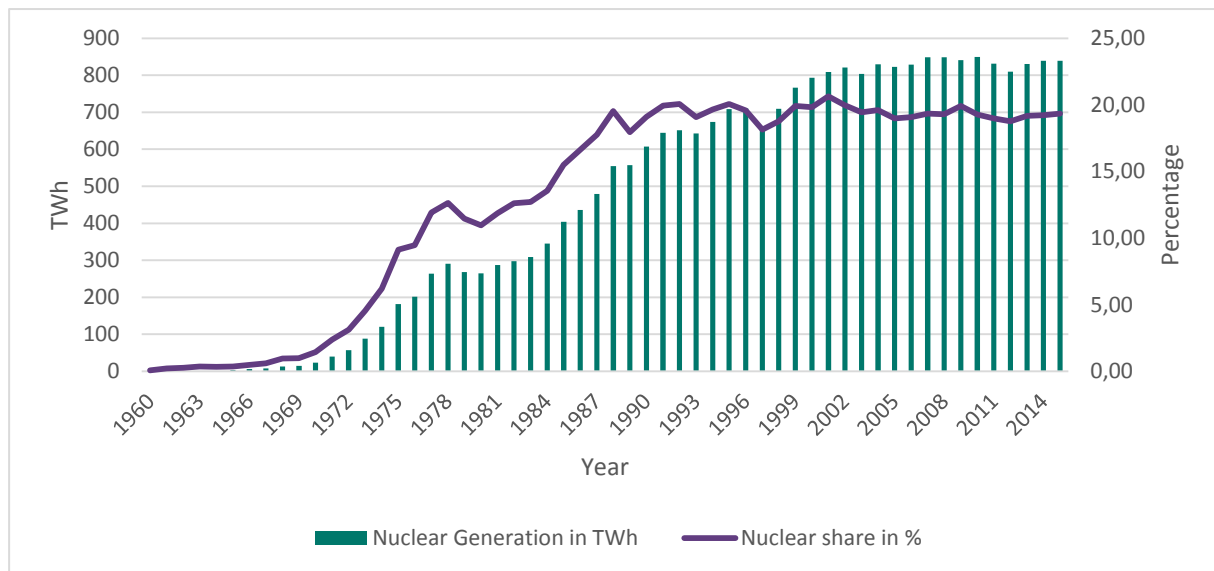
Source: Own depiction based on IAEA PRIS Database (2017).

It is evident that, after the rollout of the 1960s resp. early-1970s the number of construction starts declined significantly since 1974, to none in 1979. Thus, after TMI, no new construction projects were started until 2013. Accordingly, Hultman and Koomey (2013) argue that—considering the broader economic landscape—the accident was not the main cause for the decline of the nuclear industry. They highlight five broad categories that were drivers for the decline of US nuclear power: (1) declining growth in electricity demand, (2) high interest rates and construction costs, (3) the rise of nonutility generators, (4) structural problems in the nuclear industry, and (5) changing perceptions of the nuclear industry and its safety.<sup>68</sup>

Only in 2013, 35 years after the last construction start, orders for new nuclear power plants were placed at Westinghouse. Construction works began at four units in total: V.C. Summer (SC) and Vogtle (GA). For the first time, Gen III/III<sup>+</sup> reactors started construction. For both sites the AP1000 PWR was ordered—once again in a cost-of-service regulatory environment. The V.C. Summer project was cancelled in 2017—with a completion rate of 33.7% at that time—after Westinghouse filed for Chapter 11 bankruptcy protection in the U.S. According to the WNISR 2017, the construction costs of the two Vogtle AP1000 reactors have escalated from initially 14 billion USD (~6,200 USD/kW) in 2013 to estimated 29 billion USD in 2017

<sup>68</sup> Hultman and Koomey (2013, 66–68).

(~9,400 USD/kW). The construction at Vogtle (Georgia) was only 36% complete in 2016 and the latest estimate for commissioning of the two reactors is 2023, although this remains very speculative and the risk of further delays is likely.<sup>69</sup> Today, the U.S. has with 99 operational reactors the largest nuclear fleet and nuclear production in the world. Figure 18 shows the nuclear generation and the nuclear share in the electricity mix from 1960 until 2016.



**Figure 18: Nuclear share and nuclear generation in the U.S., 1965–2015**

Source: Own depiction based on World Bank (2016)<sup>70</sup> and BP (2017).

#### 4.1.1.5 Summary

The development of nuclear technologies differs in the U.S. in contrast to the other early adapters, as the GCR technology for dual purposes was never developed due to the availability of large-scale plutonium production facilities. Although there were no scope economies, one of the major reasons of the industrialization of the LWR was the already strong involvement of GE and Westinghouse in the military industry, e.g., the development of nuclear submarine propulsion technology. Since the first sustainable chain reaction by Fermi in 1942

<sup>69</sup> Schneider et al. (2017, 92–95).

<sup>70</sup> World Bank. 2016. “Electricity production from nuclear sources (% of total).” April, 24, 2018. <https://data.worldbank.org/indicator/EG.ELC.NUCL.ZS>

at the University of Chicago, a total of 138 NPPs have been built. 95% of these reactors are LWRs, with overall 62% PWRs and 33% BWRs. After TMI (1977), only four power plants started construction, while two of them were abandoned in 2017 after Westinghouse filed for bankruptcy protection in the U.S. Until today, not a single plant was constructed under competitive, market-based conditions. Table 6 summarizes the nuclear deployment in the U.S.

<b>First construction start (grid connection)</b>	1954: Shippingport (1957)
<b>Latest construction start:</b>	2013: Vogtle-4
<b>Latest grid connection:</b>	2016: Watts Bar-2 (constr. started in 1973)
<b>Operational capacity (NPP):</b>	99.87 GW <sub>e</sub> (99)
<b>Shut down capacity (NPP):</b>	14.437 GW <sub>e</sub> (34) <sup>71</sup>
<b>Construction capacity (NPP):</b>	2.23 GW <sub>e</sub> (Vogtle, 2 Westinghouse AP1000)
<b>Installed technologies (NPP):</b>	PWR (86), BWR (45), FBR (1), HTGR (2), PHWR (1), Other (3)
<b>Most installed reactor design (NPP):</b>	PWR W (4-Loop) by Westinghouse (33)

**Table 6: Summary for the U.S.**

Source: Own depiction.

#### 4.1.2 United Kingdom

As the other nuclear pioneers, the United Kingdom developed its nuclear program mainly to secure access to the atomic bomb. As the U.K. did not have access to enriched uranium, plutonium production from natural uranium was the inherent choice.

##### 4.1.2.1 Single-purpose reactors

After WW2, British participants in the Manhattan Project came back home, and reproduced partially what they did in the U.S. After a first experimental air-cooled graphite-moderated reactor called GLEEP in 1947, and a bigger reactor of 6 MW<sub>th</sub> in 1948 called BEPO—a fore-runner of the Windscale Piles—the U.K. was ready to start its first larger plutonium production units. The Windscale site on the coast of the Irish Sea in Cumbria—now better known as the nuclear complex Sellafield—became the first plutonium production centre in the U.K.

<sup>71</sup> Not including GE EVESR in California.

with the two reactors Pile 1 and Pile 2. These reactors were air-cooled graphite-moderated reactors with the single purpose of producing plutonium for nuclear weapons. Each reactor was cooled by blowing air through the fuel channels in the graphite core and discharging it directly back to the atmosphere through a stack.<sup>72</sup> The construction of Pile 1 started in 1947 and the unit was completed in 1950, Pile 2 became operational one year later. The uranium fuel was put in the reactor as a metal and was fabricated at Springfields, a former munitions factory converted into a uranium fuel factory in 1946. The factory used natural uranium from Canada and the colonial Belgian Congo.<sup>73</sup> The first successful atomic bomb test was executed on October 3<sup>rd</sup>, 1952, in Australia. However, the Windscale Piles were not able to satisfy U.K.'s increasing plutonium demand and additional reactors—slightly different from Pile 1 and Pile 2—were built close to the Windscale site: the Calder Hall station. In addition, in 1953, the enrichment plant (gaseous diffusion), BNFL Capenhurst, started operations.<sup>74</sup>

#### 4.1.2.2 Dual-purpose reactors

The construction of unit 1 and 2 of Calder Hall (two times 49 MW<sub>e</sub>) started in 1953 and by 1956/1957 the two units were connected to the grid. The fuel elements consisted of Magnox-encased fuel rods that were loaded into vertical channels in a large core constructed of graphite blocks; graphite was still used as a moderator and CO<sub>2</sub> to cool the reactor. The choice of CO<sub>2</sub> as coolant was driven by safety reason: air contains oxygen which under certain aspects reacts with graphite, which can lead to an ignition.<sup>75</sup> This was one of the reasons for the Windscale Pile 1 fire in 1957, where one or more of the aluminium-clad uranium metal slugs in the core caught fire. The fresh air accelerated the fire, resulting in the Windscale fire, until now the worst nuclear accident to happen in the U.K. Calder Hall was the first Magnox reactor that could work with online refuelling and U-238 in metal form. The NPP was designed for a dual-purpose: plutonium production and electricity generation.

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<sup>72</sup> Patterson (1986, 43–44).

<sup>73</sup> Berkemeier et al. (2014, 7).

<sup>74</sup> Makhijani et al. (2004, 20).

<sup>75</sup> Neutron bombardment in a graphite reactor eventually displaces carbon atoms in the crystal structure, which store energy that can be suddenly released in a surge of heat (W. C. Patterson 1986, 44).

From 1946 until 1954, government responsibility for nuclear activities was in the hands of the Ministry of Supply and in July 1954 the United Kingdom Atomic Energy Authority (UKAEA) came into service. The responsibility of the UKAEA was primarily the design, production, and testing of nuclear weapons but also drawing up plans for Britain's first nuclear power stations, which resulted in the White Paper "*A Program of Nuclear Power*" published in 1955.<sup>76</sup> The White Paper proposed 1,500-2,000 MW<sub>e</sub> of additional nuclear capacity based on the Calder Hall Magnox reactor technology to be ordered by 1965.

In 1955, construction of another six Magnox NPPs was started: Units 3 and 4 of Calder Hall, as well as the four units at Chapelcross (4 times 49 MW<sub>e</sub>). In 1957, construction of twin-units for electricity generation at each of the following stations were launched: Berkeley, Bradwell, and Hunterston A. The six reactors had a capacity between 123 and 150 MW<sub>e</sub> and were connected to the grid by 1964. The two units at Hinkley Point A—commissioned in 1964—nearly doubled their capacity to 235 MW<sub>e</sub>.

The low-power density within the core of around one MW/m<sup>3</sup> resulted in very large graphite reactor cores—a typical Magnox reactor can contain about 3,000 tons of graphite—and massive concrete shielding to yield typical outputs of only about 200-600 MW<sub>e</sub>.<sup>77</sup> UKAEA chose four different consortia as contractors for these four sites. Even if the UKAEA provided reactor design information, each consortium came up with its own design, differing significantly from that of its competitors.

In the same year (1964), the British government announced its revised and expanded nuclear program: instead of 2,000 MW<sub>e</sub> by 1965, the new goal was set to 6,000 MW<sub>e</sub> to be operational by 1965.<sup>78</sup> The last ten Magnox reactors started construction between 1960 and 1963 and were built by five different consortia. The reactors at Trawsfynydd, Dungeness A, Oldbury A, and Sizewell A all had a capacity between 195–225 MW<sub>e</sub> each. The last two Magnox reactors were installed at Wylfa and had a capacity of 490 MW<sub>e</sub>. Wylfa-1 was the latest

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<sup>76</sup> Patterson (1985, 4-6).

<sup>77</sup> Laraia (2012, 608).

<sup>78</sup> Patterson (1985, 4-6).

Magnox reactor to be shut down in the U.K. after 45 years of operation in 2015 and was worldwide the last Gen I reactor in operations until then. With around 4,300 MW<sub>e</sub> of Magnox capacities, the 6,000 MW<sub>e</sub> capacity envisioned by the British government was not achieved. Table 7 gives an overview over the Magnox reactors installed in the U.K. between 1953 and 1971, the installed capacity, as well as the mean construction time, which increased with the larger reactor designs.

Station	Capacity in MW <sub>e</sub> (NPP)	Construction time <sup>79</sup>	Permanent Shutdown <sup>80</sup>	Mean construction time
Calder Hall	196 (4)	1953–1959	2003	3.2 years
Chapelcross	192 (4)	1955–1959	2004	3.9
Berkeley	276 (2)	1957–1962	1989	5.5 years
Bradwell	246 (2)	1957–1962	2002	5.5 years
Hunterston A	300 (2)	1957–1964	1990	6.5
Hinkley Point A	470 (2)	1957–1965	2000	7.3
Trawsfynydd	390 (2)	1959–1965	1991	5.6
Dungeness A	450 (2)	1960–1965	2006	5.3
Sizewell A	420 (2)	1961–1966	2006	4.9
Oldbury	434 (2)	1962–1968	2012	5.7
Wylfa	980 (2)	1963–1971	2015	7.7
	<b>4,354 (26)</b>			

**Table 7: The Magnox reactors**

Source: Own depiction based on IAEA PRIS Database (2017).

#### 4.1.2.3 Follow-on: The AGR and Sizewell-B focus on electricity

In 1958, the first AGR reactor started construction, again at the Windscale site: the Windscale AGR. The development of the AGRs was pushed in the U.K. to increase the power density from one up to around two MW<sub>e</sub>/m<sup>3</sup>. The design of the AGR was based on the Magnox reactor, but the steam generators and gas circulators were placed within the combined concrete pressure vessel. This design change enabled higher temperatures, thus achieving higher thermal efficiencies, and higher power densities to reduce capital costs. This entailed an

<sup>79</sup> Construction start of the first reactor and grid connection of the last reactor.

<sup>80</sup> Shutdown of the last unit.

increase in cooling gas pressure and a change from Magnox to stainless steel cladding and from uranium metal to uranium dioxide fuel, which in turn led to an increase in the proportion of U-235 in the fuel.<sup>81</sup> The Windscale AGR was commissioned in 1963 and was operational until 1981. In 1963 too, construction of the only HWR was launched: Winfrith SGHWR. The plant became critical in 1967 and was shut down in 1990. The HWR technology was supposed to be an alternative to the GCRs, but the technology was not successful. In 1963, construction of the second FBR was launched: the Dounreay PFR which was in operations from 1975 until 1994.

Based on the first prototype AGR, the two first larger AGRs with a net capacity of 520 MW<sub>e</sub> were installed at Dungeness B. Windscale AGR was constructed within five years, but construction time for the first commercial AGRs for Dungeness B reactors increased by a great deal this time: 17.5 years for unit 1 and even 20.3 years for unit 2—the project was at the time of commissioning 13 years behind schedule and four times the initial cost estimates.<sup>82</sup>

Dungeness B-2 was the first larger AGR to be built, but also the latest to be connected to the grid in 1989. In the late 1960s and 1970s, construction of eight more AGRs (475–575 MW<sub>e</sub>) was started: two units each at Hinkley Point B, Hunterston B, Hartlepool A, and Heysham A. For Hinkley Point B and Hunterston B construction time lasted between eight and ten years and the reactors were commissioned in 1976/77. For the reactors at Hartlepool A and Heysham A, construction time lasted between 13 and 16 years. Ten years after the last construction start, the construction of the last four AGRs was started in 1980. Two units in Torness and two units in Heysham B, with a net capacity of around 680 MW<sub>e</sub>.

Of the 15 AGRs in total, all reactors are still operational except for the Windscale AGR prototype, which was shut down in 1981. The design life of the AGR was 25 years, but they are now expected to run for 40 years, although another lifetime extension beyond that may not be possible because of erosion and distortion problems of the graphite moderator blocks.<sup>83</sup>

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<sup>81</sup> IEE (2005).

<sup>82</sup> BBC. 2010. "A history of Dungeness nuclear power station." January 29, 2018. [http://news.bbc.co.uk/local/kent/hi/people\\_and\\_places/nature/newsid\\_8478000/8478420.stm](http://news.bbc.co.uk/local/kent/hi/people_and_places/nature/newsid_8478000/8478420.stm).

<sup>83</sup> Thomas (2010a, 26).

Table 8 gives an overview over the AGRs installed in the U.K. between 1958 and 1989, the installed capacity, as well as the mean construction time.

Station	Capacity in $MW_e$ (NPP)	Construction time <sup>84</sup>	Permanent Shutdown <sup>85</sup>	Mean construction time
Windscale AGR	24 (1)	1958–1963	1981	4.3 years
Dungeness B	1,040 (2)	1965–1985	2028 (exp.)	18.9 years
Hinkley Point B	945 (2)	1967–1976	2023 (exp.)	8.8 years
Hunterston B	960 (2)	1967–1977	2023 (exp.)	8.9 years
Hartlepool A	1,180 (2)	1968–1984	2024 (exp.)	15.5 years
Heysham A	1,155 (2)	1970–1984	2024 (exp.)	13.2 years
Heysham B	1,220 (2)	1980–1988	2030 (exp.)	8.1 years
Torness	1,185 (2)	1980–1989	2030 (exp.)	8.2 years
	<b>7,709 (15)</b>			

**Table 8: The advanced gas cooled reactors**

Source: Own depiction based on IAEA PRIS Database (2017) and World Nuclear Association (2017)<sup>86</sup>.

In 1988, construction of the only PWR in the U.K. began at the Sizewell-B station (1,198  $MW_e$ ), the reactor was commissioned seven years later, in 1995. Sizewell-B is a Westinghouse PWR (4-Loop) based on the Westinghouse/Bechtel SNUPPS concept. The reference plant is the Callaway plant in the U.S., but experience derived from the French NPP program has been taken into account, too. The reactor vessel was made by Framatome, instrumentation and control systems were largely delivered by Westinghouse, and the turbine generators were supplied by GEC Alsthom.<sup>87</sup>

#### 4.1.2.4 Current and future nuclear deployment

In 2013, EDF Energy and the U.K. government signed an agreement for two EPRs (3,200  $MW_e$ ) for the Hinkley Point site. The cost estimates have since then steadily risen and the

<sup>84</sup> Construction start of the first reactor and grid connection of the last reactor.

<sup>85</sup> Shutdown of the last unit.

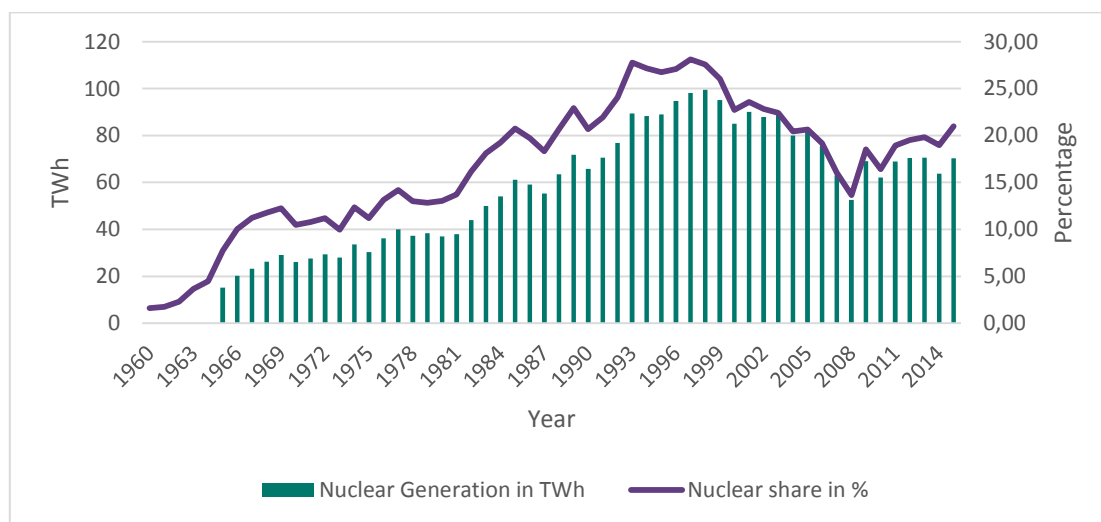
<sup>86</sup> World Nuclear Association. 2016. "Nuclear Power in the United Kingdom." April 23, 2018. <http://www.world-nuclear.org/information-library/country-profiles/countries-t-z/united-kingdom.aspx>.

<sup>87</sup> Meyer and Stokke (1997, 1–3).



overnight construction costs were estimated at 23.2 billion USD (7,250 USD/kW) in 2017; EDF maintains the official construction start target date as “mid-2019” with commissioning of the first unit at the end of 2025.<sup>88</sup> The construction of the two EPRs for Hinkley Point is carried out by China Guangdong Nuclear (CGN), although CGN has not yet successfully commissioned its two EPRs (Taishan site) under construction at home (See the case study on China). The Hinkley Point-C project is backed by low interest government loans from the China Development Bank to CGN.<sup>89</sup> More NPPs are planned at the sites Suffolk, Bradwell, and Sizewell, all part of the strategic investment agreement with CGN.

In 2017, the U.K. is still in the TOP10 of nuclear energy producers in the world and operates 15 NPPs representing a nuclear share of around 20%. Nuclear generation peaked in the late 1990s with around 100 TWh. Figure 18 shows the nuclear generation and the nuclear share in the electricity mix from 1960 until 2016.



**Figure 19: Nuclear share and nuclear generation in the U.K., 1965–2015**

Source: Own depiction based on World Bank (2016) and BP (2017).

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<sup>88</sup> Schneider et al. (2017, 73).

<sup>89</sup> Thomas (2017, 685).

#### 4.1.2.5 Summary

The deployment of nuclear power in the U.K. has been massively influenced by the economies of scope approach. Although, the later Magnox reactors and AGRs had been constructed as single-purpose reactors, the U.K. has stuck to the GCR technology. Only one PWR has been constructed so far, but more PWRs are planned to be constructed in the following years. Although, the future reactors will not be constructed by the U.K. government but (probably) by China. If these plans will be conceptualized remains to be seen. Table 9 summarizes the nuclear deployment in the U.K.

<b>First construction start: (grid connection)</b>	1953: Calder Hall (1956)
<b>Latest construction start (grid connection):</b>	1988: Sizewell-B (1995)
<b>Operational capacity (NPP):</b>	8.88 GW <sub>e</sub> (15)
<b>Shut down capacity (NPP):</b>	4.72 GW <sub>e</sub> (30)
<b>Construction capacity (NPP):</b>	-
<b>Installed technologies (NPP):</b>	GCR (41), FBR (2), PWR (1), SGHWR (1)
<b>Most installed reactor design (NPP):</b>	GCR Magnox (26)

**Table 9: Summary for the U.K.**

Source: Own depiction.

#### 4.1.3 Soviet Union and Russia

The history of nuclear power in the Soviet Union is a very peculiar combination of imitation and indigenous development, that proceeded surprisingly rapidly but also faced substantial technical and organizational challenges since the very beginnings. The start can be traced to 1943, when a nuclear laboratory (known as laboratory number two) was set up by Igor Kurchatov in Moscow and after the droppings of atomic bombs by the U.S. the USSR now moved ahead as fast as possible to set up a nuclear industry.<sup>90</sup> The first Soviet reactor was the graphite piles F-1, an experimental reactor mainly used to study the fission process and the production of plutonium, constructed on the outskirts of Moscow. The gained basic knowledge should allow the Soviet Union to then move on to the design of nuclear bombs,

<sup>90</sup> Yemelyanov and Holloway (1987).

plutonium production, and power-generating reactors. F-1 (commissioned in 1946, shut down in 2016) was the first European reactor, the design being similar to the Chicago Pile built by Fermi in the U.S.: graphite bricks as moderator and natural uranium as fuel. In comparison to the U.S., the time required to connect the reactor to the grid was a few months shorter; the reactor produced 4,000 W, whereas the American counterpart produced 800 W.<sup>91</sup>

This successful first step paved the way towards the atomic bomb. In 1948, two years after the commissioning of F-1, a plutonium enrichment facility opened in Chelyabinsk, Siberia. The first nuclear reactor of the site (reactor A) was based on the F-1 design. Only one year later, the reprocessing plant was operational; with the installation of a gaseous diffusion plant at Novouralsk enrichment of uranium began, too. In the same year, on August 29<sup>th</sup>, 1949, the first Soviet bomb exploded, only three years after commissioning F-1. The speed with which the USSR acquired the bomb astonished the world, until then the West assumed the Soviets would need no less than ten to twenty years to create a bomb.<sup>92</sup>

#### **4.1.3.1 The RBMK: From the “flagman of Soviet Atomic Energetics” to Chernobyl**

After the successful commissioning of F-1, scientists decided to create a nuclear reactor for electricity production and civilian nuclear power engineering began in Obninsk, a former military establishment 100 kilometres southwest of Moscow. AM-1 was a 5 MW<sub>e</sub> (30 MW<sub>th</sub>) channel-graphite reactor moderated with light water and fuelled by five percent enriched uranium. Construction began in 1951 and was completed in 1954. The LWGR design was the base for the first larger reactor, the AMB-100—the first Soviet “demonstration reactor”—for the Beloyarsk station, where construction started in mid-1958. Unit 1 went critical in 1963 and the installed capacity (286 MW<sub>th</sub>, 102 MW<sub>e</sub>) is comparable to the first US demonstration plant Shippingport. Unit 2 (AMB-200)—which went critical in 1967—nearly doubled its capacity (530 MW<sub>th</sub>). The reactor was designed without a containment vessel; instead it sat in an ordinary, massive concrete box with walls only 100 to 150 millimetres thick. The peculiar

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<sup>91</sup> Josephson (2005, 17).

<sup>92</sup> Yemelyanov and Holloway (1987).

“housing” construction was chosen to avoid the problems associated with manufacturing heavy steel for reactor pressure vessels.<sup>93</sup> In 1958, construction of Bohunice A1 started in Slovakia—the only HWGCR (560 MW<sub>th</sub>). In 1969, construction of the first FBR (BN-600, 1,470 MW<sub>th</sub>) was launched—Beloyarsk went online in 1981 and was still operational in 2017.<sup>94</sup> BN-600 is the largest remaining LMFBR (liquid metal FBR) in the world and has operated more successfully than any other reactor in Russia.<sup>95</sup>

In 1970, construction of the first RBMK-1000 reactors began, based on the design of the AMB reactor developed for military plutonium production. The first two reactors were built 70 kilometres west of St. Petersburg, on the shore of the Bay of Finland (at that point in time called Leningrad, which was also the name of the reactor). Leningrad-1 started operations in 1974 and unit 2 in 1976 (two times 3,200 MW<sub>th</sub> and 925 MW<sub>e</sub>), both plants are still operational in 2017. Units 3 and 4 were connected to the grid in 1980 and 1981. The reactor was a single-loop reactor, light water was used as a coolant, the core was filled with 180 tons of 1.8 percent enriched uranium, the condensers were operated with seawater from the Gulf of Finland and each reactor was equipped with two 500 MW<sub>e</sub> turbines.

As the first RBMK went online, its promoters called the Leningrad station the “flagman of Soviet atomic energetics” and advanced the notion to build 1,500 and 2,000 MW<sub>e</sub> RBMKs. However, subsequently only the RBMK-1500 was designed: the temperature of the moderator and graphite was raised, which led to an increased steam content and forced the thermal capacity to 4,800 MW<sub>th</sub> (1,185 MW<sub>e</sub>). Two RBMK-1500s were installed in Lithuania at the Ignalina station, Ignalina was considered the “queen of reactors” by the Soviet. The two RBMK-1500 reactors were shut down in 2004 and 2009 as a requirement for Lithuania to join the European Union. As it was the case for all RBMKs, the reactor was housed in a concrete vault and not a containment structure.<sup>96</sup>

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<sup>93</sup> Josephson (2005, 30).

<sup>94</sup> A second FBR (BN-800) went online in 2015. In 1964, construction of the BN-350 was started in Kazakhstan, the reactor went online in 1973 and shut down in 1999.

<sup>95</sup> Murray and Holbert (2015, 464).

<sup>96</sup> Josephson (2005, 33–34).

Of the 17 installed RBMK reactors, only six reactors have been shut down: Chernobyl 1-4 and the two Ignalina units in Lithuania. The remaining eleven RBMKs are all still operational in Russia: 4 at Leningrad, 4 at Kursk, and 3 at Smolensk. The oldest RBMK running in 2017 was Leningrad-1—now operating for 43 years.

#### 4.1.3.2 The VVER: The Soviet Union's PWR

In parallel to the development of nuclear technology for electricity generation, the Russian Soviet Republic was also interested in nuclear submarines and icebreakers that would open the way to the arctic. Several designs were proposed, like a gas-cooled reactor (too expensive), a heavy water reactor (too dangerous), as well as a PWR. So, in 1955, the technical design for the first PWR was adopted and the first icebreaker (Lenin) started operations a few years later, fuelled by five percent enriched uranium. As it was the case in the U.S., the PWR design served as the base for the Soviet branch of PWR technology called VVER (Vododnyanoi Energetichesky Reaktor: Water-Water Power Reactor).

In 1957, construction of the first VVER started: Novovoronezh-1, located forty kilometres from Voronezh, an industrial city with one million inhabitants in south-western Russia. The station was supplied with two V-120 reactors (197 MW<sub>e</sub>, unit 1 started operations in 1964, unit 2 1969, both are shut down). Units 3 and 4, two V-179 reactors (1,375 MW<sub>th</sub>, 385 MW<sub>e</sub>), went online in 1971/72. The construction of the first V-230 was started in East Germany and Bulgaria, even before construction of the first Russian units (Kola-1 and Kola-2) started. These reactors are all considered to be of the “first generation” of Russian VVER technology (V179, V-230, and V-270 were all part of the VVER-440 class). The second generation of VVER PWRs, was also in the VVER-440 class: V-213, V-311, and V-318 and installed within the Soviet Union in Armenia, Ukraine, Slovakia, and the Czech Republic; as well as in the Eastern Allies countries: East Germany, Bulgaria, and Hungary. Overall these two generations can be considered as Gen II reactors.

The first reactor of the VVER-1000 class, breaking the 1,000 MW<sub>e</sub> threshold was Novovoronezh-5 (V-187), which started operations in 1981. Significant improvements, including a containment structure, were incorporated into the VVER-1000 design. The most installed VVER-1000, is the PWR V-320, installed nine times in Russia; with the latest grid connection

being Kalinin-4 in August of 1986. The reactor had a thermal capacity of 3,200 MW<sub>th</sub> and a net capacity of 950 MW<sub>e</sub>. In the Ukraine alone, a total of 15 VVER-1000s were constructed between 1976 and 1986, as well as two units in the Czech Republic and two in Bulgaria.

Halverson (1993) refers to the “East bloc reactors” as ticking time bombs, especially the V-230 he argues, is “probably the most dangerous nuclear threat in Europe.” Although, the V-213 would be “somewhat safer”, the design still lacks a containment structure, except for the two V-213s in Finland (Loviisa-1 and 2), which have been completely modified from design to completion, including a containment.<sup>97</sup> Of the 14 totally installed V-230 reactors, including Novovoronezh 3 and 4, only Novovoronezh-4 and the two Kola units are still in operation. Of the “slightly safer” V-213, a total of 21 plants were commissioned, of which only Greifswald-5 was shut down after the reunification of Germany. The oldest V-213 running, except the Finnish Loviisa-1, is the Rovno-1 reactor in the Ukraine, now operating 40 years (in 2017). Thus, while the EU paid Bulgaria, Slovakia, and Germany to shut down its V-230 and V-213 reactors, Russia will even prolong the lifetimes of this reactors up to 25 years.<sup>98</sup>

#### 4.1.3.3 Nuclear power in Russia today

Nuclear power plays an increasing role in Russia today, and has also become a strain on the macroeconomic stability of the country. Both the nuclear weaponry arsenal and nuclear power plants are currently undergoing long-term development programs, in an effort to keep Russia among the nuclear superpowers.

With respect to electricity, Russia has produced the highest amount of nuclear generation in 2016: 184 TWh, even expected to grow through the next years. In 2015, the first grid connection since the collapse of the Soviet Union occurred: the FBR Beloyarsk-4 (2,100 MW<sub>th</sub>, 789 MW<sub>e</sub>). In 2017, a total of seven reactors were under construction (See Table 10). In 2008/9, construction of the last two VVER-1000 reactors—units 3 and 4 of Rostov—started; unit 3 started operation in 2015. In 2016, the first Gen III<sup>+</sup> (Novovoronezh 2-1, VVER V-392M)

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<sup>97</sup> Halverson (1993, 43).

<sup>98</sup> Mohr et al. (2014, 31).

reactor to start operation worldwide was connected to the grid. There are four more Gen III<sup>+</sup> reactors—all VVER-1200 NPPs—under construction: Leningrad 2 (two VVER V-491), Baltic-1 (VVER V-491), and Novovoronezh 2-2 (VVER V-392M); the reactors all have a thermal capacity of 3,200 MW<sub>th</sub>. However, already one year after the construction start of Baltic-1 in Kaliningrad, the project was suspended; one of the reasons was the recognition of the limited market for electricity and in 2017; there are no indications that construction restarted.<sup>99</sup> In addition, Russia has two floating NPPs under construction: Akademik Lomonosov 1 and 2 (two times 32 MW<sub>e</sub>). Table 10 contains the operational as well as stations under construction in 2017.

According to the WNISR 2017, a 2015 report by Russia’s Audit Chamber highlighted concerns about the financial situation of Rosenergoatom’s construction program. The deteriorating state budget as well as the lower electricity prices forced the company to take out further loans to enable the current construction projects; in 2016, 68 percent of the reserves were used to cover interest costs. A 2016 government decree called for the construction of an additional eleven reactors including seven new VVER-TOI units, one VVER-600 and two new FBRs.<sup>100</sup> The implications of this expansion program on the federal budget of Russia are unclear; this also holds for the very expensive “nuclear diplomacy”, consisting of giving away Russian nuclear technology to recipient countries practically for free.

Station	Type	Design	Operational CAP in MW <sub>e</sub> (NPP)	CAP in MW <sub>e</sub> under constr. (NPP)	Construction time
Leningrad-1	LWGR	RBMK-1000	3,700 (4)		1970–1981
Leningrad-2	PWR	VVER V-491		2,170 (2)	Since 2008/2010
Kursk	LWGR	RBMK-1000	3,700 (4)		1972–1985
Smolensk	LWGR	RBMK-1000	2,775 (3)		1975–1990
Balakovo	PWR	VVER V-320	3,800 (4)		1980–1993
Beloyarsk-3 and -4	FBR	BN-600/800	1,349 (2)		1969–1980/2006–2015
Bilibino	LWGR	EGP-6	44 (4)		1970–1977

<sup>99</sup> Schneider et al. (2017, 234)

<sup>100</sup> At the following sites: Kursk, Kola, Smolensk, Nizhny Novgorod, Kostrom, and Tatar.

Station	Type	Design	Operational CAP in MW <sub>e</sub> (NPP)	CAP in MW <sub>e</sub> under con- str. (NPP)	Construction time
Kalinin	PWR	VVER V-338 (2) and V- 320 (2)	3,800 (4)		1977–2011
Kola	PWR	VVER V-230 (2) and V- 213(2)	1,644 (4)		1970–1984
Novovoronezh- 1	PWR	VVER V-179 (1) and V- 187(1)	1,335 (2)		1967–1981
Novovoronezh- 2-1	PWR	VVER V- 392M	1,114 (1)		2008–2017
Novovoronezh- 2-2	PWR	VVER V- 392M		1,114 (1)	Since 2009
Rostov-1 and-2	PWR	VVER V-320	1,900 (2)		1981–2010
Rostov-3	PWR	VVER V-320	1,011 (1)		
Rostov-4	PWR	VVER V-320		1,011 (1)	Since 2010
Baltic-1	PWR	VVER V-491		1,109 (1)	Since 2012
Akademik Lomonosov	PWR	KLT-40S 'Floating'		64 (2)	Since 2007
			<b>26,172 (35)</b>	<b>5,468 (7)</b>	

**Table 10: Operational and stations under construction in Russia in 2017**

Source: Own depiction based on IAEA PRIS Database (2017).

#### 4.1.3.4 Former Soviet Union and Eastern Allies

Already in 1955, one year after the commissioning of AM-1, the Soviet Union, fearful that the U.S. wanted to perceive economic and industrial advantages of its East European Allies, signed agreements to provide nuclear power to Czechoslovakia, Poland, and East Germany.<sup>101</sup> Finally, Soviet-style reactors were exported to these three countries, as well as Hungary, Bulgaria and within the Soviet Union to Lithuania, Armenia, Ukraine, and Kazakhstan. Among the earliest recipients of Soviet nuclear expertise were Bulgaria, China, Czechoslo-

<sup>101</sup> Halverson (1993). In the 1980s, Poland had four Soviet VVER-440 reactors under construction, but the project was cancelled in 1990.



vakia, East Germany, Hungary, Poland, and Romania.<sup>102</sup> All these NPPs were “turnkey plants “with no transfer of large-scale technological know-how.

#### 4.1.3.5 Overview post 1986

Just as in the United States after TMI, construction starts have been substantially reduced before the big Chernobyl accident, in April 1986. In Russia, no new construction started for two decades.<sup>103</sup> Outside Russia, construction projects were also largely halted after 1988, and only re-started at a very low level in 2006.

#### 4.1.3.6 Summary

The USSR advanced nuclear power fast after the successful grid connection of APS-1 in Obninsk and developed in the 1970s a large-scale LWGR based on a design developed for military plutonium production: the RBMK, of which eleven reactors are still operational in Russia. In addition, five VVER V-440 reactors without a containment structure are still online. The Russian nuclear fleet consists for the major part of the Russian PWR of the VVER-1000 class with a full containment structure, with the most widely installed reactor design being the V-320. Table 11 summarizes the nuclear deployment in the Soviet Union and in Russia.

<b>First construction start (grid connection):</b>	1951: APS-1 Obninsk (1954)
<b>Latest construction start (grid connection):</b>	2012: Baltic-1 (VVER V-491, suspended)
<b>Latest grid connection:</b>	2016: Novovoronezh 2-1 (VVER V-392M)
<b>Operational capacity (NPP):</b>	26.17 GW <sub>e</sub> (35)
<b>Shut down capacity (NPP):</b>	1.17 GW <sub>e</sub> (6)
<b>Construction capacity (NPP):</b>	5.47 GW <sub>e</sub> (7)
<b>Installed technologies (or under constr.) (NPP):</b>	LWGR (18), PWR(28), FBR (2)
<b>Most installed reactor design (NPP):</b>	VVER V-320 (10)

**Table 11: Summary for Russia**

Source: Own depiction.

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<sup>102</sup> Jonas (1959, 379).

<sup>103</sup> With one exception, the Kalinin-4, where construction work started in November 1986.

#### 4.1.4 France

France is a very typical country where the search for nuclear military power has opened up the way to dual-use technologies, from the 1940s until today and going forward. The main objective after WW2 was to join the other nuclear powers, and to develop an indigenous, independent nuclear industry. In 1945, the government agency Commissariat à l'Énergie Atomique (CEA) was created, the key player in the early development of nuclear power. After gathering a growing team of enthusiastic scientists, digging up a few tons of French and Moroccan uranium concentrates, and reviving the Norwegian heavy water import connection disconnected in 1940, the CEA commissioned a small experimental reactor, ZOE, in 1948.<sup>104</sup> Based on this prototype and as France did not have access to enriched uranium, the next reactors would be fuelled by natural uranium, cooled by CO<sub>2</sub> and moderated by both, graphite and heavy water.

##### 4.1.4.1 Natural uranium, graphite, and heavy water

In 1951, the UNGG (Uranium Naturel Graphite Gaz) technology was developed and the construction—which initiated cooperation between government agency CEA and the state-owned Electricité de France (EDF)—of the first nuclear power plants at the Marcoule site started: the three graphite-moderated and CO<sub>2</sub> cooled G1, G2, and G3 reactors. G1 went online from 1956 until 1967 and fed a 5 MW<sub>e</sub> turbine generator with steam and produced weapons-grade plutonium, allowing France to acquire the nuclear bomb. Consequently, the first French nuclear weapons test took place four years later, in 1960, in the Saharan desert.<sup>105</sup> G2 and G3 were identical and resembled the British Calder Hall reactors; although they could be distinguished by the horizontal fuel channels, the French reactors were also the first to use a pre-stressed concrete cylinder both as pressure vessel as well as a containment building.<sup>106</sup>

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<sup>104</sup> Guéron (1970, 63).

<sup>105</sup> Bracken (2012, 102).

<sup>106</sup> Guéron (1970, 63).

The national atomic program—led by the CEA—foresaw the deployment of the UNGG technology for electricity production and construction of the first GCR was started in Chinon (Chinon A-1) in 1957, the 70 MW<sub>e</sub> reactor was operational between 1964 and 1973. The three early Chinon GCRs were used as dual-purpose reactors.<sup>107</sup> In total, six UNGG reactor construction projects were launched until 1966. The capacity was increased steadily and Bugey-1—the latest GCR to be connected to the French grid in 1972—had a thermal capacity of 1,954 MW<sub>th</sub> and delivered 540 MW<sub>e</sub> of electricity to the grid. Since 1992, all GCRs are in a state of shut down.

Based on the experiences with the first experimental reactor, France also deployed a HWGCR, the reactor called “EL-4” or Brennilis had a net capacity of 70 MW<sub>e</sub> and went online in 1967, it was shut down in 1985. Already in 1968, CEA started with the construction of FBRs mainly used for plutonium production: Phénix (130 MW<sub>e</sub>, online in 1973, and shut down in 2010), followed by the 1,200 MW<sub>e</sub> strong successor Superphénix in 1976 (the reactor went online in 1986). The initiative in the development of the FBR for commercial electricity generation was carried out in cooperation with other European Countries (Italy, West Germany, the Netherlands, and Belgium). At that time, it was argued that the main motivation for Superphénix was the needed plutonium to modernize France’s nuclear force, especially the tactical forces.<sup>108</sup> The reactor was permanently shut down in 1998 due to sodium leaks and rising public opposition.<sup>109</sup>

#### **4.1.4.2 From national independence to a US license and on to the most standardized fleet in the world**

The route of national technological independence was not sustainable, and France turned to US imports in a second phase of development. In 1962, the first imported license, a Westinghouse PWR, was launched by an association comprised of EDF and a group of Belgian utilities: Chooz-A, located on the Belgian-French border. The 280 MW<sub>e</sub> PWR was built under

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<sup>107</sup> Albright (1984, 31).

<sup>108</sup> Genestout and Lenoir in Albright (1984, 31).

<sup>109</sup> Murray and Holbert (2015, 464).

a Westinghouse license and was the first “commercial” NPP built in Europe and supplied Belgium and France with electricity. The location of the reactor was unique too, as it was installed deep inside the bedrock of a hill in the Ardennes. Two caverns were specifically excavated to accommodate the reactor and the auxiliary systems. This underground system allowed the designers to work without containment. The NPP was operational between 1966 and 1991 and is currently being decommissioned.

The full turnaround of nuclear reactor policy came with the departure of President Charles de Gaulle, in 1969. The first “commercial” ordering of a LWR by Oyster Creek (USA) had intensified the French nuclear industry’s opposition to the unsuccessful GCR route, whereas the CEA continued to advocate French-made GCRs and FBRs.<sup>110</sup> After De Gaulle left his presidency in 1969, France—the under President Pompidou—shifted its nuclear industry and started collaboration with the U.S. The UNGG technology was abandoned and the development of a French PWR design was pursued. The development of nuclear submarines, as it was the case for the U.S. and the USSR was another intrinsic motivation.

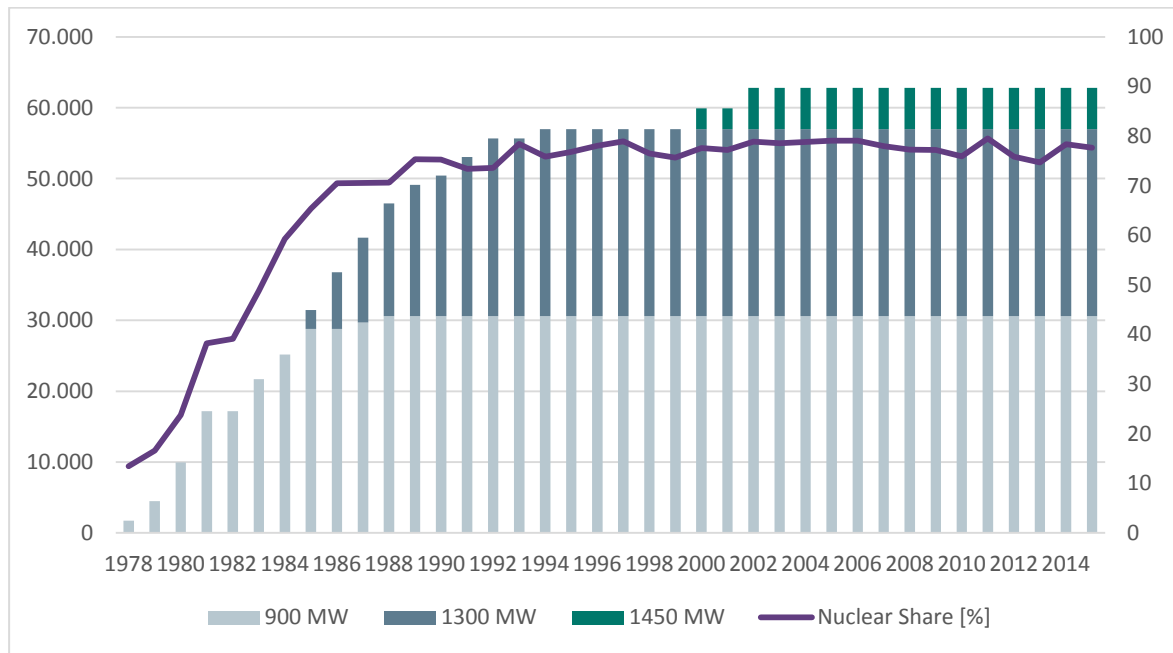
France’s major nuclear rollout did not occur until after the Arab oil embargo of 1973.<sup>111</sup> Framatome’s first generation of reactors was the 900 MW<sub>e</sub> design with three loops, built under a Westinghouse license. The first batch of six PWRs (Order series CP0) was ordered between 1970 and 1974. The first 900 MW<sub>e</sub> reactors were connected to the grid in Fessenheim (Fessenheim-1 and -2) in 1977 and one year later four more units on the Bugey site (Bugey-2 -5). The second PWR batch was ordered between 1974 and 1979 (Order series CP1) and consisted of 18 reactors, which started construction between 1974 and 1979 on four different sites. The first reactors to be connected to the grid were the four Tricastin units (Tricastin-1 -4). Other NPPs with CP1 reactors were the four units of Blayais (Blayais-1-4) and the Gravelines site in the North of France with six units (Gravelines-1-6). Gravelines is currently (in 2017) with around 5,5 GW<sub>e</sub> of installed capacity the second largest nuclear power station in Europe. The last 900 MW<sub>e</sub> reactor order (Order series CP2) consisted of 10 reac-

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<sup>110</sup> Thomas (1988, 203–4).

<sup>111</sup> Blowers et al. (1991).

tors, which started construction between 1976 and 1981. The two units of St. Laurent B were the first to be connected to the grid in 1983, the four units of Chinon-B in 1984 and 1987/88, and the four units of Cruas in 1984/85. The mean construction time of the 34 900 MW<sub>e</sub> reactors was around five years. Figure 20 shows and illustrates the speed of the French PWR roll out. In 1988, only 10 years after the first grid connection, already 30 GW<sub>e</sub> of nuclear generation capacity was installed supplying 70 percent of the electricity demand.



**Figure 20: French PWR Roll-out and nuclear share, 1978–2015**

Source: Own depiction based on IAEA PRIS and World Bank (2016); year depicts start of commercial operation.

Under then-president Giscard (1974–1981), the decision fell definitely on the PWR technology. NPP construction remained under state control, but the leadership shifted to the public company EDF, which assumed the role CEA once occupied. All major components were to be supplied by Framatome (pressure vessels, steam generators) or by other companies from within its then-parent company (Empain-Schneider Group); the turbine generators were

supplied by the French company Alsthom Atlantique and CEM.<sup>112</sup> The transition to a larger reactor design with four loops and over 1 GW<sub>e</sub> of capacity: the 1,300 MW<sub>e</sub> design—again under Westinghouse license—was based on the PWR W (4-Loop) South Texas plant in the U.S. The motivation for a larger reactor were the expected economies of scale to encounter increasing cost escalation. The first 1,300 MW<sub>e</sub> reactor was constructed at the Paluel site, also a twin reactor site, between 1977 and 1985, Paluel-1 and -2 were commissioned three years before the South Texas Plant. Construction time of this larger reactor design slightly increased to around seven years. The first reactors to be connected to the grid were the two units 1 and 2 of Paluel in 1984 (units 3 and 4 started operations in 1985/1986).

The last Framatome design was the 4-Loop 1,450 MW<sub>e</sub> line, the first fully French PWR design. In 1981, Framatome terminated its license agreement with Westinghouse, which freed Framatome to sell its product worldwide under its own name.<sup>113</sup> Between 1984 and 1991, four NPPs supplied with the N4 reactor design started construction: Chooz B-1 and B-2 and Civaux-1 and 2 (connected to the grid in 2002). Here construction time doubled to an average of 10.5 years with Chooz B-1 being the longest construction project, although relatively short for international standards. The NPP started construction in 1984 and was commissioned 12 years later in 2000.

The high standardization (only PWRs) of the French nuclear expansion is one possible explanation for the relatively short construction times and low specific investments costs of around 2,100–2600 2008 USD/kW reported by Grubler (2010). But they also illustrate the impacts of different institutional settings. Grubler (2010, 5185) argues that *“the “central planning” model in France with its regulatory stability and unified, nationalized, technically skilled principal-agent (EDF) appears economically more successful [...], than the more decentralized, market-oriented, but regulatory uncertain (and multi-layered, i.e. state and federal) U.S. system.”*

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<sup>112</sup> Thomas (1988, 209).

<sup>113</sup> Thomas (1988, 216).

#### 4.1.4.3 The European Pressurized Water Reactor (EPR)

In 1989, Siemens and Framatome formed a joint venture company, Nuclear Power International (NPI) to design a new PWR. Both companies had been using Westinghouse licenses and the design for the European PWR (EPR) was based on Siemens' Convoi design and Framatome's N4 respectively: the containment was drawn mainly from the N4 design, instrumentation was from the Convoi; a particular feature was added, a 'core catcher' so that, the core would be retained within the containment in the case of a meltdown.

In 2017, the French nuclear industry found itself between a rock (financial distress) and a hard place (technological challenges), so that its future is very uncertain. The European Pressurized Water Reactor (EPR), a design of the 1980s, has so far not been brought online, and cost estimates for the first units have increased exponentially: In 1998, Framatome claimed overnight construction costs for the EPR of 1,415 1998 USD/kW. In 2005, EDF ordered its first EPR for the Flamanville site with expected costs of 3.3 billion 2004 EUR. EDF did not seek a turnkey contract, but chose to be the contract manager.<sup>114</sup> The latest cost estimate for Flamanville-3 was around €10.5 bn (~6,500€/kW) in 2015.<sup>115</sup> The two European EPRs are well behind schedule and are now expected to enter operations in 2018/2019—with commissioning initially planned of Flamanville-3 set to 2012.

#### 4.1.4.4 Summary

In France, the early development of nuclear power was dominated by the dual purpose of the GCR technology. Only in the 1970s, motivated by the "commercial" ordering of Oyster Creek, the focus switched definitely to the LWR technology. The current French fleet is the most standardized fleet in the world—only consisting of PWRs supplied by state-owned Areva (now Framatome). In 2017, the EPR as well as its vendor are both in a financial crisis. France has with 75 percent the highest nuclear share in the world (Figure 20 shows the development of the nuclear share in France) and is with 379.10 GWh the second largest pro-

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<sup>114</sup> Thomas (2010b, 3-11).

<sup>115</sup> Schneider et al. (2017, 47).

ducer of electricity from nuclear power and Table 12 sums up the nuclear deployment in France.

<b>First construction start (grid connection):</b>	1951: G-1 (Marcoule) (1956)
<b>Latest construction start: (grid connection):</b>	2007: Flamanville-3 (EPR)
<b>Latest grid connection:</b>	1999: Civaux-2 (N4 REP 1450)
<b>Operational capacity (NPP):</b>	63.13 GW <sub>e</sub> (58)
<b>Shut down capacity (NPP):</b>	3.79 GW <sub>e</sub> (13)
<b>Construction capacity (NPP):</b>	1.6 GW <sub>e</sub> (1)
<b>Installed technologies (or under constr.) (NPP):</b>	PWR (60), GCR (9), FBR (2), HWGCR (1)
<b>Most installed reactor design (NPP):</b>	PWR 900 MW <sub>e</sub> (CP0, CP1, CP2) design (34)

**Table 12: Summary for France**

Source: Own depiction.

#### 4.1.5 India

On August 15<sup>th</sup>, 1947, India proclaimed its independency from the British Commonwealth of Nations and a few months later, in 1948, the Indian nuclear program was established. The main actors in determining the shape of the program were then first Prime Minister Jawaharlal Nehru, and Homi Bhabha, a Cambridge-trained physicist, the so-called architect of India's nuclear program.<sup>116</sup>

##### 4.1.5.1 The first nuclear reactor in Asia and India's three-stage program

In 1955, construction of the first research reactor named APSARA (1 MW<sub>th</sub>), near the city of Mumbai (then called Bombay) started; the light water swimming pool reactor went critical in 1956. APSARA—the first nuclear reactor in Asia—was fuelled by highly enriched uranium-aluminium alloy, supplied by the United Kingdom Atomic Energy Authority.<sup>117</sup> The second research reactor was supplied by Canada: CIRUS (Canadian-Indian Reactor Uranium System), a 40 MW<sub>e</sub> heavy water moderated, light water cooled and natural uranium-fuelled reactor,

<sup>116</sup> Bhargava (1992, 735).

<sup>117</sup> Banerjee and Gupta (2017).



using the same design as the Canadian NRX reactor. Although, a few Canadian diplomats realized that this could lead to the potential acquisition of weapons-grade plutonium by India and despite Canadian efforts, Bhabha refused to accept any voluntary controls or safeguards and the reactor went critical in 1960. The construction and operation of CIRUS also required help from the U.S., which supplied the heavy water, but it was likewise a US firm—Vitro International—which was awarded the contract to prepare the blueprints for India's first reprocessing plant at Trombay. The plant was later-on used for the separation of plutonium from SNF from CIRUS to be used for India's first nuclear weapons test of 1974.<sup>118</sup>

Bhabha recognized the importance of basic research and training professionals in the early phase of the program; his ambition was to maximize the use of indigenous technologies and raw materials: the quite limited natural uranium and the large reserves of thorium.<sup>119</sup> This led to a three stage-program, first announced in 1954:<sup>120</sup>

- First, the focus lied on natural uranium, of which the reserves were estimated to be around 70,000 tons, by establishing the PHWR (CANDU) reactors to produce power and plutonium.
- Second, the construction of a FBR fuelled by the produced plutonium, gained by reprocessing SNF from the PHWRs and thorium (the reserves were estimated to be around 360,000 tons). The nuclear cores of the FBR fleet, could be surrounded by a blanket of either depleted uranium from reprocessing or thorium to produce more U-233 respectively plutonium.
- Third the last stage also consisted of FBRs, which would use thorium in their blankets and U-233 in the core.

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<sup>118</sup> Ramana (2006, 5–6).

<sup>119</sup> Banerjee and Gupta (2017).

<sup>120</sup> Bhargava (1992); Ramana (2006); Banerjee and Gupta (2017).

#### 4.1.5.2 TAPS, RAPS, “Smiling Buddha”, and Indian PHWRs

India entered the large-scale nuclear power era in 1969, when the two Tarapur units (TAPS 1 and 2, two BWR-1 reactors, two times 150 MW<sub>e</sub>) station were connected to the grid in Mumbai. Construction started five years earlier with a turnkey order from GE. The enriched uranium to fuel the reactors was also imported from the U.S.<sup>121</sup> In addition, the U.S. trained more than a thousand Indian scientists in US nuclear research projects from 1955-1974.<sup>122</sup> In 1965, construction of the first 200 MW<sub>e</sub> CANDU reactor at the Rajasthan station (RAPS 1) in Rawatbhata in the state of Rajasthan, started. The reactor was constructed with Canadian technical collaboration (it was based on the Douglas Point station in Canada) and achieved grid connection in 1973. One year later, on May 18<sup>th</sup> of 1974, India’s first nuclear bomb (“Smiling Buddha”) detonated. It was the first nuclear weapons test by a non-member of the five permanent members of the UN Security Council. Subsequently, the U.S. and Canada withdrew their support. Canada was at that time involved in the construction of RAPS-2 and it is claimed, that the PHWR was 60% complete, when Canada terminated its assistance. Nonetheless, the reactor went online in 1981. Only the French provided FBR know-how later on as well as fuel for the Rajasthan reactors.<sup>123</sup> Although, Rajasthan-1 is still listed as operational by the IAEA, the reactor has not generated any power since 2004.<sup>124</sup>

Once Canada gave the CANDU license to India, India kept building PHWRs and the first Indian designed PHWR started operations in 1983/85: Madras unit 1 and 2. After the grid connection of Narora-1 and 2 in 1989/92, the design of the Indian 220 MW<sub>e</sub> PHWR was standardized. Construction of the first larger PHWRs started again at the Tarapur station in Mumbai in 2000, TAPS-3 and 4 had a thermal capacity of 1,730 MW<sub>th</sub> and delivered 502 MW<sub>e</sub> of electricity. Both plants were connected to the grid in 2005/06. The power output of the PHWR was raised from gross 220 MW<sub>e</sub> to 540 MW<sub>e</sub> by increasing the size of the core and the total inventory of fissile material; the third increment in capacity increase to 700 MW<sub>e</sub> was ac-

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<sup>121</sup> Banerjee and Gupta (2017).

<sup>122</sup> Weiss (2003, 44).

<sup>123</sup> Bhargava (1992, 738–42) and Schneider (2009, 17).

<sup>124</sup> Schneider et al. (2017, 202).

completed by allowing partial boiling of the coolant near the exit end of the coolant channel.<sup>125</sup>

In 2002, construction of the first LWRs since the 1960s, started in the southern Indian state of Tamil Nadu: Kudankulam-1 and -2. In collaboration with the contractor Atomstroyexport, a total of six VVER V-412 reactors with 1,000 MW<sub>e</sub> are planned. Unit 1 went online in 2014, unit 2 attained criticality in 2016, eight years later than planned; construction of unit 3 started in 2016.

Since 2010/12, the first four indigenous 700 MW<sub>e</sub> PHWRs are currently under construction: Kakrapar-3 and -4, and Rajasthan-7 and 8. All projects are delayed but despite these delays construction of ten more 700 MW<sub>e</sub> units was approved by the Indian Government cabinet in May 2017, “*strengthening India’s credentials as a major nuclear manufacturing powerhouse*”—an attempt to probably position itself as a reactor exporter country.<sup>126</sup>

#### **4.1.5.3 India’s future nuclear program**

India already achieved its greatest nuclear production in 2016, but the nuclear program is expected to evolve continuously in the next couple of decades and discusses the development of PHWRs, LWRs, and FBRs. The first stage consisted of indigenous PHWRs, but the availability of uranium from international sources leads to the present plan of a mixture of Indian PHWRs and foreign LWRs.

India entered the second stage of its nuclear program with the construction of the FBR prototype reactor FBTR (Fast Breeder Test Reactor). Construction of the sodium-cooled FBR started in 1971 and the FBR ought to attain criticality in 1976, but the reactor was only commissioned in 1985 at a fraction of the original 40 MW<sub>th</sub> design capacity. Since its commissioning, numerous accidents and incidents occurred, e.g., leakage of nitrogen, damage of “in-vessel” components, and only in 2000 the FBTR managed to operate continuously for 53 days.<sup>127</sup> Nonetheless, India went ahead with the construction of the 1,253 MW<sub>th</sub> FBR (Proto-

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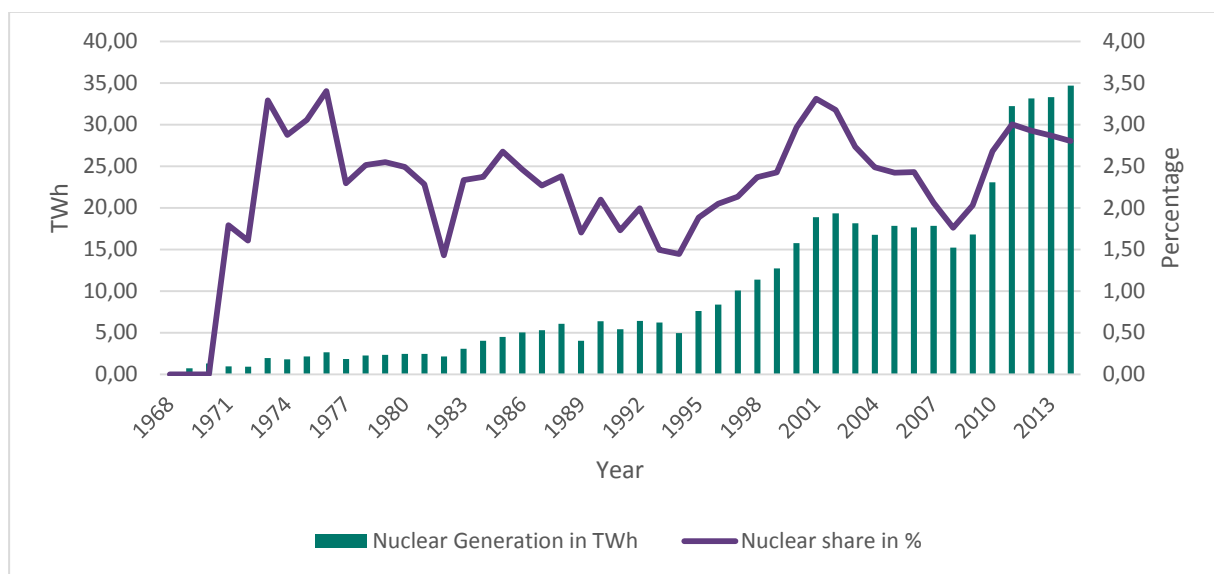
<sup>125</sup> Banerjee and Gupta (2017, 7).

<sup>126</sup> Schneider et al. (2017, 204).

<sup>127</sup> Ramana (2006, 24).

type Fast Breeder Reactor, PFBR), scaling up the FBTR by a factor of about 70, instead of the carbide fuel used, the PFBR will use thorium and UO-based fuel, with which India has up to date no experience

In 2005, India committed to finally separate its nuclear program into a civilian and a military program as it realized that the Indian nuclear program can only rapidly grow with external help and the failure of the government to adequately supply fuel for the existing reactors. Figure 21 shows the development of the nuclear share and the nuclear generation in India. In 2017, the nuclear share of the total electricity production amounted 3.2%.



**Figure 21: Nuclear share and nuclear generation in India, 1968–2014**  
Source: Own depiction based on World Bank (2016) and BP (2017).

#### 4.1.5.4 Summary

The beginning of the Indian nuclear deployment was motivated by getting hold of nuclear weapons. India imported reactor technology from the U.S. and Canada. The CANDU technology was later on indigenized and own Indian PHWR technology was developed. The initial focus shifted with the appearance of cheap uranium and India considers nowadays a mixture of PHWR and LWR technology for future deployment. Although, India is in 2017 worldwide on the third place concerning newbuild projects (6) and the nuclear share is steadily rising,

especially since the 1990s the share has increased seven-folded to around 35 TWh, nuclear power represents only around three percent of the generated electricity. Even, if all the planned and currently under construction NPPs will successfully be connected to the grid, nuclear power will remain to play a subordinate role in India, especially before the background, that the Central Electric Authority expects a share of renewable energy of around 24 percent by 2027.<sup>128</sup> Table 13 summarizes the nuclear deployment in the India.

<b>First construction start (grid connection):</b>	1964: Tarapur-1 (1969)
<b>Latest construction start (grid connection):</b>	2017: Kundankulam-3 (VVER V-412)
<b>Latest grid connection:</b>	2016: Kundankulam-2: 2016 (VVER V-412)
<b>Operational capacity (NPP):</b>	6.23 GW <sub>e</sub> (22)
<b>Shut down capacity (NPP):</b>	0
<b>Construction capacity (NPP):</b>	3.9 GW <sub>e</sub> (6)
<b>Installed technologies (or under constr.) (NPP):</b>	PHWR (22), BWR (2), FBR (1), PWR (3)

**Table 13: Summary for India**

Source: Own depiction.

#### 4.1.6 Pakistan

##### 4.1.6.1 Going nuclear by emulating India

Pakistan's nuclear development somewhat resembles India's, though with a certain time lag, and at a somewhat smaller scale. Pakistan's nuclear program starts in the 1950s, by signing a nuclear cooperation program with the U.S. and importing a 5 MW<sub>e</sub> swimming pool reactor, which achieved criticality in 1965.<sup>129</sup> In 1966 (one year after Canada supplied a CANDU reactor to India), Pakistan imported a CANDU reactor (137 MW<sub>e</sub>) and construction of the Kanupp-1 station began. Kanupp-1 achieved criticality in 1971 and operates now for 46 years (in 2017) near Karachi, a city of nearly 20 million people.

<sup>128</sup> Schneider, et al. (2017, 203).

<sup>129</sup> Khalilzad (1980, 11).

The Pakistan Atomic Energy Commission started a research program for the processing of uranium ore as well as work on heavy water production—the operation of the HWR depended on the import of heavy water from the U.S. In 1976, Pakistan and France signed an agreement for the purchase of a nuclear reprocessing facility. Pakistan argued that the facility was needed to meet the growing energy demand and for fuel production for the future FBRs—at that time only Kanupp-1 was operational.

In 1978, France backed out of the deal, mainly as a direct result of US pressure, the Carter administration used its influence to block loans to Pakistan from the World Bank.<sup>130</sup> During the negotiations with France, Pakistan had been simultaneously trying to construct a gas centrifuge enrichment plant; for this a number of front organizations had been set up around the world for the purchase of plant components. German companies and one Dutch company were used to buy the necessary material for a number of countries including the U.K., the Netherlands, Switzerland, West Germany and the U.S. (Khalilzad 1980, 11–14); this supply system was organized via the Pakistani embassy in Paris (Schneider 2009, 18). Finally, the enrichment facility was constructed at Kahuta, near Islamabad, based on an advanced design stolen (through the Pakistani spy A.Q. Khan) from the Netherlands.<sup>131</sup>

In 1979, the Soviet invasion of Afghanistan led to a shift in the US policy towards Pakistan, as Brzezinski—Carter’s national security adviser—argued, that Pakistan would constitute a perfect base for supplying more cash and weapons to the guerrillas fighting the USSR; to do so the U.S. started looking the other way on the Pakistani nuclear weapons program.<sup>132</sup> Abdul Qadeer Khan (A.Q. Khan), the self-designated “father” of the “Islamic Bomb”, who worked in 1974 (when India tested its first nuclear weapon) at a uranium enrichment plant in the Netherlands, left in 1975 with the stolen centrifuge designs for Pakistan. Khan went on to establish a sophisticated global illicit nuclear supplier network—which started with a

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<sup>130</sup> In 1976, Henry Kissinger threatened Pakistan that the U.S. would „*make a horrible example*“ of Pakistan if it pursued the same path as India towards nuclear weapons. Pakistan was always relatively clear about their ambitions to respond to the perceived Indian threat. Already in 1966, then foreign minister Buttho said that if India were to gain nuclear weapons, Pakistan would follow suit, even if this means that the population had to “eat grass” to do so (Khan and Abbas 1998, 34).

<sup>131</sup> Lovins et al. (1980, 1148).

<sup>132</sup> Collins and Frantz (2018).

handful of Swiss and German companies—which provided nuclear enrichment technology to Iran, Libya, and North Korea.<sup>133</sup>

In 1986, a Washington Post article citing classified US intelligence reported that Pakistan had produced an unspecified amount of weapons-grade uranium.<sup>134</sup> Two years later, on May 28<sup>th</sup>, 1998, five nuclear devices were tested underground, and the “Islamic Bomb” was born.

#### 4.1.6.2 Nuclear power in Pakistan today

In 1993, almost 30 years after the construction start of the Kanupp station, Pakistan imported a second NPP and the first Chinese NPP: a CNP-300 for the Chasnupp site near Chashma, in the north of Pakistan. Seven years later, in 2000, the reactor was connected to the grid. Three more CNP-300’s from China National Nuclear Corporation—all for the Chasnupp site—were imported and connected to the grid in 2011, 2016, and 2017.

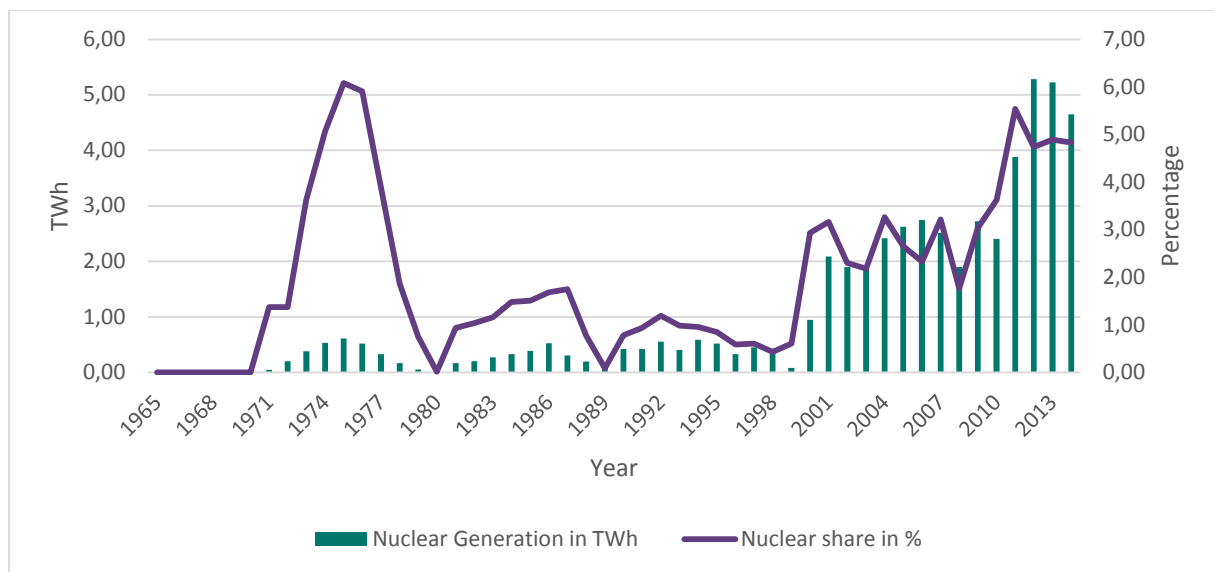
In 2015 and 2016, two more reactors were ordered from China and construction of two new units started at the Kanupp site: Both Hualong reactors (ACP-1000) have a net capacity of 1,014 MW<sub>e</sub> and are scheduled to be connected to the grid in 2021/22.<sup>135</sup> Table 14 summarizes the nuclear reactor program in Pakistan. In accordance to Figure 22, the country never witnessed a nuclear share in total electricity production beyond about six percent.

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<sup>133</sup> See Cronin et al. (2005) for a CRS Report for the US Congress on Pakistan’s nuclear proliferation activities.

<sup>134</sup> Albright (1987, 30).

<sup>135</sup> Schneider et al. (2017, 31).



**Figure 22: Nuclear share and nuclear generation in Pakistan, 1965–2014**

Source: Own depiction based on World Bank (2016) and BP (2017).

**4.1.6.3 Summary**

The beginning of the Pakistani nuclear deployment was motivated by getting hold of nuclear weapons to counter the perceived Indian aggression. Emulating their rival, Pakistan imported reactor technology from Canada. Instead of indigenizing the reactor technology, Pakistan opted for the import of turnkey plants from China. Indeed, Pakistan has been two times the first export nation for Chinese technology: the CPR-300 in the 1990s and 2015 has seen the first exports of the Gen III Hualong reactor. Table 14 summarizes the nuclear deployment in the Pakistan.

<b>First construction start (grid connection):</b>	1966: Kanupp-1 (1971)
<b>Latest construction start:</b>	2016: Kanupp-3 (ACP-1000, Hualong One)
<b>Latest grid connection:</b>	2017: Chasnupp-4 (CNP-300)
<b>Operational capacity (NPP):</b>	1.32 GW <sub>e</sub> (5)
<b>Shut down capacity (NPP):</b>	0
<b>Construction capacity (NPP):</b>	2.02 GW <sub>e</sub> (2)
<b>Installed technologies (or under constr.) (NPP):</b>	PWR (6), PHWR (1)

**Table 14: Summary for Pakistan**

Source: Own depiction.



### 4.1.7 China

The economies of scope approach can also be applied for China: the major motivation for China to enter the nuclear age was to gain access to nuclear weapons. Already in the 1950s, nuclear research for military applications began, but only in the mid-1980s civil nuclear deployment slowly enrolled.

#### 4.1.7.1 The Chinese bomb

The early Chinese nuclear weapons development can be separated in two distinct phases. The first phase (1950–1958) is characterized by heavy reliance upon and cooperation with the USSR for financial, material, and technical support. In 1950, the “Sino-Soviet Atomic Cooperation Treaty” was signed, under which the Soviet government would supply China with a 10 MW<sub>th</sub> experimental HWR for the research centre in Beijing. According to Frank (1966), the reactor was fuelled by ten percent enriched uranium and became fully operational in 1958. In the same year, the first Institute of Atomic Energy of the Chinese Academy of Sciences was established and five years later the construction of a chemical separation plant in Sinkiang, in the north-west of the country began, and the Ch’ang-Ch’un Institute of Atomic Energy was formed in Beijing. In the second phase (1959–1965) China became almost entirely self-sufficient in all branches of nuclear research, e.g., development, engineering, testing, and production. In 1961, the last Soviet technicians were withdrawn.

A smaller research reactor—the first all-Chinese built model—was constructed in Beijing, the reactor was also fuelled with enriched U-238. Then in 1961, small atomic reactors for experimental purposes were established and an entirely Chinese-designed and manufactured research reactor (3 kW<sub>th</sub>) was constructed at Nankai University. Starting 1962, larger reactors were set up at Sian and Chungking, capable of producing sufficient quantities of weapons grade plutonium in a relatively short time. A gaseous diffusion plant was installed in Lanchow in north central China, too. In total, more than 40 chemical separation plants were built on the mainland for uranium and thorium extraction. On October 16<sup>th</sup>, 1964, the first

successful test explosion of a Chinese-made atomic bomb occurred at Lop Nor, Sinkiang Province and a second, identical, bomb was exploded on May 14<sup>th</sup>, 1965.<sup>136</sup>

#### 4.1.7.2 A mixture of indigenous and imported designs

Until the 1980s, China did not seem to be interested to use nuclear technology for electricity production, as no prototype reactor had yet emerged. In 1982, the Ministry of Nuclear Industry was reorganized and renamed to China National Nuclear Corporation (CNNC). CNNC was responsible for both: the civilian and military nuclear activities.<sup>137</sup> In 1985, China developed its first PWR based on submarine propulsion technology conceived by Westinghouse in the 1950s.<sup>138</sup> The resulting PWR CNP-300 (298 MW<sub>e</sub>) was an indigenous design and developed by Shanghai Nuclear Engineering Research and Design Institute (SNERDI) and supplied by CNNC. Construction of the station began in 1985 and the PWR was commissioned in 1991.

Reactor orders were slow in the 1980s/90s. Already in 1978, China came to an agreement with France on the import of reactor technology.<sup>139</sup> But only ten years later, in 1987, construction of the Daya Bay station began, for which Framatome supplied two reactors (950 MW<sub>e</sub>) using its M310 design (equivalent of N4). Construction was managed by EDF partnering with the new state-owned company China Guangdong Nuclear (CGNPC). Framatome supplied a total of four M310 reactors to China (two reactors for each station Daya Bay and Lingao). In 2002, the fourth and last M310 reactor was commissioned (Lingao-2).

In 1997, based on the CNP-300, CNNC supplied the first larger indigenous PWR CNP-600 (610 MW<sub>e</sub>) to Qinshan-2-1 and Qinshan-2-2. Both plants entered operations already seven years later. In addition, China ordered Canadian and Russian reactors. In 1997, two Candu-600 reactors were ordered from AECL for Qinshan-3-1 and Qinshan-3-2. In 1999/2000, two

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<sup>136</sup> Frank (1966, 12–15).

<sup>137</sup> CNNC is not a government-administered body, like other large-scaled state-owned Chinese enterprises, its presidents and vice-presidents are appointed by the Premier of the State Council (Ramana and Saikawa 2011, 6781).

<sup>138</sup> Biello (2011).

<sup>139</sup> Thomas (2017, 684).

VVER-1000 (990 MW<sub>e</sub>) reactors were ordered from Atomstroyexport, the station was commissioned in 2006/07.

Since the beginning of the Chinese nuclear expansion, countries have used financing arrangements to attract Chinese interest. Ramana and Saikawa (2001) especially highlight the use of loans from Export Credit Agencies instead of private lenders. These agencies provide government-backed loans, guarantees, credits, and insurance to private corporations from their home country to enter foreign markets. The rates on the loans are lower than in the private sector. The first country to offer a reactor at low payment was Canada: Canada's Export and Development Corporation offered a loan of CAD 1.5 billion plus USD 0.35 billion in 1997 for the Candu reactors.<sup>140</sup>

CNNC developed the indigenous CNP-1000 since the 1990s, when CNNC started working with Westinghouse and Framatome. The aim was a 1000 MW<sub>e</sub> reactor with full intellectual property rights. The Gen II reactor was initially planned to be a successor to CNP-300/600 and to be built at the Fangjiashan site, next to Qinshan. However, when SNPTC recommended in 2007 to put the further development of the CNP-1000 on hold and when construction on the Fangjiashan restarted a year later, the reactor had been changed to the CPR-1000 design. Thus, the outlook for CNP-1000 seems to be very modest, although CNNC has supplied four reactors to units 1–4 of the Fuqing station and two to Tianwan in 2015/16.<sup>141</sup>

After ordering the first M310 from Framatome, CNNC and CGN started to build up their design experience and in 2005/06, construction of Lingao-3 and -4 was started. The stations were supplied with the first Chinese Version of the M310, the CPR-1000 (1,007 MW<sub>e</sub>).<sup>142</sup> In 2008, construction accelerated with six reactors based on CPR-1000 design, the largest Chinese nuclear project up until then. The CPR-1000 design was favoured by CGNPC, marking a power shift from CNNC to CGNPC as the Chinese nuclear powerhouse. Table 15 shows the technologies operational in 2017, currently 38 NPPs or 33.4 GW<sub>e</sub> are installed. With the

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<sup>140</sup> Ramana and Saikawa (2011, 6784).

<sup>141</sup> Ramana and Saikawa (2011, 6784–85).

<sup>142</sup> The CGNPC and CNNC versions of the M310 are called CPR-1000 although there are differences between the two designs; the CNNC versions is also sometimes called M310+ (Thomas 2017, 684).

exception of the two VVER-1000 (V-428) reactors, only Gen II reactors are operational in 2017.

Type	Design	Generation	Vendor/Designer	Operational Capacity in MW (NPP)
PWR	CNP-300	Gen II	SNERDI <sup>143</sup> (China)	298 (1)
PWR	M-310	Gen II	Framatome	3,788 (4)
PWR	CNP-600	Gen II	Snerdi (China)	3,669 (6)
PHWR	Candu 6	Gen II	AECL (Canada)	1,354 (2)
PWR	CPR-1000	Gen II	CGNPC and CNNC	18,293 (18)
PWR	VVER-1000	Gen III	Atomstroyexport	1,980 (2)
PWR	CNP-1000	Gen II	CNNC	4,000 (4)
FBR	B-20		CNNC	20 (1)
				<b>33, 402 (38)</b>

**Table 15: Operational Chinese nuclear capacity in 2017, clustered by reactor type**

Source: Own depiction based on IAEA PRIS Database (2017), Thomas (2017), and Ramana and Saikawa (2011).

#### 4.1.7.3 Made in China: the indigenization of imported designs

Already in 2004, two Gen III tenders were put out by the Chinese government for the Sanmen station and the Yangjiang station (later on this shifted to the Haiyang station). Among the ten international bids, Westinghouse and Areva had a strong-backing in their home country: the French bid was backed by the French export credit agency (Coface) while the Westinghouse bid was backed by a USD 5 billion loan by the US Export Import Bank and major political lobbying efforts at home. Areva lost out mainly as Westinghouse was more open to transferring its license to China.<sup>144</sup> Four AP1000 reactors were ordered, and a new company created to indigenize the technology: State Nuclear Power Technology Company (SNTPC), later on renamed to State Power Investment Corporation (SPIC). Construction of the two stations started in 2009/2010 and was the very first construction start of this design

<sup>143</sup> SNERDI became a subsidiary of SNPTC.

<sup>144</sup> Ramana and Saikawa (2011, 6785).

worldwide as well as the first orders for Westinghouse since the 1970s. Sanmen was thought to enter operations in 2013, the latest expectation is 2018.<sup>145</sup>

Upon their loss to their American counterpart, the French government intervened strongly and in 2007, the largest ever nuclear deal estimated to be around USD 12 billion for two EPRs was signed. The deal was signed without any international bidding, but the French government offered a convincing financing package with EDF taking a 30% stake in the project and in addition France finally agreed to the Chinese demand for technology transfer. Areva and CNNC also signed a contract for setting up a reprocessing plant. In 2008, Areva and CGNPC formed a joint-venture for the development of an EPR and other PWR plants in China and abroad.<sup>146</sup> Construction of the two EPRs for the Taishan site started in 2009/2010. However, the project was considerably delayed, and is several years late, commissioning was originally planned for 2013.

Thomas (2017) evokes that Chinese authorities already recognized in 2006 that more modern designs were needed, as until then only Gen II reactors had been constructed. Based on the imported French and American designs, Chinese Vendors started producing indigenous Gen III designs: CGN developed the ACPR-1000, CNNC the ACP-1000 (both designs are based on the M310 design), and SPIC developed the CAP1400 (no construction start until 2017), a scaled-up AP1000. In 2013, the Chinese government required CGN and CNNC to “merge” the two Gen III designs, which resulted in the Hualong One design (HPR-1000). Two years later, both companies created the joint venture Hualong International Nuclear Power Technology Co. At the moment, it is not clear, if this will lead to the merger of the two separate HPR-1000 capabilities of CGN and CNNC or whether it will be a “figurehead company” with both companies pursuing their own separate market.<sup>147</sup> Up until the merger, four ACPR-1000s by CGN started construction in China and ACP-1000 reactors were ordered by Pakistan.

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<sup>145</sup> Schneider et al (2017, 200).

<sup>146</sup> Ramana and Saikawa (2011, 6785).

<sup>147</sup> Thomas (2017, 684–85).

The development of indigenous and uncommon designs is also part of the Chinese strategy. One exception to this rule is the FBR. The German model of HTGR was adapted in 1992 into a research reactor: the HTR-10. The pebble-bed technology was transferred via a technology license from Germany in the mid-1980s.<sup>148</sup> A scaled-up version, the HTR-PM, went under construction in 2012 (Shidao Bay-1), making China the only country to develop this model. Moreover, China plans to build several molten salt reactors. Table 16 shows the current technologies under construction in 2017. Currently, 19 NPPs or 19.5 GW<sub>e</sub> of installed capacity are being constructed.

After the 2011 Fukushima accident, the Chinese State Council terminated the approval of new-build projects; this policy was inverted in February of 2015 as projects gained restart under the impetus of new policies. According to the Long-term Nuclear Power Development Plan (2011–2020), the installed nuclear capacity in operations should be 58 GW<sub>e</sub> by 2020 with 29 GW<sub>e</sub> of capacity under construction. As Table 15 and Table 16 show, China is going to miss this goal. Zeng et al. (2016) assume that with investment costs of 12,000 yuan per kW<sub>e</sub>, the annual investment costs will reach over CNY 70 billion (~ 9 billion EUR in 2017).<sup>149</sup> If China wants to expand nuclear power, inland sites will have to be developed, but there is significant opposition to this, in addition the Chinese government prohibited this after Fukushima.<sup>150</sup>

Type	Design	Generation	Vendor/Designer	Construction Capacity in MW <sub>e</sub> (NPP)
PWR	CNP-1000	Gen II	CNNC (China)	2,000 (2)
PWR	AP1000	Gen III	Westinghouse	4,000 (4)
PWR	ACPR-1000	Gen III	CGN	4,000 (4)
PWR	EPR-1750	Gen III	Framatome	3,320 (2)
PWR	HPR1000	Gen III	CGN	4,000 (4)
HTGR	HTR-PM	(SMR)	Tsinghua University	200 (1)
PWR	VVER V-428M	Gen III	Atomstroyexport	1,980 (2)
				<b>19,500 (19)</b>

<sup>148</sup> Ibid.

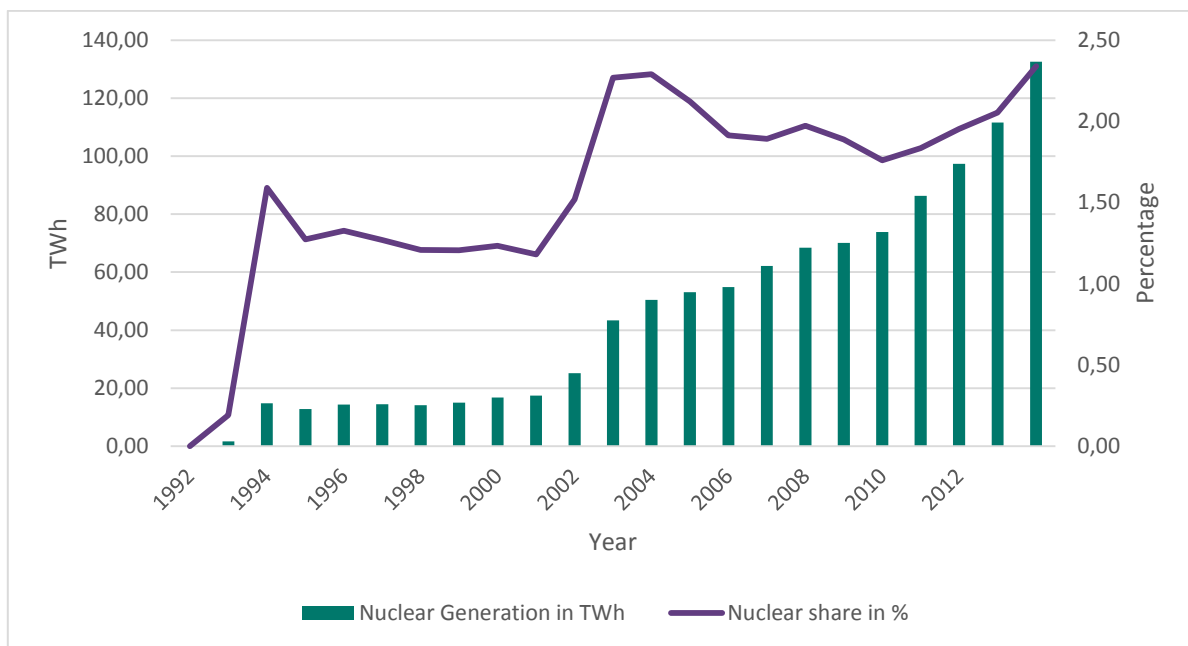
<sup>149</sup> Zeng et al. (2016, 1374).

<sup>150</sup> Thomas (2017, 685).

**Table 16: Nuclear capacity under construction in 2017 in China, clustered by reactor type**

Source: Own depiction based on IAEA PRIS Database (2017), Thomas (2017), and Ramana and Saikawa (2011).

In 2017, China is the only country world-wide where nuclear growth is accelerating, although the 32 GW<sub>e</sub> of installed capacity only generates around 2.5% of electricity in 2015. In 2017, China overtook Russia in the amount of electricity generated based on nuclear power and is now worldwide on the third place behind the U.S. and France (in 2002 China was on the 15<sup>th</sup> place among 31 countries). China currently operates 38 NPPs and is on the first place concerning newbuild with a total of 19 NPPs under construction, which should push the installed capacity to 52 GW<sub>e</sub>. Figure 23 shows the nuclear share in the electricity mix as well as the amount of nuclear generation from 1999 to 2014.



**Figure 23: Nuclear share and nuclear generation in China, 1990–2014**

Source: Own depiction based on World Bank (2016) and BP (2017).

#### 4.1.7.4 Summary

China became in 30 years a major actor in the nuclear sector and has been animated by two developments: on one hand, in a very innovative way, China developed its own technology, the PWR CNP-300, bought the technology of other countries like France, Canada, U.S., and Russia, and indigenized the designs to create new Chinese reactor designs. On the other hand, China kept developing its original designs such as FBR or more recently molten salt reactors. Table 17 summarizes the nuclear deployment in China. China's strategy has propelled the country to the research and industrial frontier of nuclear technology world-wide.

<b>First construction start (grid connection)</b>	1985: Qinshan-1 (CNP-300, 1991)
<b>Latest construction start:</b>	2016: Fangchenggang-4 (HPR1000)
<b>Latest grid connection:</b>	2017: Yangjiang-5 (CPR-1000, construction started in 2012)
<b>Operational capacity (NPP):</b>	33.4 GW <sub>e</sub> (38)
<b>Shut down capacity (NPP):</b>	-
<b>Construction capacity (NPP):</b>	19.5 GW <sub>e</sub> (19)
<b>Installed technologies (or under constr.) (NPP):</b>	PWR (53), PHWR (2), HTGR (1), FBR (1)
<b>Most installed reactor design (NPP):</b>	CPR-1000: 18. 3 GW <sub>e</sub> (18)

**Table 17: Summary for China**

Source: Own depiction.

#### 4.1.8 Iran

##### 4.1.8.1 Iran's dual-use technology

Iran has sought very close synergies between military use of nuclear power and electricity generation, in a very controversial and politically sensitive program. On the military side, Iran had started to build a HWR (IR-40) in operation near the town of Arak with foreign support; it is generally assumed that the intention was to produce weapons-grade plutonium. Under the Joint Comprehensive Plan of Action agreed on in July 2015, the reactor will be redesigned so it cannot produce any weapons-grade plutonium; in addition all SNF will be sent



out of the country as long as the reactor exists.<sup>151</sup> In addition, Iran operates a uranium enrichment program (the P-1 centrifuge design was developed by Iran from plans acquired through the network of the Pakistani scientist A. Q. Khan) with the main installation being in the town of Natanz, as well as a uranium conversion facility at Isfahan.<sup>152</sup>

#### 4.1.8.2 Current and future nuclear deployment

Parallel, perhaps also preceding the military program, a nuclear power plant program was developed. The 1970s increase in oil prices and the new oil wealth led the Shah to launch an ambitious nuclear energy program; under the Atoms for Peace program, the U.S. was happy to support this vision with proposing six to eight NPPs for 6 billion USD.<sup>153</sup> The 1979 Iranian revolution put an end to the US plans. Construction of Bushehr-1 started in 1975 with the German supplier Siemens KWU.<sup>154</sup> Construction was stopped after four years by Siemens due to dried up financial sources in the course of the Iranian revolution. During the Iran-Iraq war in 1984–88, the units were exposed to Iraqi bombings which caused severe damage to the reactors.<sup>155</sup> In 1995, the construction of Bushehr 1 was taken up by the Russia. Requested help to continue the production of the nuclear reactor was rejected by Germany to avoid diplomatic conflicts with the U.S.<sup>156</sup> As a consequence, all main reactor parts were constructed in Russia by Atomstroyexport. Under adaption of Siemens parts, the Russians built a VVER V-446 reactor with 915 MW<sub>e</sub>.<sup>157</sup> After several delays and incidents, operation finally started in 2013.

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<sup>151</sup> BBC 2015. „Iran’s key nuclear sites.“ November 22, 2017. <http://www.bbc.com/news/world-middle-east-11927720>.

<sup>152</sup> Albright (2006, 29).

<sup>153</sup> Ramana and Mian (2016, 39).

<sup>154</sup> Two PWR based on the German Biblis B reactor were planned with 1,293 MW<sub>e</sub> (gross) capacity each at the Bushehr site. According to the initial plan in 1974, Iran wanted to build eight reactors to come online in mid1980s: four at Bushehr, two at Isfahan, and two at Saveh. World Nuclear Association. 2017. "Nuclear Power in Iran." April, 2017. <http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/iran.aspx>.

<sup>155</sup> Lévêque (2014, 15).

<sup>156</sup> NTI. 2017. "Bushehr Nuclear Power Plant (BNPP)." July 10, 2017. <http://www.nti.org/learn/facilities/184/>.

<sup>157</sup> World Nuclear Association. 2017. "Nuclear Power in Iran." April 23, 2018. <http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/iran.aspx>.

In 2016, Iran ordered two more VVER reactors for Bushehr (construction started in 2017): Bushehr 2 and 3 are scheduled to be completed in 2024 and 2026.<sup>158</sup> Both reactors are delivered from Atomstroyexport under a turnkey contract. Bushehr-1 remains under the operation of Russian engineers while local Iranian staff is being trained. In 2016, the country achieved its greatest nuclear production with 5.92 TWh, but the Islamic Republic seems to have much larger nuclear deployment plans and announced a year prior, that it has approved 14 more sites for NPPs.<sup>159</sup>

#### **4.1.9 South Africa**

South Africa constitutes an interesting case, as there were no obvious attempts to reap economies of scope but the country set up a secretive nuclear weapons program in the 1980s, which was abandoned with the fall of the apartheid regime in 1991.

##### **4.1.9.1 South Africa's secret weapons program**

In contrast to its ongoing civil nuclear program, South Africa is the only country worldwide that has fully dismantled its nuclear weapons. During the apartheid regime, South Africa strongly invested in nuclear weapons and research. The first research reactor was Safari-1, the light water cooled and moderated reactor was commissioned in 1965 at the Pelindaba Nuclear Research Centre. Over the next ten years, the U.S. supplied the country with enriched uranium. South Africa also installed an enrichment facility, which produced a steady output of highly enriched uranium for the weapons program (Y-Plant, the plant was shut down in 1990). Estimations say that there were seven nuclear warheads in the 1980s and a secret collaboration with Israel for know-how and equipment which culminated, in 1979, in a conjoint nuclear testing off the coast of South Africa. But with the end of apartheid, the new government with President de Klerk ended the nuclear weapons program and at the beginning of the 1990s South Africa started the dismantling of its nuclear arsenal. In September

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<sup>158</sup> World Nuclear News. 2017. "Excavation work starts for Bushehr 2." October 31, 2017. <http://www.world-nuclear-news.org/NN-Excavation-work-starts-for-Bushehr-2-31101701.html>.

<sup>159</sup> Krane et al. (2016, 46).

2017, President Zuma eventually signed the international UN treaty on the ban of nuclear weapons.<sup>160</sup>

#### 4.1.9.2 Nuclear Power in South Africa

Operating two 970 MW<sub>e</sub> reactors (PWR) at the Koeberg site east of Capetown, South Africa is the only country on the African continent hosting running nuclear power plants. The two French-built turnkey PWRs provide six percent of South Africa's electricity, while the majority (more than 90%) is produced by coal-fired power stations.<sup>161</sup> Construction of the two power plants started in 1976 and they were connected to the grid in 1984 and 1985.<sup>162</sup> Plans to renew the now 31- and 32-year old and aging Koeberg reactors were already decided in 2010 but are delayed due to a legal fight between the rival suppliers AREVA (now Framatome) and Westinghouse, with the outcome still uncertain.<sup>163</sup>

To address the national shortage of energy supply, caused by the outdated energy infrastructure and growing energy needs, the government pushes forward ambitious nuclear expansion plans.<sup>164</sup> As a result the state-owned South-African utility operator Eskom, wants to introduce 20 GW<sub>e</sub> of generating capacity by 2025. But as costs kept escalating, a Revised Strategic Plan was released in 2012 that scheduled 9.6 GW<sub>e</sub> (six units) by 2030. In 2014, South Africa signed a Nuclear Cooperation Agreement with Russia, covering the delivery of reactors with capacity up to 9,6 GW<sub>e</sub> (thus potentially the entire program).<sup>165</sup> However, the main obstacle remains Eskom's finances. The credit rating agency Moody's even downgraded Eskom's ratings in 2012 and it remains in critical financial condition ever since.<sup>166</sup>

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<sup>160</sup> Albright (1994, 37-47).

<sup>161</sup> van Wyk (2013, 6).

<sup>162</sup> The Koeberg construction site was attacked with bombs by the ANC in 1982, which led to the destruction of the control rods (Schneider 2009, 18).

<sup>163</sup> Schneider et al. (2016, 117).

<sup>164</sup> van Wyk (2013, 27).

<sup>165</sup> Schneider et al. (2016, 118).

<sup>166</sup> van Wyk (2013, 24).

#### 4.1.10 Israel

In 1949, only two years after the foundation of the State of Israel, France invited two Israeli scientists to study at the newly created nuclear research centre (CEA), which cemented the future close nuclear cooperation between the two countries. In 1954, the first French-Israeli nuclear agreement was signed (uranium extraction from phosphates and heavy water production) to be followed by the 1956 deal for a large research reactor as well as an underground reprocessing plant for the Dimona facility; separated plutonium was also delivered to the Israelis (Schneider 2009, 15). Israel has been for a long time (until the connection of the Iranian reactor Busheh) the only country in the Middle East that had at least one known large nuclear facility, although outside of the international safeguard system.<sup>167</sup>

Although, the Kennedy and Johnson administrations inspected the Dimona installations, the Israelis were adept at concealing their activities and by 1966, Israel reached the nuclear threshold but decided not to conduct an atomic test (Cohen and Burr 2006, 24). France saw Israel as an ally who could help them to hold on to Algeria in the 1960s (Bracken 2012), but also as a counterweight to Egypt that had considerably increased its military capabilities with assistance from Eastern bloc countries (Schneider 2009, 14). This motivated France to supply Israel with nuclear research reactors and detonator technology, which led to the Dimona plutonium facility and a first weapon in 1966.<sup>168</sup> One year later already, in 1967, during the six-day war, Israel had already two atomic bombs primed for hitting Cairo and Damascus.<sup>169</sup> In 1969, Richard Nixon made it clear—during the meeting with Israeli Prime Minister Golda Meir, where the main U.S.-Israel nuclear deal was struck—that Israel would no longer be asked to sign the NPT; in return, Israel would forgo nuclear testing and maintain a position of nuclear opacity with the often-repeated statement that *“It would not be the first nation to introduce nuclear weapons into the Middle East.”*<sup>170</sup> The most serious challenge to US-Israel

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<sup>167</sup> Khalilzad (1980, 15).

<sup>168</sup> France also supplied a research reactor to Iraq, which Israel bombed in 1981 and destroyed it before the plant became operational (Ramana and Mian 2016, 39).

<sup>169</sup> Bracken (2012, 102).

<sup>170</sup> Weiss (2013, 66).

nuclear deal came in 1979 with the conjoint nuclear testing with South Africa, off the coast of South Africa.

Nonetheless, until this day, Israel succeeded to maintain the opacity of its nuclear weapons program. In 2017, the Israeli nuclear arsenal is estimated to include 80-85 warheads at five locations; but like the other nuclear states, Israel has been modernizing its nuclear weapons program, too.<sup>171</sup> At the moment, there are no plans for nuclear power plants. Also, as Israel has not signed the NPT, getting international assistance for the construction of a commercial power plant would not be possible.

#### **4.1.11 North Korea**

North Korea operates a 5 MW<sub>e</sub> GCR fuelled by Magnox fuel at Yongbyon. The station started operating in 1986 and has been the centrepiece of North Korea's plutonium production. The reactor is a smaller version of the Calder Hall reactor and intended as a pilot reactor in preparation for two larger GCRs: a 50 MW<sub>e</sub> (at Yongbyon) and a 200 MW<sub>e</sub> reactor (near Taechon). These reactors were partially constructed in the early 1990s. A reprocessing plant began operating next to the Yongbyon station by 1990. North Korea also started the construction of an experimental LWR and enrichment program. North Korea became signed the NPT in 1985 but withdrew in 2003, leading to nuclear weapons test in 2006, 2009, and in 2013.<sup>172</sup> Overall North Korea has conducted six underground nuclear test (the most recent on September 13<sup>th</sup>, 2017) and is estimated to in possess a nuclear materials inventory for roughly 25 to 30 nuclear weapons.<sup>173</sup>

## **4.2 Countries with major nuclear industry but no scope-economies**

Countries which did not pursue the deployment of nuclear power under scope economies but were mainly interested in nuclear power for large-scale electricity production pursued in most cases a cooperative transfer of knowledge. The first NPPs were mostly built under

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<sup>171</sup> Kristensen and Norris (2017, 295).

<sup>172</sup> Braun et al. (2016). There

<sup>173</sup> Hecker (2017).

cooperation with a foreign country (mainly the U.S.) to acquire the technology; later on, in some cases an own nuclear supply chain was established; none of the countries were able to set up a nuclear infrastructure by themselves.

#### **4.2.1 Germany**

Although it was never acknowledged officially, a main motivation behind Germany's entry into the nuclear sector was driven by military considerations. In an historical account of post-World War 2, Radkau (1983) and Radkau and Hahn (2013) provide a detailed account of the emergence of the German nuclear program in the 1950s, driven by attempts to catch up with global trends, in different forms. Since the beginning, the development of nuclear technology was done on two parallel streams: one on the investigation towards proper innovative reactors, the other based on the acquisition of US technology.

##### **4.2.1.1 Federal Republic of Germany: Prototype and research reactors**

In 1956, the German Atomic Commission was founded and in the same year six research centres were set up, with Karlsruhe and Jülich being the most important ones. Both were publicly-funded and while the research centre in Jülich mainly focused on HTR, scientists in Karlsruhe concentrated first on the development of HWR and switched later on to FBR technology. On October 31<sup>st</sup>, 1957, the first research reactor—a pool-type reactor called the “Atomic Egg”—went into operation in Garching (Bavaria). Besides the research centres trying to develop an own reactor design, industry companies like Siemens, AEG, RWE, and Brown Boveri and Krupp got involved in nuclear power. Thomas (1988) points out, that these industrial interests were instrumental in setting up the German Atomic Forum in 1959—a powerful sponsor of nuclear power. Thus, Siemens was interested in HWR, Brown Boveri and Krupp in HTR, Deutsche Babcock developed the PWR for civil marine propulsion.

In 1957, the Atomic Commission—largely dominated by big electrical and chemical manufacturers—formulated the “Elville program” that declared which direction nuclear energy should take in the coming years. The first priority lay on the development of an own German reactor design in order to secure independency from foreign corporations. If foreign reactor types would conflict with domestic ones, they should not be supported. The goal to achieve

was 5,100 MW<sub>e</sub> of reactor capacity to be in operation by 1965. The priority of an own German design was also motivated by the idea that at that time no existing reactor design was ideal and that they were currently only in the development stage towards the optimal reactor design in the long-term, probably the FBR. One year later, in 1958, the Eltville program was re-evaluated with the conception of five reactor types, which would be most valuable to enter the development stage:

- a PHWR;
- a light water moderated gas-cooled reactor;
- a gas-cooled, graphite moderated, natural uranium reactor;
- a high temperature reactor with gas-cooling and enriched uranium;
- and an advanced reactor cooled by an organic fluid.<sup>174</sup>

During WW2, German physicists (Heisenberg among others) worked on plans for a HWR fuelled by U-238, but even if these plans were abandoned, they influenced the early research on nuclear technologies.<sup>175</sup> It was thought, that the official way to go forward was natural uranium, inspired by the British achievements in Calder Hall. The goal to design a “German reactor” was reached in 1960 in Karlsruhe with the grid connection of the 12 MW<sub>e</sub> HWR “FR2” and the construction start of the 50 MW<sub>e</sub> “MZFR”, also in Karlsruhe. The former was only used for research purposes and served as a basis for following reactors. MZFR, the multi-purpose reactor supplied by Siemens, was completed in 1965 and mostly used for electricity generation. Only RWE and Bayernwerk thought enriched uranium was the way to go and ordered already in 1956—when the U.S. lifted the embargo on enriched fuel—a LWR for the VAK Kahl station.<sup>176</sup> VAK Kahl started construction in 1958, the BWR—supplied by AEG and General Electric—was connected to the grid in 1961 (shutdown in 1985). In 1959 BBC/Krupp ordered a reactor from Siemens which was based on the “pebble-bed” design for

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<sup>174</sup> Thomas (1988, 140–41).

<sup>175</sup> Radkau and Hahn (2013, 25).

<sup>176</sup> Radkau and Hahn (2013, 50).

the Jülich site. Both experimental reactors AVR Kahl and AVR Jülich had a net power of 15 MW<sub>e</sub>, were used for research purposes, and were entirely state-financed.

#### 4.2.1.2 The first demonstration and “commercial” reactors

In 1962, RWE and Bayernwerk placed an order at GE for the supply of the first larger reactor in Germany: a 237 MW<sub>e</sub> BWR for the Gundremmingen station in Bavaria. Gundremmingen-A was the first demonstration reactor in Germany. This order came within the framework of the Euratom-U.S. power station program and suggested that LWR technology was the quickest way of establishing a German reactor industry. Contrary to the U.S. research on further reactor technologies was continued after the first demonstration reactor.

AEG and Siemens sought to develop and improve their LWRs over their American parent designs. In order to improve the efficiency, AEG installed in the Lingen plant—which was similar to the GE Mark 2 BWR—a superheater using oil, this increased the production by 90 MW<sub>th</sub> to 250 MW<sub>th</sub>.<sup>177</sup> The last demonstration reactor was Obrigheim (340 MW<sub>e</sub>, 1,050 MW<sub>th</sub>) constructed by Siemens (KWU) under US license, Obrigheim was also the last reactor to receive government subsidies, all subsequent orders were wholly utility financed.<sup>178</sup> The first three demonstration reactors relied on public financing, being constructed following the “Gundremmingen model”, where the responsibility of the private investor and operator was reduced to a third of total costs (in Gundremmingen: < 100 mn DM).<sup>179</sup> At that time, it was expected that a NPP would be three times as expensive as a conventional power plant, thus the Atomic Commission followed, that two thirds of the costs must be taken over by government subsidies.<sup>180</sup> Another reactor design from this early stage was the HWGCR Niederaichbach built by Siemens and the THTR-300 pebble bed reactor (the “thorium-reactor”) operational from 1985 until 1987.

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<sup>177</sup> AEG also installed the prototype reactor Großwelzheim where the nuclear energy was used to superheat the steam.

<sup>178</sup> Thomas (1988, 142–43).

<sup>179</sup> Hirschhausen (2017, 8).

<sup>180</sup> Radkau and Hahn (2013, 127).



Two years later, in 1967, construction of the second PWR and the first “commercial” reactor was launched: the 640 MW<sub>e</sub> NPP Stade equipped with a Siemens BWR (under Westinghouse license). The station started operations in 1972 and is currently being decommissioned. One year later, construction of the NPP Würgassen, with a BWR, built by AEG (under US license) started; the plant was connected to the grid in 1975. Table 18 gives details about the three demonstration reactors and the first two large scale “commercial” reactors in Germany.

Station	Capacity [MW <sub>e</sub> ]	Reactor Design	Vendor/Designer	Construction time	Permanent Shutdown
Gundremmingen-A	237	BWR	AEG, GE	1962–1966	1977
Lingen	183	BWR	AEG, GE	1964–1968	1977
Obrigheim	340	PWR	Siemens	1965–1968	2005
Stade	640	PWR	Siemens	1967–1972	2003
Würgassen	640	BWR	AEG	1968–1975	1994

**Table 18: The three German demonstration reactors and the two first “commercial” NPPs**

Source: Own depiction based on IAEA PRIS Database (2017).

#### 4.2.1.3 The emergence of KWU: the German nuclear vendor

In 1968, Kraftwerke Union AG (KWU) was created with the bundling of the conventional and nuclear activities of AEG and Siemens. One year later, KWU won an order to supply Biblis-A with the first German indigenous PWR design: the 1,167 MW<sub>e</sub> reactor was in operations from 1975 until 2011. In 1970, Siemens cancelled its license contract with Westinghouse and supplied in 1972 a second PWR to Biblis B, Neckarwestheim-1, and Unterweser. The PWRs had a power output between 785–1,345 MW<sub>e</sub> and were connected to the grid between 1976–1979. Contrary to the U.S., where Westinghouse supplied the PWR and GE the BWR, KWU supplied the two designs, but (until 1973) with the Siemens PWR team at Erlangen and the AEG BWR team at Frankfurt. Simultaneously negotiations for reactor exports with Iran, Spain, Switzerland, and Brazil were progressing.<sup>181</sup> The AEG side of KWU supplied between 1970 and 1974, the reactor type BWR-69 to the stations Isar 1, Brunsbüttel, Philippsburg-1

<sup>181</sup> Thomas (1988, 144).

and Krümmel. These reactors differed from the previous BWR built under US license and the reactor was an own German concept.<sup>182</sup> AEG encountered major technical problems (severe difficulties arose due to intergranular stress corrosion cracking, all four reactors had to undergo major repairs) with the BWR-69, which led to heavy losses; in 1977 Siemens bought out the entire AEG stake. Krümmel was with net capacity of 1,346 MW<sub>e</sub> one of the largest BWRs worldwide. All these plants had a bad operational record and were shut down in 2011. In 1972, an order for the 300 MW<sub>e</sub> FBR Kalkar was placed, the government-funded reactor was to be supplied by an international consortium of German, Dutch, and Belgian companies with a 70 percent share taken over by the 100 percent Siemens-subsi-dary Interatom who had supplied the KNK experimental FBR.<sup>183</sup> The FBR never entered operations.

In 1975, RWE ordered a PWR (1,219 MW<sub>e</sub>) at the only KWU-competitor: Brown Boveri Reaktor GmbH (a joint-venture of Brown, Boveri & Cie. and Babcock&Wilcox) for the Mülheim-Kärlich site. But the construction was stopped by a court ruling in 1987 and the plant was never connected to the grid.<sup>184</sup> In the same year, in 1975, construction of the 1,275 MW<sub>e</sub> PWR of the reactor type “pre-convoi” (“Vor Konvoi”) for the Grafenrheinfeld station started construction, the KWU reactor was in operations from 1982 until 2015. In 1976, construction of two pre-convoi reactors were launched: Brokdorf and Grohnde, which started operations in 1985/86. One year later, the last Vor-Konvoi construction project was started: Philippsburg 2, the plant was connected to the grid in 1988. In 1976, KWU supplied two of its “second generation” reactors to Gundremmingen B and C, the BWR-72 had a net capacity of around 1,280 MW<sub>e</sub> and were commissioned in 1984/85.

In 1982, KWU supplied its last generation of PWRs, the convoy (Konvoi) reactor, which a net capacity between 1,310 and 1,410 MW<sub>e</sub> to the stations Emsland, Isar-2, and Neckarwestheim-2. These were the last NPPs to be connected to the German grid in 1988/89. The convoy reactor was the first German standardized PWR with among others the following main

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<sup>182</sup> Kromp et al. (2010).

<sup>183</sup> Thomas (1988, 146).

<sup>184</sup> Radkau and Hahn (2013, 210).

features: one common set of engineering documents applied to all projects and only four licensing steps (three for construction and one for commissioning).<sup>185</sup> The German nuclear company supplied around 20.5 GW<sub>e</sub> of nuclear capacity or 17 NPPs (See Table 19). In 2001, KWU was merged into a French-German joint venture Framatome SA.

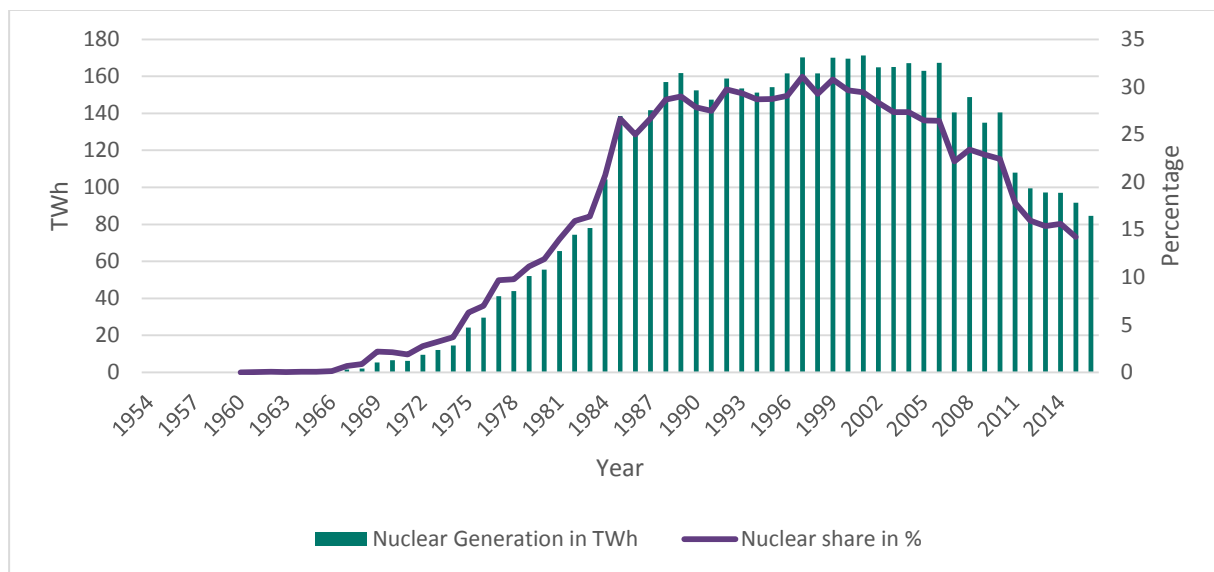
Reactor design	Construction Capacity in MW <sub>e</sub> (NPP)	Stations	Construction time	Permanent Shutdown
PWR	4,537 (4)	Biblis-A, Biblis-B, Neckarwestheim-1, Unterweser	1970–1978	2011
PWR Pre-Convoi	5,447 (4)	Grafenrheinfeld, Philippsburg-2, Grohnde, Brokdorf	1975–1984	Grafenrheinfeld in 2015
Convoi	4,055 (3)	Isar 2, Emsland, Neckarwestheim-2	1982–1989	
BWR-69	3,885 (4)	Brunsbüttel, Philippsburg-1, Isar-1, Krümmel	1970–1983	2011
BWR-72	2,572 (2)	Gundremmingen-B/-C	1976–1984	Gundremmingen-B in 2017
	<b>20,496 (17)</b>			

**Table 19: The KWU reactors**

Source: Own depiction based on IAEA PRIS Database (2017).

In 2011, as a response to the Fukushima disaster, the 13<sup>th</sup> amendment of the Atomic Energy Act of 2011 withdrew the operating licenses of the seven oldest NPPs (BWR-69 and the first KWU PWRs) and Krümmel. The Pre-Convois are scheduled to shut down in 2019 and 2021. Gundremmingen-B was shut down in 2017, unit C is scheduled for shut down in 2021. The latest reactors to shut down are the three convoi reactors in 2022. Figure 24 illustrates the development of the nuclear share and the generation in Germany.

<sup>185</sup> Thomas (1988, 150).



**Figure 24: Nuclear share and nuclear generation in Germany, 1960–2016**

Source: Own depiction based on World Bank (2016) and BP (2017).

#### 4.2.1.4 Nuclear power in the German Democratic Republic (GDR)

In 1956, the USSR agreed to cooperate with the German Democratic Republic for the construction of its first pilot plant Rheinsberg, north of Berlin. Construction started in 1960 and the plant achieved criticality in 1966. The PWR (VVER-70) was of the first generation of Soviet PWRs and had a net capacity of 62 MW<sub>e</sub>. Early plans in 1957 called for construction of a network of 20 NPPs by 1970.<sup>186</sup>

In 1970, construction of the Greifswald station started in Lubmin on the shore of the Baltic Sea (construction on units 3 and 4 started two years later). All five units were PWRs (VVER V-230) constructed with the help of Soviet know-how and had a net capacity of 408 MW<sub>e</sub>. Greifswald-5 (V-213) went online in 1989. Construction of unit 6 was nearly completed, while unit 7 and 8 were still under construction, when the decision was taken to shut down all East German reactors at the moment of the German reunification (1990). The decision

<sup>186</sup> Pravda (1957); Neues Deutschland (1957) in Jonas (1959, 380).

was mainly economical driven, as to continue operations under the “West German” Atomic law, a high number of safety requirements would had been necessary.<sup>187</sup>

#### 4.2.1.5 Summary

(West) Germany started with a lot of different prototype reactors with the intention to build an own German technology. The first focus on FBRs and heavy water reactors switched to the LWR technology as the utilities ordered LWRs for their demonstration reactors. The concept of an own German reactor was dropped, when LWRs were constructed under GE and Westinghouse licenses. But Germany was the first country that succeeded in becoming independent from the U.S. after opting for the LWR technology and developed own indigenized designs. The PWR technology proved more reliable and with the convoi design, the first German standardized PWR concept was introduced. Table 20 summarizes the deployment of nuclear power in Germany.

<b>First construction start (grid connection):</b>	1958: VAK Kahl (1961)
<b>Latest construction start (grid connection):</b>	1982: Neckarwestheim-2 (PWR Konvoi, 1989)
<b>Latest grid connection:</b>	1989: Greifswald-5 (VVER V-412)
<b>Operational capacity (NPP):</b>	9.52 GW <sub>e</sub> (7)
<b>Shut down capacity (NPP):</b>	16.86 GWe (29)
<b>Construction capacity (NPP):</b>	-
<b>Installed technologies (or under constr.) (NPP):</b>	PWR (20), BWR (11), FBR (1), HTGR (2), HWGCR (1), PHWR (1),
<b>Most installed reactor design (NPP):</b>	PWR Pre-Convoi (4), BWR-69 (4)

**Table 20: Summary for Germany**

Source: Own depiction.

#### 4.2.1 Japan

Until 2017, Japan was the only country ever to be bombarded with nuclear weapons, fired on Hiroshima and Nagasaki in August 1945. After WW2, the U.S. gradually introduced Japan to nuclear technology: In 1954, the Operations Coordinating Board—a committee of the

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<sup>187</sup> Thierfeldt and Schartmann (2012, 42).

United States Executive created in 1953, reported to the National Security Council and was responsible for integrating the implementation of national security policies across several agencies—recommended a "*vigorous offensive on the non-war uses of atomic energy*" for Japan. Already in the context of the "Atoms for Peace" speech the possibility of building a nuclear reactor in Japan was evaluated by the U.S.<sup>188</sup> Consequently, in early 1955, Japan and the U.S. agreed to cooperate in research and development of atomic energy, followed by the passing of the Atomic Energy Basic Law, laying the foundation for the U.S. to supply Japan with fuel and nuclear technology.<sup>189</sup> Several research reactors were constructed. Japan's first commercial reactor was a British MAGNOX, however, the country quickly switched to US LWR technology. The Japanese-U.S.-cooperation allowed Japanese companies such as Mitsubishi, Toshiba, and Hitachi to construct NPPs by themselves later-on.

#### 4.2.1.1 Research Reactors

Japan's first two reactors—the Japan Research Reactor (JRR) No. 1 and 2—were built by the Japanese under US license. JRR-1 was a small BWR (50 kW<sub>e</sub>) and reached first criticality in 1957. Three years later, JRR-2 started operation—a Chicago Pile-5 (CP-5) type with 10 MW<sub>th</sub> thermal output.<sup>190</sup> The 10 MW<sub>th</sub> light-water pool type reactor JRR-3 reached first criticality in 1962—a milestone in Japanese nuclear reactor history. For the first time a reactor was constructed solely with home-grown technology. With several modifications in 1990, the power of JRR-3 amounted to 20 MW<sub>th</sub>.<sup>191</sup>

One year later, for the first-time electricity was generated by the Japan Power Demonstration Reactor (JPDR), a BWR with the net capacity of 10 MW<sub>e</sub>, in service from 1965 until 1976. From 1986 until 1996, JPDR was decommissioned and, hereby, served as a centre for devel-

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<sup>188</sup> Jones (2010, 197).

<sup>189</sup> The change in opinion from atom reluctance in post-war Japan to acceptance of nuclear technology was accompanied by several campaigns initiated by the US Embassy, the US Information Service, as well as the CIA (Kuznick 2011).

<sup>190</sup> Yamashita (2015).

<sup>191</sup> Ibid.

opment and demonstration of decommissioning technology as well as a field for data and knowledge acquisition.<sup>192</sup>

For the purpose of nuclear research, different prototype reactor types were built such as the Japan Materials Testing Reactor (JMTR) in 1968 and the Nuclear Safety Research Reactor (NSRR) in 1975. The JMTR is a 50 MW<sub>e</sub> light water cooled reactor which was utilized among other purposes for irradiation tests of fuel for LWRs. The NSRR was constructed as a so-called TRIGA-reactor (Training, Research, Isotopes, General Atomic) with a pulse power of 23 MW<sub>e</sub>. It mainly served as a facility for nuclear fuel safety research.

#### 4.2.1.2 Fast breeders and advanced thermal reactors

In the early days, Japan also invested in research and development of FBR technology. In 1967, the Japan Atomic Energy Commission (JAEC) launched a program and established the Power Reactor and Nuclear Fuel Development Corporation (PNC). Ten years later, in 1977, the PNC-built experimental FBR Joyo reached criticality—the first FBR in Japan. In the following years of operation, the core was updated recurrently from initial 50 MW<sub>th</sub> to 140 MW<sub>th</sub> in 2003. The main purpose of Joyo was to deliver technical experience for follow-up FBR projects.<sup>193</sup> JAEC stressed in 1987, that fast breeders were crucial for countries with high energy consumption. Therefore, the Commission advised the construction of the FBR Monju and several other demonstrations FBRs (DFBR). According to the long-term plan, fast breeders ought to be commercialized between 2020 and 2030.<sup>194</sup>

Monju was designed with a 246 MW<sub>e</sub> power output and achieved first criticality in 1994. An accident in the same year caused a long-term shutdown of 15 years. Besides reactor technology, PNC also carried out reprocessing activities to produce MOX-fuel for Advanced Thermal Reactors (ATR) and FBRs. Both, utilities and manufacturers of nuclear technology benefited from the FBR program by sending staff and equipment. Japan Atomic Power Com-

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<sup>192</sup> JAEA. 2018. "JPDR (Japan Power Demonstration Reactor)". April 23, 2018. [https://www.jaea.go.jp/english/04/ntokai/decommissioning/01/decommissioning\\_01\\_01.html](https://www.jaea.go.jp/english/04/ntokai/decommissioning/01/decommissioning_01_01.html).

<sup>193</sup> Yoshimi and Hachiya (1990).

<sup>194</sup> Kondo (1998, 619).

pany (JAPC) stands out as a major player in the FBR development and commercialization. The company was charged with the supervision of the balance-of-plant part of Monju. Furthermore, JAPC accepted to design, construct, and operate the first DFBR. PNC carried out research for installing a FBR technology base for economically competitive plant designs. Feasibility studies and the technology demonstrations regarding the commercialization of fast breeders received funding by the Ministry of International Trade and Industry.<sup>195</sup>

In the early 1990s, the FBR technology was promoted as a “safe and competitive technology” leading in the 21st century to the replacement of LWRs. The downward-revised nuclear expansion uncovered that the commercialization by the 2020s and 2030s was too ambitious.<sup>196</sup> The Japanese government, however, decided to continue its spending as well as to support relevant utilities in favour of the FBR. In 2010, JAEA resumed the operation of Monju but already after five months another incident paralyzed the unit. A 3.3-ton machine fell into the reactor vessel and caused immediate shutdown. After the Fukushima Daiichi incident in March 2011, Monju—like all NPPs in Japan—was subjected to security checks by the newly established Nuclear Regulation Authority (NRA) and failed. In May 2013, the agency stated that JAEA is not able to operate the reactor safely and thus, the government needed to find a new operator. This caused serious difficulties so that in December 2016 the decision was made to stop operations and to decommission Monju.<sup>197</sup>

However, according to the government, the official policy direction regarding FBRs has not changed. Japan pursues cooperation with France on the ASTRID-Program (Advanced Sodium Technological Reactor for Industrial Demonstration). On May 5th, 2014, the General Arrangement was signed in Paris by Japanese and French representatives. The collaboration will end on December 31st, 2019.<sup>198</sup> Parallel to this, Japan resumes its efforts to open the Rokkasho reprocessing plant in 2018.

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<sup>195</sup> Kondo (1998, 620–621).

<sup>196</sup> Ibid.

<sup>197</sup> Takubo (2017).

<sup>198</sup> Kayama (2014).



Besides light water reactors and fast breeders, Japan developed a so-called Advanced Thermal Reactor (ATR). This term describes a heavy water moderated and boiling light water cooled reactor design (HWLWR). Its main benefits are the good characteristics of using MOX fuel. In 1966, the starting signal for ATR technology development was given by the JEAC. A national research project was initiated mainly accompanied by PNC as a key partner. International experiences with HWRs from Canada and the U.K. as well as the simple applicability of LWR technologies made the construction of an experimental reactor unnecessary.<sup>199</sup> Thus, PNC started right off the bat with the design of a prototype reactor, the Fugen Nuclear Power Station. It was built in 1972 and reached first criticality in 1978 with a net capacity of 148 MW<sub>e</sub>. Fugen ATR was put into permanent shutdown in March 2003 and since 2008 the reactor is under decommissioning.

In 1973, design works for a Demonstration ATR (DATR) as a successor of Fugen ATR were launched by PNC with the main purpose to prove the feasibility and efficiency of the design. The plans were presented to JAEC which approved the construction of a 606 MW<sub>e</sub> demonstration reactor in 1982. The Electric Power Development Company (EPDC) was charged with its construction and operation enjoying guaranteed support of the government as well as the utilities and PNC. One year later, site selection surveys were carried out at Ohma in the Aomori prefecture.<sup>200</sup> However, in 1995, the project was abandoned.<sup>201</sup>

In the 1990s, the ATR technology was seen as a supplement for FBRs which were designated to replace LWR in the long term. Due to the capability to load fuel from recovered uranium ATRs were intended to reduce uranium consumption.<sup>202</sup>

#### 4.2.1.3 Commercial Reactors

In 1966, Tokai-1 started operation as the first “commercial” NPP in Japan: a MAGNOX reactor from the U.K. (160 MW<sub>e</sub>). The reactor pressure vessel as well as the in-core structure was

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<sup>199</sup> Mita et al. (1993).

<sup>200</sup> Ibid.

<sup>201</sup> World Nuclear Association. 2017. "Nuclear Power in Japan." December 12, 2017. <http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/japan-nuclear-power.aspx>.

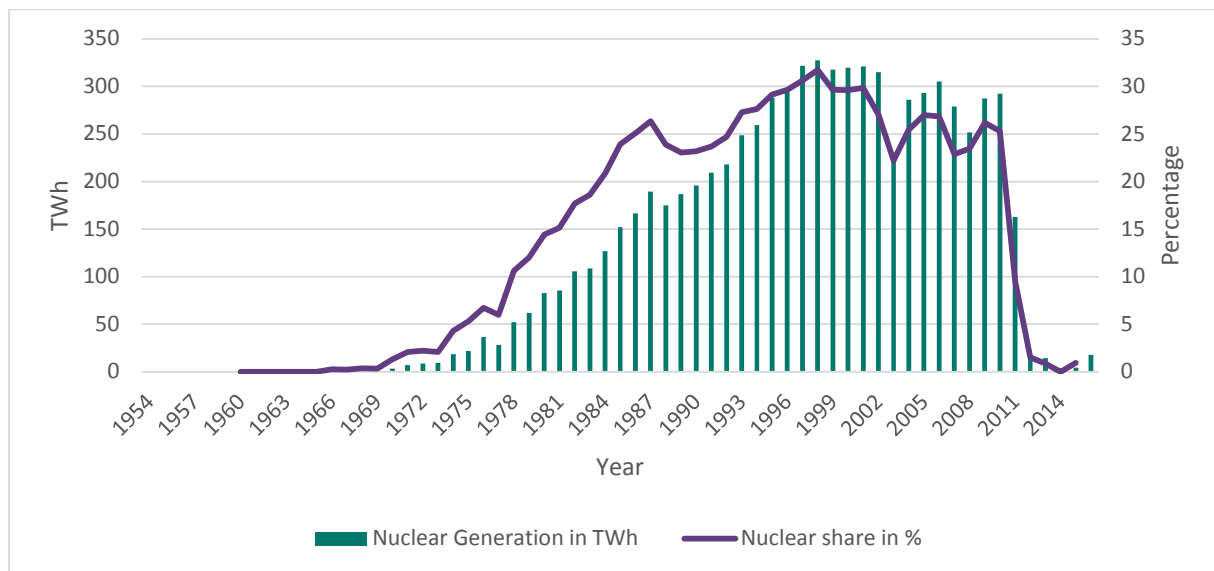
<sup>202</sup> Mita et al. (1993).



60 years by a consortium of Toshiba, Hitachi and GE. Kashiwazaki Kariwa-6 and 7, Hamaoka-5, and Ohma, for instance, use this design. Currently, the consortium is researching a more powerful 1,800 MW<sub>e</sub> ABWR class. Apart from high performance reactors, GE-Hitachi promotes a small BWR with a net capacity between 600 and 800 MW<sub>e</sub> predominantly in South-east Asia.

#### 4.2.1.4 Post-Fukushima

Figure 25 illustrates Japan's path to become a major nuclear country. One can clearly see that, after the accident in Fukushima in March 2011, the nuclear share collapsed. In 2017, nuclear energy contributed to the total electricity production of about 806 TWh—only a marginal 3.6%.



**Figure 25: Nuclear share and nuclear generation in Japan, 1960–2016**

Source: Own depiction based on World Bank (2016) and BP (2017).

Currently, two reactors are under construction in Japan. In 2005, works at the 1,373 MW<sub>e</sub> ABWR Shimane 3 started. Prior to Fukushima, the reactor pressure vessel has been installed in 2009 and begin of commercial operation was set to 2011. The construction was complet-

ed by 91.3% in December 2010 according to the operator Chugoku Electric Power Co.<sup>206</sup> The accident caused a delay of several years but in February 2018, Chugoku announced plans to apply for permission to start operation of Shimane 3.<sup>207</sup> Since 2010, the ABWR reactor of the Ohma plant is still under construction. After Fukushima, works were interrupted at a stage of completion of about 40% but the construction was resumed in October 2012. After several modifications and delays to the initial construction plan, Ohma is projected to be finished in 2024.<sup>208</sup>

APWR made in Japan reach a capacity of 1,700 MW<sub>e</sub>. With full-core MOX capacity, Mitsubishi currently offers the APWR+ type to customers in Europe and the U.S. With the acquisition of Westinghouse in 2006, Toshiba joined the PWR business. Westinghouse/Toshiba's main product is the AP1000, a two-loop, 1100 MW<sub>e</sub> PWR. MHI introduced a compilation of its PWR technologies in two market specific configurations, the EU- and the U.S.-APWR.

#### 4.2.1.5 Summary

In accordance with US foreign policy Japan was provided with civil nuclear technology for clearly non-military purposes within the context of Eisenhower's Atoms for Peace doctrine. After a campaign to promote nuclear technology for electricity generation led by US authorities, the first research reactors were built. With the gained experience and know-how, the Japanese were quickly able to build reactors independently from their American donors. The country became the third largest country in the world using nuclear energy predominantly in BWRs (33) and PWRs (24). Toshiba Co has the biggest market share with 17 BWRs (10 BWR-5, 5 BWR-4, 2 ABWR) and additional two in cooperation with General Electric; 10 BWRs were constructed by Hitachi. Especially in the late 1960s and early 1970s 13 commercial reactors were built under US license. The more recent cooperation with US companies from 1990

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<sup>206</sup> World Nuclear News. 2011. "Start-up of new Shimane unit delayed." February 15, 2011. [http://www.world-nuclear-news.org/NN-Start\\_up\\_of\\_new\\_Shimane\\_unit\\_delayed-1502115.html](http://www.world-nuclear-news.org/NN-Start_up_of_new_Shimane_unit_delayed-1502115.html).

<sup>207</sup> JAIF. 2018. "Chugoku Electric Power Applies to NRA for Compatibility Examination for Shimane-3." February 20, 2018. <http://www.jaif.or.jp/en/chugoku-electric-power-applies-to-nra-for-compatibility-examination-for-shimane-3/>.

<sup>208</sup> World Nuclear News. 2016. "Further delay in completion of Ohma plant." September 12, 2016. <http://www.world-nuclear-news.org/NN-Further-delay-in-completion-of-Ohma-plant-1209164.html>.

until 2010 resulted in the development of ABWRs. In the PWR business Mitsubishi Heavy Industries is the biggest actor with 18 reactors built. The first PWRs were Westinghouse constructions. Japan's only FBR Monju has turned out to be prone to accidents and is currently being decommissioned. Japan's two newbuild projects Ohma and Shimane-3, both ABWRs, are not yet completed. Ohma is projected to be finished in 2024.

<b>First construction start: (grid connection)</b>	1961: Tokai-1 (1965)
<b>Latest construction start (grid connection):</b>	2001: Ohma-1: (-)
<b>Installed capacity (NPP):</b>	39.93 GW <sub>e</sub> (42)
<b>Shut down capacity (NPP):</b>	9.05 GW <sub>e</sub> (18)
<b>Construction capacity (NPP):</b>	2.76MW <sub>e</sub> (2)
<b>Installed technologies (or under constr.) (NPP):</b>	BWR (35), PWR (24), FBR (1), GCR (1), HWLWR (1)
<b>Most Installed reactor design (NPP):</b>	BWR-5 by Toshiba

**Table 22: Summary for Japan**

Source: Own depiction.

#### 4.2.1 Republic of Korea

After WW2, Korea was freed from Japanese occupation. After the Korean war, the country found itself split into two, the Republic of Korea (“South Korea”), and the People’s Republic of Korea (“North Korea”). To become a strong and modern nation, Korea staked on science and technology including nuclear energy as a symbol for power and progress. In the context of the Cold War, the north and the south part of Korea set up independent governments resulting into the Korean War from 1950 to 1953. The conflict disrupted the common endeavour for industrialization and a unified modern society. As a consequence of the separation and the Cold War, South Korea was directly threatened by nuclear attacks. For both Koreas, the threat of staying weak and vulnerable to aggressions from the neighbour and its protector induced a policy of technological, industrial as well as military armament.<sup>209</sup>

In 1956, Seoul and Washington agreed on the cooperation about the peaceful use of nuclear energy in the course of the “Atoms for Peace” initiative. The Atomic Energy Department was

<sup>209</sup> Jasanoff and Kim (2009, 131-132).

established and one year later, South Korea joined the IAEA. In 1958, the nuclear power program was given a legal basis with the Atomic Energy Act and several new organizations such as the Atomic Energy Department (AED) or the Korea Atomic Energy Research Institute (KAERI) established. This indicated the starting signal for NPPs and research efforts. In 1961, the three former regional electricity companies merged into the Korea Electric Company which later became the Korea Electric Power Corporation (KEPCO). The new entity combines responsibilities for the construction of NPPs as well as various nuclear related activities.<sup>210</sup> KEPCO is a state-owned corporation.

#### **4.2.1.1 The modernization and military perspective of nuclear power**

One strong driver of nuclearizing the country was certainly the vision of economic modernization and industrialization. The Republic of Korea is scarce on natural resources. After an energy supply cut from the North to the South in 1948, Korea stressed the importance to be less dependent from energy imports. Major government representatives and political leaders considered nuclear power as an important instrument to improve energy security and a guarantee for international sovereignty. At the time, nuclear expansion was used synonymous to energy security.<sup>211</sup> Moreover, the promotion of advanced technology was seen as a key driver for economic growth and prosperity.

The military dimension of the nuclear power program in South Korea, however, should not be underestimated. In 1969, President Park Chung Hee introduced the Weapons Exploration Committee (WEC) in the context of the Force Improvement Plan, a strategy to modernize and enhance defence forces. The WEC was tasked among other things to obtain enriched uranium for the development of nuclear weapons.<sup>212</sup> In the 1970s, US President Nixon and Carter fuelled these efforts affiliated to the nuclear weapons program after their call on Korea to strengthen its capacity of self-defence. The strategy of strengthening self-defence by reducing US military presence in Asian allied countries is often referred to as the Nixon

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<sup>210</sup> Valentine and Sovacool (2010, 7975).

<sup>211</sup> Kim and Byrne (1996, 271-297).

<sup>212</sup> Siler (1998, 63-64).

Doctrine.<sup>213</sup> However, in 1976 the military efforts of the nuclear power program were abruptly stopped after the U.S. had realized that Korea was carrying out efforts to arm itself with nuclear rather than conventional weapons. The reaction was that the U.S. threatened to end the cooperation regarding civil nuclear technology in case the Koreans did not abandon plans to pursue the development of nuclear weapons.<sup>214</sup> In 1977, President Park concluded that the country "will not go nuclear". US President Carter cancelled the plan to reduce military forces in South Korea one year later and since 1975, the NPT is in effect.<sup>215</sup>

#### 4.2.1.2 Research Reactors

With the support from the U.S., Korea's first research reactor, a 100 kW<sub>th</sub> version of the TRIGA mark-II, reached criticality in 1962. The Korean Research Reactor No. 1 (KRR-1) mainly served as a training reactor for nuclear engineers and university students. With an update with home-grown technology in 1969 it reached a power level of 250 kW<sub>th</sub>. The project for a second research reactor was launched in 1969. The KRR-2 provided additional experience for nuclear engineers and a larger infrastructure for nuclear technology to prepare the construction of the first commercial reactor in the late 1970s. Both research reactors were permanently shut down in 1996, and subsequently decommissioned.<sup>216</sup>

The successor of the KRRs reached criticality in 1995. The High-flux Advanced Neutron Application Reactor (HANARO) is a 30 MW open-pool type multi-purpose research reactor run by KAERI. It combines different domestic nuclear technologies and various experimental facilities including an irradiation facility for the development of new fuels for example high burn-up PWR fuel.<sup>217</sup>

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<sup>213</sup> Kang and Feiveson (2001, 71-72).

<sup>214</sup> Kim and Byrne (1996, 271-297).

<sup>215</sup> Kang and Feiveson (2001, 72).

<sup>216</sup> Ha et al. (2011).

<sup>217</sup> Ibid.

#### 4.2.1.3 From turnkey plants to Korean technology

In 1968, Korea passed a long-term nuclear power development plan and signed the Treaty on the Non-Proliferation of Nuclear Weapons which came into effect in 1975. At the same time, the country gave the starting signal for bids to construct the first commercial NPP. In the early stages of the nuclear power program, transfer of technology from overseas was crucial. However, Korea's insufficient foreign currency reserves were a major obstacle and considerably high financial risks associated with NPPs hampered the setup of nuclear infrastructure. To tackle these difficulties, the Korean state stood in for the nuclear power program and expressed its strong commitment as well as investment priority to affiliated projects. The construction of the first NPP was made possible by a loan from EXIM Bank under the credit of the state-controlled KEPCO.<sup>218</sup> In 1971, a PWR WH 60 from Westinghouse was bought. The 558 MW<sub>e</sub> reactor (Kori-1) started commercial operations in 1978. Kori-2, a 618 MW<sub>e</sub> PWR WH F, was connected to the grid in 1983. One year earlier, the heavy water moderated PWR Wolsong-1 went online. This CANDU 6 reactor was purchased from AECL from Canada and produced 670 MW<sub>e</sub>. Three additional reactors of the same type were commissioned in 1997, 1998, and 1999 to complete the Wolsong Plant.

In the following years after the first reactor began operation, the Kori plant was expanded by two more WH F reactors from Westinghouse. In 1981, two additional reactors of the same type were installed in the Hanbit Plant and connected to the grid in 1987/87. While the first reactors in South Korea were turnkey plants by Westinghouse and AECL, the country witnessed a successful development of the heavy and chemical industry and thus managed to include domestic subcontractors in the NPP construction supply chain.<sup>219</sup> Four of these reactors, with a cooperative transfer of knowledge were: Kori-3 and 4, and Hanbit-1 and 2 supplied by Westinghouse (both PWR WH F, between 900 and 1,000 MW<sub>e</sub> each), and the Hanul Plant, for which Framatome supplied two FRANCE CPI (two times 903 MW<sub>e</sub>) in 1983. The reactors were connected in 1988 and 1989.

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<sup>218</sup> Choi et al. (2009, 5499).

<sup>219</sup> Choi et al. (2009, 5496-5503).



Intensive research and development efforts mainly conducted by KAERI and KEPCO aimed at raising the share of domestic technology in the nuclear industry. Korea started to standardize and indigenize the technology.<sup>220</sup> This corresponds to a transfer of knowledge in both management and design of nuclear reactors construction. Table 23 shows the organizations involved in the localization process and their respective roles. KEPCO was responsible for the management of the construction (assisted by foreign companies e.g., Westinghouse and Framatome). Later, KEPCO and KAERI in cooperation with Doosan Heavy Industries and Construction Co. Ltd. designed the Optimized Power reactor 1000 (OPR1000), often referred to as the Korean Standard Nuclear Power Plant.<sup>221</sup> However, some components were designed and fabricated overseas or in license domestically. After a construction period of five years, two such reactors were connected to the grid in 1994/95 (Hanbit-3 and 4). KEPCO internalized the management of the construction with foreign subcontractors such as General Electric and Combustion Engineering (CE). With unit 5 and 6, the Hanbit Plant was completed by two additional OPR1000 in 2001 and 2002. After some design modifications, six improved OPR1000s were fully constructed by Korean Companies: Hanul-5 and -6 were connected to the grid in 2003 and 2005, Shin-Kori-1 and -2 followed in 2010 and 2012, and Shin-Wolsong-1 and -2 in 2012 and 2015.

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<sup>220</sup> Ibid.

<sup>221</sup> Ibid.

	KEPCO	KAERI	KOPEC	Doosan	KNFC	KPS
Project Management	x					
Design and Architectural Engineering			x			
NSSS						
Design		x				
Manufacture				x		
Turbine generator				x		
Balance of Plant						
Design			x			
Manufacture				x		
Repair						x
Fuel (LWR)						
Design		x				
Manufacture					x	
Fuel (HWR)		x				

**Table 23: Organizations in the Korean localization process<sup>222</sup>**

Source: Own depiction based on Choi et al. (2009, 5503).

The latest reactor development is the Advanced Power Reactor 1400 (APR1400) designed by KEPCO and its subsidiary Korea Hydro and Nuclear Power Company (KHNP). The APR1400 is an evolution of the OPR1000 with a gross capacity of 1,400 MW<sub>e</sub> and a design lifetime of 60 instead of 40 years. For the reactor design the System 80+ by CE was incorporated under license.<sup>223</sup> According to KEPCO, the APR1400 was designed particularly to improve safety aspects and exceed the technological standards of Gen III reactors. In particular, the earthquake protection measures were improved, as well as the capability to better manage ex-

<sup>222</sup> KOPEC: Korea Power Engineering Company, Doosan: Doosan Heavy Industries and Construction Co., Ltd., KNFC: Korea Nuclear Fuel Co., Ltd., KPS: Korea Plant Service & Engineering.

<sup>223</sup> Thomas (2010a).

ternal shocks like fire or floods.<sup>224</sup> Construction start of the first APR1400 was in 2008 at the Shin-Kori Power Plant. Shin-Kori-3 was connected to the grid in 2016. Currently, five APR1400 are under construction, scheduled to start commercial operations in 2018/2019.

Projected costs of Shin-Hanul-1 and -2 amount to about 2,300USD/kW. The independent newspaper Hankyoreh quotes Korea Hydro and Nuclear Power Co (KHNP) that the initial contract amount of USD 6.26 billion was exceeded by 11.9% in the final bill for the Shin-Hanul units. Shin-Kori-3 and -4 passed the initial USD 4.89 billion by 32.3%.<sup>225</sup> In 2014, the construction of two additional Shin-Kori units was authorized. Original plans to start construction in the same year were delayed and postponed to June 2016. In the course of the change in government one year later, the construction was put on hold by an administrative order of the newly elected President Moon Jae-in to await a poll of a Citizen's Jury about the further progress of the two reactors. In October 2017, with 59.9% the Jury voted to resume the construction. The President declared that the works at Shin-Kori-5 and -6 will continue but no new plants will be built. According to Woo Won-sik, a representative of the Democratic Party, both reactors witnessed a cost increase of 54.9% over nine years. This was due to additional equipment to support safety after the Fukushima accident.<sup>226</sup> In advance of the president's election, Moon has voiced for a Korean nuclear phase-out of Korea and shut down Kori-1, the oldest NPP. KHNP plans to begin operation of the two units in March 2021 and 2022.<sup>227</sup> In accordance with Moon's convictions, the government will not permit the construction of further reactors which were planned under the previous administration of President Park Geun-hye.<sup>228</sup>

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<sup>224</sup> KEPCO. 2018. "APR1400." April 23, 2018. <https://www.kepco-enc.com/eng/contents.do?key=1533>.

<sup>225</sup> Hankyoreh. 2017. "Final decision nearing on ending construction of Shin-Kori 5, 6 reactors." October 10, 2017. [http://english.hani.co.kr/arti/english\\_edition/e\\_national/813938.html](http://english.hani.co.kr/arti/english_edition/e_national/813938.html).

<sup>226</sup> Hankyoreh. 2017. "Final decision nearing on ending construction of Shin-Kori 5, 6 reactors." October 10, 2017. [http://english.hani.co.kr/arti/english\\_edition/e\\_national/813938.html](http://english.hani.co.kr/arti/english_edition/e_national/813938.html). In addition, Woo said: "If Shin-Kori 5 and 6 are built, they won't be able to provide cheap electricity during the 60 years of their lifespan as we have now. They could ultimately become major headaches that depend on subsidies from the government, as in the US."

<sup>227</sup> World Nuclear News. 2017. "Citizens recommend completion of Korean units." October 20, 2017. <http://www.world-nuclear-news.org/NP-Citizens-recommend-completion-of-Korean-units-2010175.html>.

<sup>228</sup> World Nuclear News. 2017. "South Korean president accepts public decision." October 23, 2017. <http://www.world-nuclear-news.org/NP-South-Korean-president-accepts-public-decision-2310175.html>.

In 2017 and 2018, two APR1400 reactors were scheduled to start construction at the Shin-Hanul-Plant with a commissioning date set to 2022/23. In 2014, the government agreed with the local administration of Yeongdeok County to build an entire new NPP at Cheonji consisting of two new APR+ reactors and an option of additional two units. KEPCO was optimistic that Cheonji-1 and -2 would begin operation in December 2026/27.<sup>229</sup> The APR+ type comes without any foreign technology and is therefore seen as particularly suitable for exportation.<sup>230</sup> Compared to its predecessor, the last core components such as the reactor coolant pump, man-machine interface system, and safety and performance analysis code are henceforth manufactured domestically. Apart from further security improvements, the APR+ grew by 16 nuclear fuel rods compared to the APR1400 and now reaches a total output of 1,500 MW<sub>e</sub> with a lifetime of 60 years.<sup>231</sup> As mentioned above, plans to build APR+ reactors in Korea were abandoned with the election of Moon Jae-in in May 2017.

Figure 26 shows the nuclear generation and the nuclear share in the electricity mix from 1977 until 2016. In 2016, the nuclear share amounted 30.3% (154,253 GWh) of the total electricity production.<sup>232</sup>

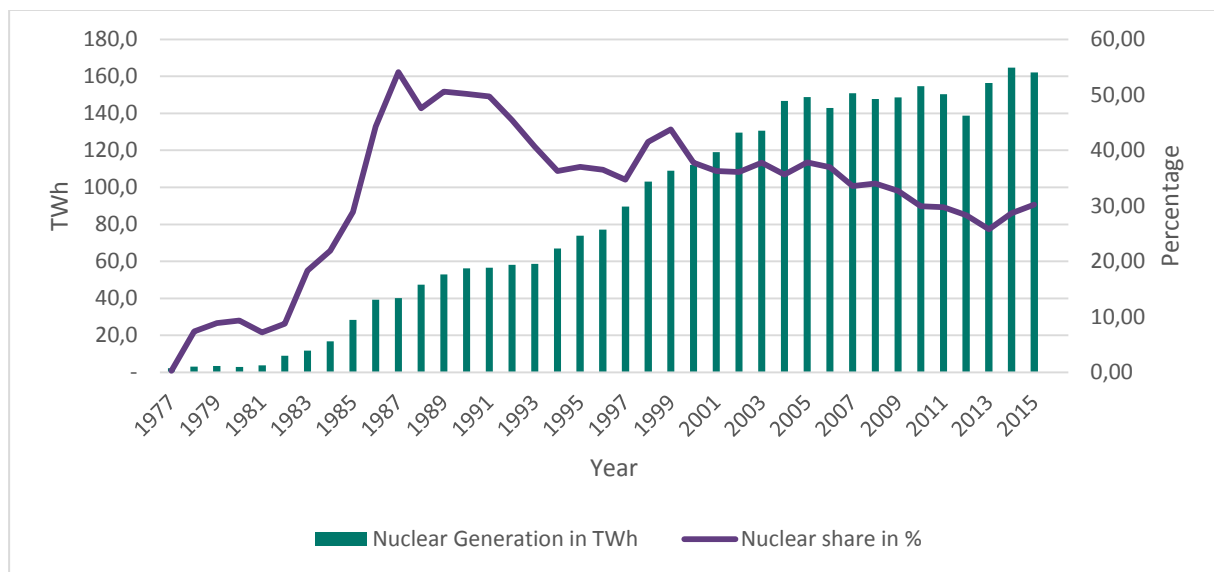
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<sup>229</sup> World Nuclear Association. 2017. "Nuclear Power in South Korea." December 2017. <http://www.world-nuclear.org/information-library/country-profiles/countries-o-s/south-korea.aspx>.

<sup>230</sup> Lévêque and Berthélemy (2011).

<sup>231</sup> KEPCO. 2018. "APR+." April 23, 2018. <https://www.kepco-enc.com/eng/contents.do?key=1534>.

<sup>232</sup> IAEA. 2018. "Country Statistics. Japan." March 3, 2018. <https://www.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=JP>.



**Figure 26: Nuclear share and nuclear generation in Korea, 1977–2015**

Source: Own depiction based on World Bank (2016) and BP (2017).

#### 4.2.1.4 Summary

The Republic of Korea is a good example of the diffusion of nuclear technology in the “Western World”. The first step consisted in buying foreign nuclear technology without taking part in the design phase. A key factor to become independent from technology imports was the localization of technology: Whereas the first three NPPs were turnkey plants by Westinghouse and Canada, the public corporation KEPCO engaged in the construction of further reactors. Korea's strategy for technology transfer was to increase the share of domestic suppliers as sub-contractors in projects led by foreign companies. In doing so, these companies were obliged to ensure a certain level of localization. By the “on the job training and participation” philosophy, KEPCO was gradually able to take over more responsibility in the construction of NPPs. Since the late 1980s, Korea is building its reactors under own supervision. The first Korean designed model was the OPR1000. Further development led to its successor, the APR1400. The latest reactor (Shin-Kori-3) which was connected to the grid in 2016 is of this type. KEPCO's latest development is the APR+, which is not yet in service. Plans to build APR+ reactors in Korea were abandoned after a change of government in 2017. In general, under President Moon, the administration is rather reluctant and an-

nounced its convictions to phase out nuclear power. All commercial reactors in Korea are pressurized reactors, 84% are PWRs, 16% use heavy water (PHWR). Table 24 summarizes the nuclear power sector in Korea.

<b>First construction start: (grid connection)</b>	1072: Kori-1 (1977)
<b>Latest construction start:</b>	2017: Shin-Kori-5 (Shin-Kori-3: 2016)
<b>Installed capacity (NPP):</b>	22.5 GW <sub>e</sub> (24)
<b>Shut down capacity (NPP):</b>	558 MW <sub>e</sub> (Kori 1)
<b>Construction capacity (NPP):</b>	7 GW <sub>e</sub> (5)
<b>Installed technologies (or under constr.) (NPP):</b>	PWR (24), PHWR (4)
<b>Most installed reactor design (NPP):</b>	OPR1000: 11.9 GW <sub>e</sub> (12)

**Table 24: Summary for Korea**

Source: Own depiction.

## 4.2.2 Canada

### 4.2.2.1 Research and demonstration reactors

In 1944, Canada started with the construction of its first reactor called NRX (“National Research X-perimental”). The reactor was based on heavy water technology and achieved criticality in 1947. In 1950, construction of the NRU (“National Research Universal”) reactor was started. It was entirely designed and manufactured in Canada and was initially supposed to provide plutonium to sell to the U.S. during the Cold War.<sup>233</sup> NRU and NRX laid the foundation for the development of the CANDU (Canadian Deuterium Uranium) reactor.

In 1952, five years after NRU achieved criticality, the state-owned corporation Atomic Energy of Canada Limited (AECL) was established. In January 1958, the first large-scale NPP (Rolphton NPD) in Rolphton, Ontario started construction. This prototype reactor NPD 2 (22 MW<sub>e</sub>) was built by AECL and Canadian General Electric (CGE) in cooperation with the operator Ontario Hydro. The reactor started operating in October 1962 (shut down in August 1987). Two years later, in 1960, the second power plant Douglas Point started construction.

<sup>233</sup> Brooks (1993, 3).

This first larger reactor was the CANDU 200 (206 MW<sub>e</sub>, 704 MW<sub>th</sub>) supplied by AECL. Douglas Point was commissioned in 1968, with a power output of 203 MW<sub>e</sub> (shut down after operating for 16 years). Based on this design, two two-unit reactors were exported to India and Pakistan. In 1968, CGE withdrew from reactor sales in 1968, making AECL the sole supplier of CANDU technology.

In 1966, construction on two demonstration reactors started: Pickering-1 and Gentilly-1. Pickering-1—a CANDU 500A reactor—was a direct evolution of the Rolphton and Douglas Point reactors. Pickering (515 MW<sub>e</sub>, 1,744 MW<sub>th</sub>) is now operating for 47 years. The second demonstration reactor was Gentilly-1; this time light water was used as a coolant. Construction of the HWLWR—motivated by rising worries about shortages of heavy water—was built and financed by AECL, but the prototype was not successful. The reactor was shut down in 1977 and the technology abandoned. As AECL was funding the reactor, this led to heavy financial losses for the company.<sup>234</sup> In the late 1960s, three more CANDU 500A reactors were ordered for the Pickering station, all three reactors were operational by 1973 and are (in 2017) in a state of shut down.

#### 4.2.2.2 The roll-out of the CANDU reactor

By the early 1970s, the CANDU technology was achieving commercial status and exports grew, too. But from 1975 on, Canada refused to sell reactors to countries not applying to the IAEA safeguards (see the case studies on India and Pakistan) mainly because CANDU reactors are a good source for weapons-grade plutonium. Different CANDU models were developed with different power outputs. The Bruce station was supplied with two CANDU 791 (~ 700 MW<sub>e</sub>) and two CANDU 750A (750 MW<sub>e</sub>) reactors, all were operational by 1979. Gentilly-2 and the Point Lepreau station were supplied with CANDU 6 reactors (635–660 MW<sub>e</sub>, ~ 2,100 MW<sub>th</sub>), operational by 1983, Gentilly-2 was shut down in 2012. Four CANDU 500B reactors (516 MW<sub>e</sub>, 1,744 MW<sub>th</sub>) were installed at the Pickering station and four CANDU 750B (817 MW<sub>e</sub>, 2,690–2,832 MW<sub>th</sub>) reactors were installed at the Bruce station, all operational latest

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<sup>234</sup> Thomas (1988, 174).

by 1986. From 1979 onwards, nuclear expansion declined and only four more units were installed at the Darlington station, all CANDU 850 reactors. Darlington is the biggest power plant with 4 reactors with a power output of 878 MW<sub>e</sub> each (Darlington 1 started operating in 1990, Darlington 2 in 1992 and Darlington 3 and 4 in 1993). These were the last CANDU reactors to be constructed in Canada and reactor exports decreased too. Four more units were ordered by Romania, but it was feared that the agreement would give too much knowledge away, questioning the benefits for Canada.<sup>235</sup> After all, only two CANDU reactors were installed in Romania.

#### 4.2.2.3 Summary

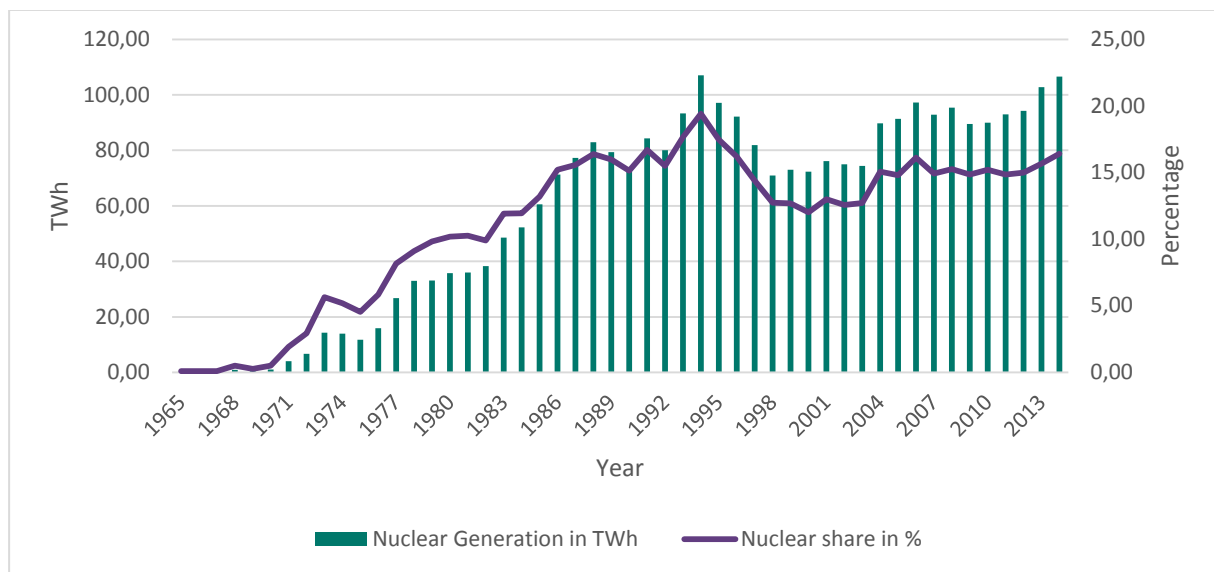
In 2017, 19 power plants were still operating while 6 were already shut down.<sup>236</sup> In 2016, the 19 NPPs generated around 100 TWh of nuclear energy (putting Canada on the fifth place worldwide) or around 15 percent of Canada's total electricity generation. Nuclear share peaked in the mid-1990s. Currently, there are no newbuild plans in the foreseen future and the nuclear generation is assumed to decline from 98 TWh in 2014 to 77 TWh in 2040. Figure 27 shows the nuclear share and the nuclear generation in Canada from 1965 until 2015 and Table 25 summarizes the nuclear deployment in Canada.

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<sup>235</sup> Thomas (1988, 176).

<sup>236</sup> The latest shut down is the permanent shut down of Gentilly-2 in 2012 (Gentilly-2 is also the strongest power plant which has been shut down so far with 645MW<sub>e</sub>).





**Figure 27: Nuclear share and nuclear generation in Canada, 1965–2015**

Source: Own depiction based on World Bank (2016) and BP (2017).

<b>First construction start (grid connection)</b>	1958: Rolphton NPD (CANDU, 1962)
<b>Latest construction start:</b>	1985: Darlington-4 (CANDU 850, 1993)
<b>Operational capacity (NPP):</b>	13.52 GW <sub>e</sub> (19)
<b>Shut down capacity (NPP):</b>	2.14 GW <sub>e</sub> (6)
<b>Construction capacity (NPP):</b>	
<b>Installed technologies (or under constr.) (NPP):</b>	PHWR (25), HWLWR (1)
<b>Most installed reactor design (NPP):</b>	CANDU 500 (8)

**Table 25: Summary for Canada**

Source: Own depiction.

### 4.2.3 Sweden

Sweden was among the early nuclear adapters with a nuclear program based on both: civil and military purposes since the end of the World War II.<sup>237</sup> The military purposes were later on dropped and Sweden switched from HWR technology to LWRs. Although, imported

<sup>237</sup> Jonter (2010).

weapons grade plutonium from France and the U.K. led to a series of sub critical implosion experiments as late as 1971 and 1972.<sup>238</sup>

#### 4.2.3.1 Swedish uranium and heavy water from Norway

Having access to its proper natural uranium sources and purchasing heavy water from Norway the country focused first on HWR technology.<sup>239</sup> In 1954, the first experimental prototype reactor (R-1) was commissioned in Stockholm. The reactor was an own indigenous HWR design developed by the Swedish semi-public company AB Atomenergi. R1 was the first reactor to be located deep underground. In 1960, a second, larger reactor (R-2) achieved criticality; this time the reactor was cooled and moderated with light water. Then in 1957, construction of the PHWR Agesta 1—also built underground in bedrock—was started in Stockholm. According to Kåberger and Swahn (2015), while the reactor (10 MW<sub>e</sub>, 80 MW<sub>th</sub>) delivered hot water for district heating and some electricity, the main purpose of the reactor was to produce plutonium, in case the decision to produce nuclear weapons was made. Initial Swedish plans foresaw a large reprocessing facility in the early 1960s, which could be used to produce plutonium from SNF. However, in the late 1960s, Sweden abandoned the idea of nuclear weapons production and by 1970 the Nuclear Non-Proliferation Treaty was enforced.<sup>240</sup>

#### 4.2.3.2 Swedish BWRs and US PWRs

Sweden switched from domestic reactor technology, based on heavy water, to imported enriched uranium from the U.S. Until the late 1960s, Sweden refused to import enriched uranium offered by the U.S. against the certification not to produce weapons-grade plutonium with it. It became clear, though, that Swedish firms considered the LWR technology option as more economical.<sup>241</sup> Therefore, the abandonment of the HWR technology corresponded to a switch towards the cheaper enriched uranium from the U.S. and to the devel-

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<sup>238</sup> Schneider (2009, 14).

<sup>239</sup> Gueron (1970, 63).

<sup>240</sup> Kåberger and Swahn (2015, 204–5).

<sup>241</sup> Jonter (2010, 71).

opment of the first BWR designed without any help of an US company in the western world. Construction of the first BWR by the General Swedish Electric Company (or ASEA) started in 1966 in Oskarshamn. This first reactor called ABB-I had a thermal capacity of 1,375 MW<sub>th</sub> and an electrical output of 440 MW<sub>e</sub>; Oskarshamn-1 produced electricity and heat from 1972 until 2017. In 1969, construction of Oskarshamn-2 started, the new ABB-II reactor (600 MW<sub>e</sub>) was operational from 1974 until 2016. ABB-II reactors were also installed in the Barseback station (Barseback-1: 1975–1999; Barseback-2: 1977–2005, 570 MW<sub>e</sub> each).

In the early 1970s construction at the Forsmark station began. ASEA supplied two ABB-III BWR-2500 reactors with a thermal capacity between 2,900 and 3,300 MW<sub>th</sub> and electrical output of 900 MW<sub>e</sub>. Both reactors were connected to the grid in 1980/81. The last reactor designed by ASEA was the ABB-III BWR-3500 reactor for Forsmark-3 and Oskarshamn-3. The thermal capacity was again increased up to 3,900 MW<sub>th</sub> (Oskarshamn-3), both reactors had an electrical output of 1,050 MW<sub>e</sub> and were commissioned in 1985. In 1988, ASEA merged with the Swiss Company Brown, Boveri & Cie to form the ABB Group (two years later ABB purchased Combustion Engineering).

In 1968, two orders—one for a BWR and one for PWR—were placed for the Ringhals station in Halland County, in the southwest of Sweden. Construction of Ringhals-1, an ABB-I reactor, started in 1969 and the reactor achieved criticality in 1973 and is still operational today (in 2017). Although, Ringhals-1 is also an ABB-I reactor, the capacity was nearly doubled (2,450 MW<sub>th</sub> and 760 MW<sub>e</sub>). Westinghouse supplied three PWR W (3-Loop) reactors for the other units. Construction of the PWRs started in 1970/72/73. Ringhals-2 (807 MW<sub>e</sub>, 2,500 MW<sub>th</sub>), started operations after five years, while units 3 (1,063 MW<sub>e</sub>, 3,135 MW<sub>th</sub>) and 4 (1,118 MW<sub>e</sub>, 3,300 MW<sub>th</sub>) were commissioned in 1981/83.

In April 2015, Vattenfall announced, due to unfavourable economic conditions the closure of Ringhals units 1 and 2 by 2020. The lifetime of the remaining nuclear fleet is expected to be extended to 60 years. If this will be the case, remains to be seen; as, although, there were extensive lifetime extension programs for the two older units at Oskarshamn, even allowing for 60 years of operation; the two stations were prematurely shut down. Table 26 shows the operational stations and the installed reactor designs.

Station	Capacity in MW <sub>e</sub> (NPP)	Technologies	Supplier
Forsmark	3,271 (3)	ABB-III, BWR-2500 (3)	ASEA
Oskarshamn	1,400 (1)	ABB-III, BWR-2500	ASEA
Ringhals	3,869 (4)	ABB-I (1), PWR W (3-Loop) (3)	ASEA (1), Westinghouse (3)
	<b>8,540 (8)</b>		

**Table 26: NPPs in operation in Sweden in 2017**

Source: Own depiction based on IAEA PRIS Database (2017).

#### 4.2.3.3 Summary

Although, Sweden started with military ambitions and used natural uranium and heavy water, the plans for nuclear proliferation were dropped and the technology was switched to LWR. Sweden started importing enriched uranium and designed for the first time a BWR without any US help. Later on, three PWRs were ordered from Westinghouse for the Ringhals station. Today, the share of nuclear is still significant, about 40% of electricity generation (2016), but no new plants are planned, so the phase-out is imminent. Table 27 sums up the deployment of nuclear power in Sweden.

<b>First construction start (grid connection):</b>	1957: Agesta (1964)
<b>Latest construction start (grid connection):</b>	1980: Oskarshamn-3 (1985)
<b>Latest grid connection:</b>	1985: Forsmark-3 (construction started in 1979)
<b>Operational capacity (NPP):</b>	8.54 GW <sub>e</sub> (8)
<b>Shut down capacity (NPP):</b>	2.32 GW <sub>e</sub> (5)
<b>Construction capacity (NPP):</b>	-
<b>Installed technologies (or under constr.) (NPP):</b>	BWR (9), PWR (3), PHWR (1)
<b>Most widely installed reactor:</b>	ABB-III, BWR-2500 by ASEA (4)

**Table 27: Summary for Sweden**

Source: Own depiction.

### 4.3 Countries with significant nuclear electricity share, but no significant domestic nuclear industry

This subsection describes countries that use nuclear power to generate electricity, but have not developed a national industry themselves, although nuclear power represents a large share in the national electricity mix. These countries mostly imported “turnkey plants” for electricity generation. This subsection includes the countries with high shares of nuclear electricity generation, all well above 20 percent.

#### 4.3.1 Slovakia

In 2016, Slovakia generated 13.7 TWh of nuclear power and had with a share of 54.1 percent, worldwide the highest nuclear share after France. Today, the country operates four nuclear power plants and has three under construction. Thus, together with France and Finland, the country is one of the three European countries with ongoing nuclear newbuild projects, although the only Gen II construction projects.

During Slovakia’s consolidation into Czechoslovakia, a total of 9 construction projects were started between 1958 and 1987. The first station was Bohunice in western Slovakia: a heavy water moderated, gas cooled reactor (“A1”, 560 MW<sub>th</sub>, 93 MW<sub>e</sub>). Construction started in 1958, the reactor entered operations in 1972, but was shut down five years later. In 1972, construction of Bohunice was started, the station was supplied with two VVER V-230 reactors (two times 408 MW<sub>e</sub>, 1,375 MW<sub>th</sub>), which were connected to the grid in 1978/80. The two units were shut down in 2006 and 2008 as a condition for Slovakia entering the EU.

In 1976, construction of the third and fourth reactor at the Bohunice site started. This time the USSR supplied two V-213 reactors (two times 471 MW<sub>e</sub>, 1,471 MW<sub>th</sub>). In 1985, Bohunice-3 and -4 were connected to the grid. Two V-213 reactors (two times 436 MW<sub>e</sub>, 1,471 MW<sub>th</sub>) were also installed at the Mochovce site. The reactors entered operations in 1998 and 2000. These two sites are the only NPPs that the state-owned utility Slovenské Elektrárne operates in 2017. There are plans to extend the lifetime for the operational VVERs to 60 years.<sup>242</sup>

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<sup>242</sup> Mohr et al. (2014, 29).

Construction of the units 3 and 4 of the Mochovce station started in 1987 but was later on abandoned. According to the WNISR 2017, construction restarted in 2009 and the station was expected to be commissioned in 2012/13. But the project is currently delayed, with an expected commissioning date set to 2019. By May 2016, the estimated costs for completion of the two Gen II reactors had risen to around 5.1 billion EUR.<sup>243</sup>

### 4.3.2 Ukraine

In 2017, Ukraine operates through the state-owned Energatom 15 NPPs at four sites, or 13,107 MW<sub>e</sub> of installed capacity, producing 76.08 TWh or 52.3 percent of power in 2016. Ukraine has worldwide the third highest nuclear share (in 2016).

During Ukraine's consolidation in the USSR, a total of 21 NPPs or 18,522 MW<sub>e</sub> started construction. The Chernobyl station near Pripjat on the Ukrainian-Belarussian border was the first construction project in the Ukraine (four RMBK-1000s). Construction started with unit 1 in 1970 (Chernobyl-1 went online in 1978) and was completed with the commissioning of unit 4 in 1984, in which it came—two years later on April 25<sup>th</sup>, 1986—to a meltdown, resulting in the Chernobyl disaster. This led to the abandonment of the construction plans for two more units. The Chernobyl station is now completely shut down (Chernobyl-3 was shut down in 2000, unit 2 in 1991 after a turbine hall fire, unit 1 in 1996).

The second station to be commissioned was Rovno, where construction of two second generation VVER PWRs (VVER-440 class) started in 1973. The rest of the Ukrainian fleet consists of VVER-1000s, where construction started between 1976 and 1986. As a matter of fact, the majority (9) of the operational NPPs came only online after the Chernobyl disaster. Two construction sites were interrupted in 1990 (Khmelnitsky-3 and -4). According to the WNISR 2017, a contract to finish the construction of the two reactors was signed with Russia in 2011, the latter taking 80% of the funds. In 2017, the Russian Government confirmed the cancellation of the 2011 deal, which the Ukrainian Parliament voted to cancel in 2015. In 2010, Rovno 1 and 2 were granted a lifetime extension to 60 years, 20 years beyond their

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<sup>243</sup> Schneider et al. (2017, 231).

design lifetime. The EU and the European Bank for Reconstruction and Development have already invested billions of Euros on safety upgrade programmes, which will probably lead to an additional 20 years of operation of an older fleet reaching its expected end of its design life.<sup>244</sup> Table 28 contains the operational stations in 2017.

Station	Design	Operational Capacity in MW <sub>e</sub> (NPP)	Construction time
Khmelnitski-1 and -2	VVER V-320 (2)	1,900 (2)	1981/85–1987/2004
Rovno	VVER V-213 (2), V-320 (2)	2,657 (4)	Unit 1/2: 1973–1980/81 Unit 3/4: 1980/86–
South Ukraine	VVER V-302, V-338, V-320	3,800 (3)	1972–1985–1986/2004
Zaporozhye	VVER V-320	5,700 (6)	1980/81/82/83/85/86– 1984/85/86/87/89/95
		<b>13,107 (15)</b>	

**Table 28: Operational and stations under construction in Ukraine in 2017**

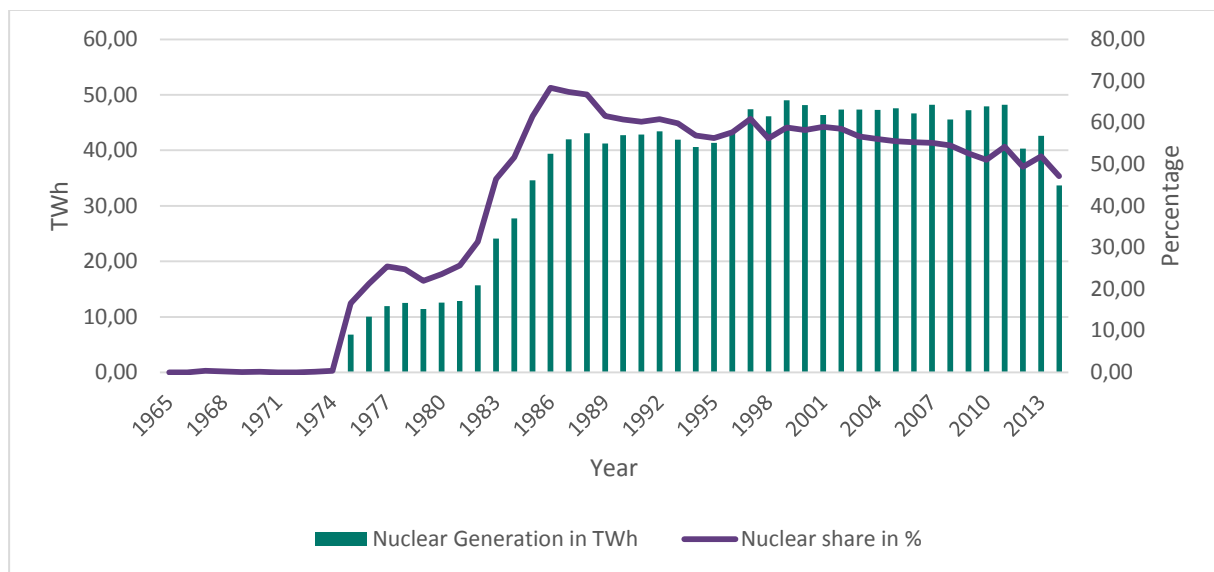
Source: Own depiction based on IAEA PRIS Database (2017).

### 4.3.3 Belgium

Although Belgium runs an outdated park of NPPs—with an on average age of around 37 years in 2017—Belgium still relies heavily on nuclear power with a nuclear share of around 50 percent—putting it worldwide on the fourth place. The Belgian park is not only outdated but faces serious technological problems, e.g., multiple cracks have been found in the RPVs of Doel 3 and Tihange 2.<sup>245</sup> Figure 28 shows the nuclear generation and the nuclear share in the electricity mix from 1975 until 2015.

<sup>244</sup> Mohr et al. (2014, 31).

<sup>245</sup> See Mohr et al. (2014, 38–43) for more details.



**Figure 28: Nuclear share and nuclear generation in Belgium, 1973–2015**

Source: Own depiction based on World Bank (2016) and BP (2017).

Belgium was among the first atomic countries and the first research reactor BR1 (Belgian Reactor 1) has been in operations since 1956, although not continuously. BR1 is an air-cooled graphite-moderated reactor fuelled by natural uranium.<sup>246</sup> As Belgium provided uranium ore to the U.S. from its Congo colony in the early days of the Manhattan Project, it was entitled to preferential treatment. Relying on this US treatment for the import of enriched uranium and with the import of nuclear grade graphite from the U.K. Belgium started the construction of its second prototype reactor BR-2 in 1957—the plant started operations in 1962.<sup>247</sup>

Construction of the first prototype PWR BR3 supplied by Westinghouse also started in 1957, the turnkey plant is currently undergoing decommissioning as it was shut down in 1987 after 25 years of operation. Construction of the first larger PWR, a W (2-loop) by Westinghouse, began in in 1970 at the Doel station; Doel-2 started construction one year later. The two 392

<sup>246</sup> SCK CEN. 2017. "Research Infrastructure: Reactor BR1." April 23, 2018. <https://www.sckcen.be/en/Research/Infrastructure/BR1>.

<sup>247</sup> Guéron (1970, 63).



MW<sub>e</sub> reactors were connected to the grid in 1985. Unit-3, an 890 MW<sub>e</sub> W (3-loop) was added in 1983, and unit-4 a 1,000 MW<sub>e</sub> W (3-Loop) in 1985.

In 1970, after the successful cooperation with the French in 1962 for the construction of Chooz-A and before building the first larger PWR in France, Framatome together with the Belgian company ACECO (later taken over by Westinghouse) started construction on a 870 MW<sub>e</sub> PWR in Tihange via a Westinghouse license. The three-loops PWRs started commercial operations in 1975 (Tihange-1), Tihange-2 started construction in 1976 and was connected to the grid in 1975. In 1978, two more Westinghouse W (3-loops) were supplied for Tihange-3 (1,020 MW<sub>e</sub>, 1985).

With the exception of BR3, all Belgian reactors were still in operation in 2017. The three oldest reactors (Doel-1-2 and Tihange-1) had a design lifetime of 30 years but are now well over 40 years. In 2013, a new legislation was adopted by the Belgian Council of Ministers to close Doel 1 and 2 in 2015, while the other reactors should close at the age of 40, except for Tihange-1 which was awarded a lifetime extension of 10 years, i.e. running 50 years and shutting down in 2025. In 2017, the two oldest Doel reactors are still running and a new energy pact foresees the phase out of the seven Belgian reactors by 2025.<sup>248</sup> Table 29 contains the operational stations in 2017.

Station	Design	Operational Capacity in MW <sub>e</sub> (NPP)	Construction time
Doel 1-2	PWR W (2-loop)	866 (2)	1969/71–1974/75
Doel 3-4	PWR W (3-loop)	2,039 (2)	1975/78–1982/85
Tihange 1	PWR (3-loop)	962 (1)	1970–1975
Tihange 2-3	PWR W (3-loop)	2,046 (2)	1976/78-1982/85
		<b>5,913 (7)</b>	

**Table 29: Operational stations in Belgium in 2017**

Source: Own depiction based on IAEA PRIS Database (2017).

<sup>248</sup> World Nuclear Association. 2018. April 23, 2018. <http://www.world-nuclear-news.org/NP-Belgium-maintains-nuclear-phase-out-policy-0404184.html>

#### 4.3.4 Hungary

Hungary currently operates four nuclear reactors in central Hungary, in Paks on the Danube river (Paks 1-4), accounting for over 50% of electricity generated in the country (in 2016). This puts Hungary on the fifth place world-wide. Construction on the Soviet VVER reactors started as a turnkey project in 1974, unit 1 was connected to the grid in 1982, unit 2 two years later. In 1979, construction of the last two units started and in 1986/87 the station was fully operational. The four reactors are VVER-440 V-213 reactors and were originally granted an operating license for 30 years, with the possibility for renewal. In 2017, the last unit of the Paks station was granted a lifetime extension; the station will now operate for 60 years, with the last unit planned to shut down in 2047.

In 2017, discussions were ongoing about an expansion of the nuclear power plant with additional reactors. As Hungary is unwilling or unable to finance this plant, Russian Atomstroy has offered a build-operate-transfer contract. It is unclear, though, if this subsidy is compatible with EU competition law, and whether the higher electricity costs at the end of the lifetime can be rolled over to the consumer of electricity.

#### 4.3.5 Slovenia

Slovenia only operates one reactor (Krsko), which provided (in 2016) 5.4 TWh or 35.2 percent of Slovenia's electricity. In 1975, construction of a Westinghouse PWR W (2-Loop) (688 MW<sub>e</sub>, 1,994 MW<sub>th</sub>) was launched, the reactor was started in 1981 and has been operational since 1983. The station is co-owned with Croatia. Initially, the reactor was thought to operate for 40 years, but in 2015 the operational life was extended to 60 years, i.e. 2043.<sup>249</sup>

#### 4.3.6 Bulgaria

In 1970, construction of units 1 and 2 of the Kozloduy station started. The station was a "turnkey plant" from the USSR, supplied with two V-230 reactors. The two units were commissioned in 1974/75. In 1973, construction of units 3 and 4 and in 1980/82 construction of

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<sup>249</sup> Schneider et al. (2017, 232).

units 5 and 6 started. All units were supplied with V-230 reactors. In 1991, the station was fully operational.

Kozloduy 1-4 were shut down in 2002 and 2006 as part of an agreement for Bulgaria to join the EU. The two remaining V-230 reactors provided around 15 TWh or 47.3 percent of the country's electricity in 2016. The two units are undergoing a relicensing program with an envisioned lifetime of 60 years.<sup>250</sup>

#### 4.3.7 Switzerland

With no reserves of coal, oil, or natural gas, Switzerland opted for nuclear power. Construction of the first pilot test reactor (called Lucens) started in 1962 in the village of Lucens. The plant was a HWGCR with two loops (6 MW<sub>e</sub>, 28 MW<sub>th</sub>) and it was thought to be the base for a future indigenous Swiss reactor design. The reactor achieved criticality in 1966. In 1969, a partial core meltdown occurred during a loss-of-coolant accident. The Swiss studied the possibility of a nuclear weapons program until they signed the NPT in 1969 and possibly even later (Schneider 2009, 14). This initial ulterior motive of scope economies can also be deduced by the chosen reactor technology, i.e. HWGCR.

In 1965, the goal of a Swiss NPP was dropped with the first order of a PWR W (2-loop) (365 MW<sub>e</sub>, 1,130 MW<sub>th</sub>) from Westinghouse. A second PWR W (2-Loop) was ordered in 1967. Construction of Beznau-1 was completed by 1969, Beznau-2 by 1971. However, since March 2016, Beznau-1 is in long-term outage, caused by failed security checks concerning the reactor pressure vessel.<sup>251</sup> It is not clear if Beznau-1 is going to start producing electricity again.

In 1967, GE supplied a BWR-4 (373 MW<sub>e</sub>, 1,097 MW<sub>th</sub>) for the Muehleberg station, which entered operations in 1972, the reactor is scheduled to shut down on December 20<sup>th</sup>, 2019. In 1974, construction of Leibstadt began. The station was supplied with a BWR-6 (1,220 MW<sub>e</sub>, 3,600 MW<sub>th</sub>) and was commissioned in 1984. In 1973, construction of the Goesgen

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<sup>250</sup> Schneider et al. (2017, 224).

<sup>251</sup> Schneider et al. (2016, 197).

NPP started, the PWR (3-Loop) was supplied by the German KWU. It is the same reactor as Neckarwestheim-1, i.e. the first PWR design by KWU (under Westinghouse license).

In 2016, around 35 percent of the net electricity production in Switzerland was provided by nuclear power generated in four nuclear reactors—the oldest nuclear fleet in the world. After the Fukushima disaster in 2011, the Swiss parliament decided to stop plans to construct new NPPs. In 2016, a national referendum aimed at the constitutional prohibition of nuclear power generation and the limitation to 45 years of operation was turned down.<sup>252</sup> The complete nuclear phase out in Switzerland is now expected in 2035.

#### 4.3.8 Finland

The first nuclear power station in Finland was on the island of Hästholmen near the city of Loviisa, on the southern coast of Finland. The state-owned Imatran Voima Oy (IVO) chose the USSR as supplier and ordered two V-213s (496 MW<sub>e</sub>, 1,500 MW<sub>th</sub>) for the Loviisa station, the choice on the USSR was politically motivated.<sup>253</sup> Construction started in 1971/72 and the station was commissioned in 1977 and 1981. The two Soviet PWRs have been completely modified from design to completion, the capacity was aggressively updated, and a containment structure was incorporated.<sup>254</sup> In 1974, TVO (Teollisuuden Voima Oyj) ordered two BWRs from Swedish ASEA (two ABB-III, BWR-2500, two times 880 MW<sub>e</sub> and 2,500 MW<sub>th</sub>) for the Olkiluoto site—a small island in the Baltic Sea. Construction started in 1974/75 and the two units started producing electricity in 1979/82. The VVER reactors were granted a lifetime of 50 years, setting the shutdown date to 2027 and 2041, the BWRs were granted 60 years of lifetime; all reactors are subject to a safety evaluation every ten years.<sup>255</sup>

In 2003 (even one year before the French regulator approved the EPR), TVO signed a turnkey contract with Framatome for a fixed 3 billion 2003 EUR (or 2,250–2,475 2004 USD/kW).<sup>256</sup>

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<sup>252</sup> Schneider et al. (2017, 223).

<sup>253</sup> Notter (2015, 53).

<sup>254</sup> Halverson (1993, 44).

<sup>255</sup> Mohr et al. (2014, 27).

<sup>256</sup> Including interest during construction and two fuel charges reducing the OC somewhat—well over the industry target from the 1990s.

The latest cost estimate for Olkiluoto-3 was around €10.5 bn (~6,500€/kW) in 2015.<sup>257</sup> Olkiluoto-3 is well behind schedule and is now expected to enter operations in 2019—with commissioning initially planned for 2009. Plans for a fourth reactor were abandoned by Parliament in 2016.

#### 4.3.9 Armenia

As it is the case with Slovenia, Armenia only operates one nuclear reactor, which supplies around 30 percent of the nation's electricity demand in 2016. In 1977, when Armenia was still a part of the USSR, construction of the first of two VVER V-270 reactors started: Armenian-1 and -2 (376 and 375 MW<sub>e</sub>), 30 kilometres of the state capital Yerevan. The stations were commissioned in 1977 and 1980. According to the WNISR 2017, in 1988 a major earthquake (that killed 25,000 people) led to the closure of the two units one year later. Armenian-2 re-entered electricity production in 1993 (the country suffered from an energy blockade due to a territorial dispute with Azerbaijan), but the reactor is planned to be shut down in 2026.<sup>258</sup>

#### 4.3.10 Czech Republic

In 2016, the two operational Czech stations supplied around 30 percent (22.7 TWh) of the total generated electricity. Construction of the first nuclear power plant started in 1979 at the Dukovany site (the first NPP was Bohunice, constructed in today's Slovakia in 1958). The station was a "turnkey plant" equipped with four VVER-440 V-213 reactors (four times ~ 470 MW<sub>e</sub>, 1,444 MW<sub>th</sub>). Units 1–3 started operations in 1986, unit 4 in 1987 and are now licensed to run until 2035/37. In the same year construction at the Temelin site began, this time two V-320 reactors were supplied (two time 1,026 MW<sub>e</sub>, 3,120 MW<sub>th</sub>). After the collapse of the USSR, Temelin was completed with financial assistance from the US Export and

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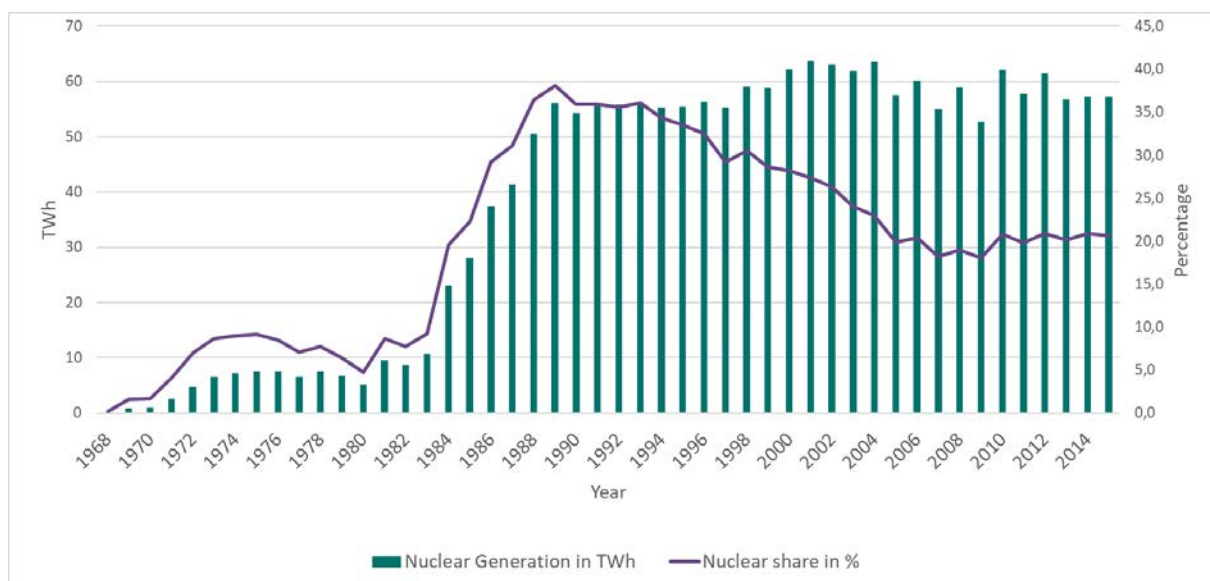
<sup>257</sup> Schneider et al. (2017, 47).

<sup>258</sup> Schneider et al. (2017, 232).

Import Bank, linked to the supply of instrumentation and control technology by Westinghouse.<sup>259</sup> The lifetime of the six Czech reactors is foreseen to be 60 years.<sup>260</sup>

#### 4.3.11 Spain

In 2016, the seven operational NPPs generated around 56 TWh or 20.4 percent of Spain’s generated electricity. The nuclear share peaked in 1990 with 40 percent but has been declining until settling on around 20 percent since the mid-2000s (See Figure 29).



**Figure 29: Nuclear share and nuclear generation in Spain, 1968–2015**

Source: Own depiction based on World Bank (2016) and BP (2017).

Already in 1964, Spain ordered a turnkey first generation W (1-Loop) reactor from Westinghouse for the Jose Cabrera station, 70 kilometres east of Madrid. The reactor (141 MW<sub>e</sub>, 510 MW<sub>th</sub>) entered operations in 1969 and was permanently shut down in 2006, after 38 years of operation. In 1966, a second NPP started construction: Santa Maria de Garona in Burgos. This time the reactor was supplied by GE, a BWR-3 (446 MW<sub>e</sub>, 1,381 MW<sub>th</sub>). After five years of construction time, the station was operational from 1971 until 2013. In 2017, the regula-

<sup>259</sup> Schneider et al. (2017, 226).

<sup>260</sup> Mohr et al. (2014, 26).

tory authority granted a new 20-year license to Garona, on the condition, that it undergoes retrofits.<sup>261</sup> GE also supplied a BWR-6 (1,064 MW<sub>e</sub>, 3,237 MW<sub>th</sub>) to the Confrentes station (seventy kilometres southwest of Valencia), commissioned in 1985, 10 years after construction started.

In 1968, construction of Vandellos-1 began in Catalonia, a GCR UNGG supplied by the French state agency CEA. Vandellos-1 (480 MW<sub>e</sub>, 1,670 MW<sub>th</sub>) was operational from 1972 until 1990, when it was shutdown following an accident that damaged one of its turbogenerators. A second reactor (1,045 MW<sub>e</sub>, 2,941 MW<sub>th</sub>) was added to the Vandellos site in 1980: a PWR W (3-Loop) from Westinghouse (connected to the grid in 1988).

The Almarez NPP, situated 100 kilometres from the Portuguese border, started construction in 1973, supplied with two W (3-Loop) reactors (two times ~ 1,010 MW<sub>e</sub>, 2,947 MW<sub>th</sub>), again from Westinghouse. The still operational (in 2017) station was started up in 1983/84. Westinghouse also supplied two W (3-Loop) reactors (two times ~ 995 MW<sub>e</sub>, 2,954 MW<sub>th</sub>) to the Asco site near Tarragona. In 1979, construction of Trillo-1 (1,003 MW<sub>e</sub>, 3,010 MW<sub>th</sub>) started, a PWR (3-Loop) supplied by German KWU. The station entered operations 1988. All NPPs were granted a ten years lifetime extension to around 40 years of operation; however the industry is seeking lifetime extensions of 20 years, pushing the operational time to 50 years.<sup>262</sup>

#### 4.4 “Other” countries

This subsection covers countries that do not correspond to any of the previous categories, i.e. which did not develop under the “scope approach” nuclear reactors and nuclear weapons, did not develop a national nuclear supply industry, and where nuclear energy plays a rather insignificant role in the nation’s electricity mix.

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<sup>261</sup> Schneider et al. (2017, 219).

<sup>262</sup> Mohr et al. (2014, 30).

#### 4.4.1 Brazil

Brazil constitutes an interesting case, as there were attempts to reap economies of scope approach as well as endeavours to establish a Brazilian nuclear industry. In the 1950s, Brazil first started investing in nuclear energy, when the government established the National Committee for Nuclear Energy (CNEN). In the following years, three research reactors were built with the goal of making Brazil more self-sufficient in terms of nuclear energy, as Brazil has large natural uranium and thorium reserves.

Nevertheless, in 1970 the government obtained offers for a power plant and purchased a PWR from Westinghouse. Construction of the power plant called Angra-1 (609 MW<sub>e</sub>) started one year later in 1971 at Angra dos Reis and was finished and connected to the grid in 1982. De Castro et al. (1989) point out, that at that time most Brazilian scientists strongly disapproved of the deal for a "turnkey plant", as no local technology development would be fostered, and it would entail dependence on foreign enriched uranium. Then, five years later, in 1975, the military government signed a contract with Germany for eight PWRs (pre-convoy) to be constructed over a period of 15 years, each with a capacity of 1,3 GW<sub>e</sub>. Subsequently, a newly founded state-owned enterprise (Nudebras) in association with KWU started the construction of a second power plant, Angra-2, in the following year (1976). Although, the deal was again highly controversial, it is clear today a major factor in the deal was the special clause specifying that Germany would supply a complete fuel package making Brazil's nuclear program self-sufficient.<sup>263</sup> In addition, this time the deal was not for a "turnkey" plant, but also for technological transfer, as components would be supplied by Germany only as needed to supplement the local industry.<sup>264</sup> Angra-2 entered operations in 2001, 25 years after construction start.

According to the WNISR 2017, in 2013 the completion of Angra 3 (construction started in 1984 but was stopped in 1991) was tendered to Areva (now Framatome). The deal was financed by a 3.6 billion USD loan by the Brazilian National Development Bank. Commissioning

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<sup>263</sup> In addition to reactor technology, German firms were to provide Brazil with the know-how to enrich and reprocess uranium.

<sup>264</sup> De Castro et al. (1989, 22–23).



got delayed again and again and eventually Angra-3 was laid down completely, as multiple persons involved in the project got arrested because of their involvement in some financially and politically shady businesses (bribery, money laundering). In 2017, the government intends to complete Angra 3, but it is yet unclear, when the station will enter operations (still unfinished—27 years after construction first started).<sup>265</sup>

#### 4.4.2 Argentina

Argentina has pursued a very peculiar way of adopting nuclear: first, the military ordered German and Canadian equipment, and today, the country is considering importing Chinese reactors.

In the early days (1950s/1960s), there was strong military lobbying in favour of a (domestic) nuclear program. Yet the first three operating power plants were supplied by German and Canadian companies. Construction of the first NPP began in June 1968 at the Atucha site in the province of Buenos Aires. The PHWR Atucha-1 (319 MW<sub>e</sub>) was built by the German company KWU and started operations in 1984—16 years after construction start. In 1981, a second PHWR (692 MW<sub>e</sub>) was added, Atucha-2 only entered commercial operations in 2016.

In 1974, a Candu 6 reactor (600 MW<sub>e</sub>) was ordered from AECL for the inland station Embalse. The NPP was connected to the grid in 1984. According to the WNISR 2017, Embalse was shut down at the end of 2015 in order to enable major overhaul, after which the PHWR is expected to operate for an additional 30 years.

In 2015, a contract between the Chinese company CNNC and Nucleoelectrica for assistance on building Atucha-3 was signed. CNNC will supply an 800 MW<sub>e</sub> CANDU-type reactor. In addition, Argentina placed an order for a Hualong reactor, for which construction start is set to 2020.<sup>266</sup> Currently, one NPP is under construction: the SMR Carem-25.

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<sup>265</sup> Schneider et al. (2017, 194–97).

<sup>266</sup> Schneider et al. (2017, 192–93).

### 4.4.3 Italy

In Italy, an organizational separation between military structures and fundamental research prevented the development of a unified domestic nuclear industry. In the early 1950s, political struggles led to discord between the National Research Centre and the army about a common direction for nuclear energy to adopt. As a consequence, two Italian entities were created, the CNRN (Comitato Nazionale per le Ricerche Nucleari, National Commission for Nuclear Research) in 1952 and the CAMEN (Centro Applicazioni Militari Energia Nucleare, Center for the Military Applications of Nuclear Energy) in 1955. This split did not occur primarily in any other country and could be the reason why Italy did not develop its own technology program: there was no correlated push for military and civil purposes.<sup>267</sup>

In 1958, Italy imported a turnkey Magnox reactor from the U.K., the reactor (153 MW<sub>e</sub>, 660 MW<sub>th</sub>) was the first Magnox reactor to operate outside of the U.K.—the Latina station was operational from 1964 until 1987.<sup>268</sup> One year later, in 1959, construction of the Garigliano station started: a light water BWR-1 reactor (150 MW<sub>e</sub>, 506 MW<sub>th</sub>) was ordered from GE. Garigliano was operational from 1964 until 1982. In 1961, construction of the Enrico Fermi station started, the Westinghouse (4-Loop) PWR was connected to the grid in 1965. The last reactor to be constructed in Italy was Caorso, from 1970 until 1978. GE supplied a BWR-4 (860 MW<sub>e</sub>, 2,65 MW<sub>th</sub>) to the station.

After the Chernobyl disaster, Italy held a referendum on nuclear power, which resulted in the shutdown of all NPPs (the last NPP in 1990) and a moratorium on the construction of nuclear newbuild, extended indefinitely in 1993.

### 4.4.4 Taiwan

Taiwan entered nuclear with the construction of the first NPP at the Chinshan site in 1972/73. GE supplied two BWR-4 reactors (604 MW<sub>e</sub>, 1,840 MW<sub>th</sub>) to unit 1 and 2. Construction time lasted only around 5 years and the two NPPs started operations in 1977/78. In

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<sup>267</sup> Nuti (2011).

<sup>268</sup> A dual-purpose Magnox reactor as the choice for a first nuclear power plant, may be a possible indication for the inherent motivation to gain access to plutonium, rather than use nuclear power for electricity production.

1975/76, GE delivered two more reactors, this time of the BWR-6 design (985 MW<sub>e</sub>, 1,894 MW<sub>th</sub>), the Kuosehng station was connected to the grid in 1981/83.

In 1978, two more NPPs were ordered, this time supplied by Westinghouse and two WE 312 (based on the W (3-Loop) reactor) started construction in 1978/79, the Maanshan station started producing electricity in 1979. All three sites are operated by state-owned utility Taipower. According to the WNISR 2017, Chinshan-1 is in a state of long-term outage, as no electricity has been produced since 2015; the shutdown is scheduled for 2018.

In 2017, Kuosheng-2 as well as Chinshan-2 are offline. The current government is committed to phase-out nuclear power by 2025. Two ABWRs supplied by GE were under construction at the Lungmen site since 1999. In 2014, the government announced that Lungmen-1 will be mothballed (although construction is around 99 percent complete) and construction work on the second was officially frozen. Lungmen is estimated to have cost about 10 billion USD.<sup>269</sup>

#### 4.4.5 Romania

In the early 1980s, Romania placed an initial order for four CANDU reactors at AECL, of which two started construction in 1982/83. The “turnkey plants” began operating in 1996 and 2007 (34 years after construction start). The Cernavoda station (two times 650 MW<sub>e</sub>, 2180 MW<sub>th</sub>) was partly funded by the Canadian Export Development Corporation, the second unit also partially by Euratom.<sup>270</sup> Romania also started with three more CANDU-designed reactors, but these plants were abandoned. In 2016, the two reactors supplied around 18 percent or 10.3 TWh of Romania’s electricity.

#### 4.4.6 Lithuania

In 1977, construction of the two units for the Ignalina station started, unit 1 started operations in 1983 and unit 2 in 1987. The two RBMK-1500 reactors were shut down in 2004 and 2009 as a requirement for Lithuania to join the European Union. The Ignalina station was the

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<sup>269</sup> Schneider et al. (2017, 207–8).

<sup>270</sup> Schneider et al.(2017, 229).

only station that was supplied with RBMK-1500 reactors. The site is currently being decommissioned.

#### 4.4.7 Mexico

In 1976/77, Mexico imported two BWR-5 reactors from GE (665/775 MW<sub>e</sub>, 2,027/2,317 MW<sub>th</sub>) for the Laguna Verde station in Veracruz situated on the Gulf of Mexico. Construction of unit 1 was completed in 1988 and the unit entered operations one year later. Unit 2 was completed in 1994, 17 years after construction start. Mexico's two reactors produced in 2016 around 10 TWh or roughly 6 percent of the country's electricity.

#### 4.4.8 Netherlands

The Netherlands only operates one single NPP, which provided in 2016 3.75 TWh or 3.4 percent of Netherlands' power. The reactor was supplied by KWU in 1965: a 480 MW<sub>e</sub> PWR (2-Loop). The station Borselle, started commercial operations in 1973 and is currently operated by the Dutch utility Delta and German utility RWE. In 2006, the stations operating licence was extended to 60 years, setting the shutdown date to 2033.<sup>271</sup>

A second reactor was imported from GE in 1965, a BWR-1 (55 MW<sub>e</sub>, 183 MW<sub>th</sub>) for the Dodewaard station. Construction was finished in 1969 and the reactor was operational from 1969 until 1997.

#### 4.4.9 Kazakhstan

In Soviet times, in 1964, construction of the FBR Aktau (135 MW<sub>e</sub>, 1,000 MW<sub>th</sub>) near the city of Aktau started. The reactor was operated between 1972 and 1999. In 2017, Kazakhstan did not operate nuclear power plants, but a number of countries (Russia, Japan, South Korea, and China) have all signed co-operation agreements for the development on nuclear power plant projects; in 2016, the government announced it was researching five different sites for new NPPs—favourably Gen III or Gen III<sup>+</sup> reactors.<sup>272</sup>

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<sup>271</sup> Mohr et al.(2014, 28).

<sup>272</sup> Schneider et al. (2017, 119–20).

## 4.5 Potential newcomers

This subsection provides a brief overview of newcomers and potential newcomers to the nuclear sector.

### 4.5.1 Belarus

Already in the 1980s—when Belarus was part of the USSR—construction plans for two reactors near the city of Minsk existed but they were put on hold after the Chernobyl incident.<sup>273</sup> Over 30 years later, in 2013, the first NPP construction project started at the Ostrovets site near the Lithuanian border (called Belarusian-1). The two reactors (construction of unit-2 started one year later) are Russian Gen III<sup>+</sup> reactors (VVER V-491, 1,109 MW<sub>e</sub>). According to the WNISR 2017, Belarusian-1 and -2 are currently expected to enter commercial operation at the end of 2019 respectively late 2020 for unit 2. The deal between Atomstroyexport and the Belarus Directorate for Nuclear Power Plant Construction was signed in 2012 for an estimated cost of USD 10 billion, of which 90 percent stem from a 25-year long-term loan from the Russian government.<sup>274</sup>

### 4.5.2 Bangladesh

Bangladesh became an independent state in 1991, when it was split away from Pakistan. Like its historical partner countries, India and Pakistan, Bangladesh has for a long time aspired to become a nuclear power; the Bangladesh Atomic Energy Commission was already established in 1973.

Bangladesh is a typical example of nuclear diplomacy as well, in this case Russia being most successful in offering nuclear power at almost no cost to the country. Already in 2011 Bangladesh and Russia were about to sign a deal for two 1,000 MW<sub>e</sub> reactors, ought to be constructed by 2017/18 for 1.5-2 billion USD. The proposed site was at Rooppur (or Ruppur)—this site was chosen on the largest river (Ganges) in the country in the 1960s (when the

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<sup>273</sup> NTI 1997. „Belarus: Nuclear Power Reactors in Belarus.“ November 24, 2017. <https://web.archive.org/web/20081014090445/http://nti.org/db/nisprofs/belarus/facils/overview.htm>.

<sup>274</sup> Schneider et al. (2017, 263).

country was still part of Pakistan). In addition to the Rooppur site (chosen in the 1960s), the Bangladeshi government has shortlisted eight more sites for a second nuclear site. Thus, in 2016, another contract was signed, for 2.4 GW<sub>e</sub> of capacity (two VVER1200 reactors) with an expected construction start set to 2016 and operation to 2022 and 2023. 90 percent of the needed financing for 12.65 billion USD deal is again offered by Russia in form of low interest loans (Libor interest rate plus 1.75 percent, the loan has to be paid back in 28 years with a 10-years grace period). In addition, an agreement has been reached with Russia to take back SNF.<sup>275</sup>

In November 2017, construction of Rooppur 1 officially started. The turnkey plant is expected to go online in 2023. In 2018, Russia, Bangladesh, and India signed a memorandum on cooperation in the implementation of the Rooppur project; cooperation will be in personnel training, but Indian companies can also be involved in construction and installation works as well as supply of materials and equipment.<sup>276</sup>

### 4.5.3 Middle East

There have been diverse calls for a nuclear weapons free Middle East, e.g., at the 1974 session of the UN General Assembly, when Egypt and Iran introduced a resolution calling for a nuclear-weapons-free Middle East (Boutwell 2011), more recently, a similar call was put forward by the Saudi Arabian HRH Prince Turki Al Faisal (Al Faisal 2013). Yet, one has to acknowledge that the region has become a hot spot for nuclear power, at least since 2012, with the construction of the first nuclear power plant in Iran, Busheer-1. Today, the Middle East is representative for what Bracken (2012) calls “the second nuclear age”: this implies the proliferation of nuclear power plants in the region, which is characterized by rich and often hostile super- resp. regional powers, e.g., Saudi Arabia and Iran and “failed states” like Iraq or Libya. In addition, the region is very sensitive to the “U.S.-Iran” nuclear deal, i.e. if the

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<sup>275</sup> Schneider et al. (2017, 109–10).

<sup>276</sup> World Nuclear News. 2018. “India to assist in Rooppur implementation.” <http://www.world-nuclear-news.org/NN-India-to-assist-in-Rooppur-implementation-0203184.html>.

deal is cancelled and Iran opts for reprocessing or enrichment technology, other nations will probably follow suit, especially Saudi Arabia.

Nuclear power first emerged in the early 1960s in the region; today, one notes, when looking at the planned newbuild projects in the region, that nearly the entire Middle East seems to be fully under the influence of Russian nuclear diplomacy, with Atomstroyexport being the main contractor in the region, except for UAE, where South Korea constructs the power plants.

#### **4.5.3.1 United Arab Emirates (UAE)**

Somewhat representative for the “second nuclear age”, the United Arab Emirates (UAE) have followed Iran, and may be preceding Saudi Arabia and others, with the installation of nuclear power plants. In January 2009, Foreign Minister Abdullah bin Zayed signed an agreement (“123 Agreement”) with the U.S. about the civil nuclear cooperation under agreed non-proliferation conditions and control.<sup>277</sup> In accordance with the “123 Agreement”, UAE committed itself to go without domestic enrichment and reprocessing capabilities in order to produce fuel and theoretically be able to equip itself with weapons-grade material. Thus, to obtain fuel, the country will have to import it.<sup>278</sup>

To join the circles of countries using nuclear power for electricity generation, the UAE opened a tender to install a NPP in the country. In December 2009, the Korean state-controlled KEPCO won the USD 18.6 billion project.<sup>279</sup> In order to win the tender, KEPCO reportedly bid at about 20 percent beneath the industry average.<sup>280</sup> The deal consists of four APR1400—each of them with a design capacity of 1,400 MW<sub>e</sub>. With the construction of the Barakah plant, KEPCO<sup>281</sup> enters unknown territory as the company has never not yet built a reactor outside of its home country. Even if this was Korea's first export of reactor technolo-

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<sup>277</sup> US Department of State (2009).

<sup>278</sup> Lévêque (2014, 15).

<sup>279</sup> It is contended that overnight construction might be around 2,930 USD/kW, though no evidence for this is provided. Lévêque and Berthélemy (2011, 7).

<sup>280</sup> Ramana and Mian (2016, 41).

<sup>281</sup> KEPCO leads a consortium of companies including Hyundai, Doosan Heavy Industries, Samsung, Westinghouse, and Toshiba (Krane, Jaffe, and Elsas 2016, 46).

gy, they also practice some form of nuclear diplomacy with a 2.5 billion USD loan from the Korean Export-Import Bank; in 2016, KEPCO also took an 18 percent equity stake in the project.<sup>282</sup>

Construction of Barakah-1 started in June 2012, Barakah-2 in May 2013, Barakah-3 in September 2014, and Barakah-4 in September 2015. All four units are scheduled to start service around 2020. Once finished, the Barakah plant is planned to cover approximately one quarter of the country's electricity demand need. This deal can be characterized as the importation of turnkey plants from South Korea, as there is no large knowledge transfer. UAE has not only imported the South Korean reactor technology, but also the South Korean nuclear experts (e.g., operational experience, radiation, radioactive waste management) to begin building the reactors. In January 2013, the country unveiled its long-term energy strategy, which foresees an energy mix consisting of 44% clean energy and 6% nuclear by the year 2050; the remaining half should be achieved with fossil fuels.

#### 4.5.3.2 Turkey

Turkey is a major economic and political power at the crossroads between Europe and the Near and Middle East. It has claimed ambitions to become a nuclear power for a long time. Officially, the reason is to reduce its import dependency, currently Turkey imports 98 percent of its gas, 92 percent of its oil, and nearly half of its coal.

Currently a member of NATO, Turkey has nonetheless engaged into nuclear diplomacy with Russia. A Memorandum of Understanding was signed between the two countries, in 2010, under which Russia would supply nine NPPs, for about USD 20 billion.<sup>283</sup> The most advanced project is Akkuyu, here Turkey opted for the Russian “BOO” model. According to the WNISR 2017, the 2010 deal foresees the construction of four VVER1200 reactors, initial construction start was set to 2015 but a full construction license is expected to be granted in 2018 or later. The project consists of a 15-year Power Purchase Agreement for 70 percent of electricity generated in units 1 and 2 and for 30 percent generated in units 3 and 4. In total, 50 per-

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<sup>282</sup> Schneider et al. (2017, 107).

<sup>283</sup> Bronson (2016, 12).



cent of the generated electricity for the first 15 years will be sold at fixed guaranteed price, while the rest is sold on the market. Due to further delays, financing issues, the rejection of the environmental impact assessment by the Ministry of Environment, commissioning of the first unit was postponed and the estimated budget was increased to 22 billion USD, but not for the nine projects, only for the two first units.

The two other sites currently being investigated for nuclear power projects are Sinop on the northern coast and İğneada on the Black Sea. The latest project proposal consists of 4.4 GW using the ATMEA reactor design for another 22 billion USD.<sup>284</sup> This would constitute the first construction start-up of this jointly developed reactor design by Mitsubishi and Areva (now Framatome). The financial troubles of Areva and the leaving of the nuclear sector of the third consortia partner Engie question the validity of the project. The most likely contractors for the third site İğneada was Westinghouse in cooperation with Chinese SNPTC, but Westinghouse bankruptcy raises serious questions about the future of the project.

#### **4.5.3.3 Saudi Arabia**

Saudi Arabia is another major country in the Middle East that aspires to become a nuclear power. In 2010, Saudi Arabia set up the King Abdullah City for Atomic and Renewable Energy (K.A. CARE) with a mandate to support the development of nuclear and renewable energy in the country. Currently, there are ideas to build a significant amount of nuclear power. Riyadh has signed several general nuclear energy cooperation pacts with South Korea, Argentina, China, Russia, and France for a total of 16 NPPs (17 GW<sub>e</sub>) in the next two decades, at projected costs of 80 billion USD.<sup>285</sup> One major motivation for this drastic change in energy policy seems to be the high ratio of burning oil for electricity generation, as a larger nuclear share would mean more Saudi Arabian oil would be destined for exports.

Initially, France had high hopes for entering the Saudi market and in order to do so, EDF and Areva (now Framatome) started training Saudi engineers and set up an office in Riyadh; and

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<sup>284</sup> Schneider et al. (2017, 111).

<sup>285</sup> Bronson (2016, 11).

in 2015 the two countries agreed to build two EPRs.<sup>286</sup> However, Saudi Arabia has signed multiple cooperation agreements, feasibility studies, and memorandums of understanding with South Korea, Russia, and China too and agreed with Argentina on a SMR design envisaged for desalination.<sup>287</sup> There were also discussions with the U.S. to export nuclear reactors, but the deal never materialized due to the more restrictive conditions imposed by Washington (if this will change under the Trump administration remains to be seen). Recently, the nuclear diplomacy between Saudi Arabia and Russia has intensified: The most promising deal was signed in 2015 with Russia: an agreement outlining a series of cooperative measures for building NPPs. Although, the two countries have differences, especially concerning their Syria and Iran policies (Russia is involved in operating the only nuclear power plant in Iran), the two countries signed an atomic energy cooperation roadmap in 2017.

An increasing debt-to-GDP ratio led to the postponement of the forecasted nuclear start from 2030 to 2040.<sup>288</sup> In addition to the pursuit of installing Gen III/III<sup>+</sup> reactors, Riyadh also keeps exploring future reactor designs and (in 2017) a co-operation agreement was signed with China Nuclear Engineering Corp. on the development of a HTGR.<sup>289</sup> Contrary to UAE, Saudi Arabia intends to set up some form of nuclear industry with the launch of a nuclear engineering program at the King Abdulaziz University; the Kingdom is also sending its scientists to train in France or in other nuclear countries.<sup>290</sup>

If Saudi Arabia tries to gain access to nuclear weapons technology remains to be seen, but as the oil share—apparently the major motivation for nuclear development—could also be reduced by a higher penetration of renewables, this raises concerns, that the nuclear deployment is also motivated by geopolitical ambitions. If Iran is allowed to have access to

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<sup>286</sup> Ramana and Mian (2016, 40).

<sup>287</sup> Krane et al. (2016, 45).

<sup>288</sup> Bronson (2016, 14).

<sup>289</sup> Schneider et al. (2017, 120).

<sup>290</sup> Krane et al. (2016, 46).

enrichment technology, Saudi Arabia will claim the same “privilege” or in the worst case, if Iran succeeds in going nuclear, Riyadh will follow suit.<sup>291</sup>

#### 4.5.3.4 Egypt

Already in 1955, Egypt attended the first Geneva Conference and made a case for why the country would like to acquire nuclear power. In the mid-1970s, the government’s Nuclear Power Plants Authority was established, which developed plans for ten reactors by the end of the century. Although there were discussions with several suppliers, these plans never materialized. Under the Atoms for Peace program, both superpowers, the U.S. and the USSR, trained scientists from Egypt, while the latter also supplied a research reactor to Cairo.<sup>292</sup> In 1958, construction of ETRR-1, a light water moderated and cooled reactor, started at the Inshas nuclear research centre in Cairo; three years later the reactor achieved criticality. A second research reactor at the same site in Inshas (ETRR-2, 22 MW<sub>e</sub>) achieved criticality in 1997, this time the reactor was supplied by the Argentinian company Invap.<sup>293</sup>

In 2006, the minister of energy announced plans to construct a 1,100 MW<sub>e</sub> reactor for 1.5 billion USD at El-Dabaa on the Mediterranean coast (initial plans foresaw in total three plants (1,800 MW<sub>e</sub>); moreover at that time it was reported that UAE, Saudi Arabia, and Oman promised to contribute financial aid to revive Egypt’s nuclear program.<sup>294</sup> In 2015, Russia and Egypt signed a deal to finance and build four VVER-1200 units in Egypt for 29.4 billion USD. In 2016, Russia and Egypt concluded a financial deal: a 25 billion USD Russian State backed loan, which should cover 85 percent of the project cost; the three-percent interest loan is to be paid back over 22 years starting in 2029.<sup>295</sup> Contrary to the BOO model sold to Turkey, Rosatom will also help to set up Egypt’s nuclear industry: “several dozen”

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<sup>291</sup> This was openly admitted by the Saudi Crown Prince with CBS’ 60 Minutes on March 18, 2018. See Washington Post. 2018. “Why does Saudi Arabia want to spend billions to enrich its own uranium?” April 23, 2018. [https://www.washingtonpost.com/business/economy/why-does-saudi-arabia-want-to-spend-billions-to-enrich-its-own-uranium/2018/03/19/1ce87608-2225-11e8-badd-7c9f29a55815\\_story.html?utm\\_term=.348dcfb752b3](https://www.washingtonpost.com/business/economy/why-does-saudi-arabia-want-to-spend-billions-to-enrich-its-own-uranium/2018/03/19/1ce87608-2225-11e8-badd-7c9f29a55815_story.html?utm_term=.348dcfb752b3).

<sup>292</sup> Ramana and Mian (2016, 39).

<sup>293</sup> Wisconsin Project on Nuclear Arms Control. 1996. “Egypt’s Budding Nuclear Program.” April 23, 2018. <https://www.wisconsinproject.org/egypts-budding-nuclear-program/>

<sup>294</sup> Salama and Weber (2007, 48).

<sup>295</sup> Schneider et al. (2017, 114).

Egyptian companies will be involved in the construction of the reactors with a localisation level of around 20 percent for the first unit, to be increased for the remaining units.<sup>296</sup>

Although, Egypt has often called for a nuclear weapons free Middle East and asserted its commitment to the NPT, it remains to be seen if Egypt tries to develop a nuclear weapons program. This depends especially on the dynamics in the Middle East, e.g., Iran and Saudi Arabia planning to construct enrichment facilities.

#### 4.5.3.5 Jordan

Already in 1955, Jordan attended the first Geneva Conference and made a case for why the country would like to acquire nuclear power. More than 50 years later (in 2007), the Jordan Atomic Energy Commission (JAEC) and the Jordan Nuclear Regulatory Commission were established.

Before 1990, Jordan received heavily subsidized oil imports from the Arab Gulf states, which vanished when Jordan backed Iraq during the first Gulf War; then Jordan established a firm energy partnership with Egypt, but exports have disappeared as the pipelines connecting Egypt and Jordan were repeatedly targeted in the recent political unrest. In the midst of this unrest, Jordan engaged in nuclear diplomacy with Russia, that offered the country two NPPs, to be built at Amra; the Memorandum of Understanding for a USD 10 bn deal was signed in March 2015.<sup>297</sup> Like elsewhere, a substantial fraction of the potential investment—representing roughly more than a fourth of Jordan’s GDP (38.65 billion USD in 2016)—is backed by Russian low-cost loans. In addition, the two 1,100 MW<sub>e</sub> reactors imply an infrastructure problem; they are so large, that they could destabilize the entire national grid.<sup>298</sup>

According to the WNISR 2017, Jordan received different options for the reactor technology: the ATMEA-1 Design from Areva and Mitsubishi, the Candu-6 from AECL, or the APR-1400 from KEPCO. But Russia’s nuclear diplomacy with offering the reactor, state-backed loans,

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<sup>296</sup> World Nuclear News. 2017. “‘Notice to proceed’ contracts signed for El Dabaa.” April 24, 2018. <http://www.world-nuclear-news.org/NN-Notice-to-proceed-contracts-signed-for-El-Dabaa-1112178.html>.

<sup>297</sup> Bronson (2016, 11–12).

<sup>298</sup> Ramana and Mian (2016, 41).

and the offer to take back the spent fuel led to the ordering of two VVERs. Russia offered to finance 49.9 percent, while Jordan should come up with the remaining 50.1 percent, which has been unsuccessful this far.

In December 2016, Korea (Korea Atomic Energy Research Institute and Daewoo Engineering & Construction) completed Jordan's first nuclear research reactor, the Jordan Research and Training Reactor – JRTR, 5 MW<sub>e</sub>, for 161 million USD. For this Korea provided a loan for the construction of 70 million USD, starting in 2020, over 29 years, and 0.2 percent interest rate.<sup>299</sup>

#### 4.5.4 Further “newcomers”

According to the WNISR 2017, there have also been signed contracts on nuclear newbuild in Lithuania (project has been shelved indefinitely due to unfavourable market conditions) and Vietnam. The latter had signed an agreement with Russia for a turnkey VVER1200 for the Ninh Thuan site, construction was supposed to begin 2014 but the plans were cancelled in 2016.

There were also “committed plans” in Poland, Indonesia, Thailand and “developing plans” in Algeria, Israel, Kenya, Laos, Malaysia, Morocco, and Nigeria. In 2016, China (CNNC) and Sudan also signed a framework agreement for the import of a Hualong One reactor.<sup>300</sup>

With the exception of UAE, Belarus, and Bangladesh where construction has physically started, Schneider et al. (2017) only see Turkey as actually being able to or seriously aspiring to deploy nuclear power plants in the near-term future.

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<sup>299</sup> Schneider et al. (2017, 115).

<sup>300</sup> Sudan is one of China's main oil suppliers. World Nuclear News. 2018. “China to help Sudan develop first nuclear plant.” April 23, 2018. <http://www.world-nuclear-news.org/NP-China-to-help-Sudan-develop-first-nuclear-plant-2405164.html>

## 5 Conclusion

Nuclear energy is among the most important innovations of the twentieth century, and it continues to play an important role in twenty-first century discussions. In particular, there is a debate about the potential contribution of nuclear power to policies of climate change mitigation and energy security in both, industrialized and emerging countries. In this context, many existing nuclear countries, and others considering entering the sector, are facing questions of how to structure organizational models for nuclear power, and what lessons to be learned from the past seven decades of civilian use of nuclear power.

The objective of this Data Documentation is to trace the development of nuclear power since its beginnings, by providing both a technological and a country-specific perspective, to allow a better understanding of issues on nuclear power going forward. Our hypothesis, based on the early literature on nuclear power post World War 2, e.g., the Acheson-Lilienthal Report (1946), Lovins and Lovins (1980) but also a more recent survey of the literature (Hirschhausen 2017), is that nuclear power is the “child of scientific research and the military” (François Lévêque 2014, 212), the development of which follows an “economies-of-scope”-logic: nuclear power is developed for military and civilian purposes (e.g., electricity, medical services), and thus obeys no simple economic logic that could be expressed, e.g., in simple business investment calculus (Davis 2012). Rather than searching for an economic rationale where there is none, it is therefore instructive to analyze specific diffusion patterns of nuclear power, based on stylized organizational models, and going back to the origins in the middle of the last century.

A certain understanding of nuclear reactor physical principles is useful to understand the link between different applications of nuclear power, and the inherent link between military and other uses. Nuclear fission was developed at industrial scale to produce the atomic bomb, in the Manhattan Project. All subsequent applications derive from the first large-scale military application, be it more sophisticated nuclear weaponry, electricity, medical uses, etc. Post-WW2 reactor technologies were developed with the scope-objectives, be it the graphite-moderated reactors in the U.K., France, and the Soviet Union, or the heavy-water reactors in Canada and Sweden; the light-water route, pursued by the U.S. thanks to a separate pluto-

nium facility, was also rooted in a military application, i.e. submarine propulsion. There is no purely “civil” (sometimes used “peaceful”) use of nuclear power.

A historical analysis of the emergence of nuclear power since 1945 suggests to distinguish four periods:

i/ Between 1945 and into the mid-1950s, four major countries had established independent, national pathways of nuclear technologies for military purposes and electricity generation: the U.S., the Soviet Union, the U.K., and France;

ii/ subsequent to the mid-1950s, and the failure of US attempts to control proliferation of nuclear material, mainly the “Atoms for Peace” program, lead to fierce competition between the two nuclear superpowers, the U.S. and the Soviet Union, for controlling technological diffusion. The US approach was much more “liberal”, by selling technology and licenses to adoption countries, like Japan, Korea, and Germany, whereas the Soviet Union kept the technology and only gave away turnkey reactors to satellite states. Some countries were able to develop their own nuclear pathway, such as India, Pakistan, and Israel;

iii/ starting in the mid-/late 1980s, China developed its nuclear sector, to become the third nuclear superpower, and the move from the first to the “second nuclear age” (Bracken, 2012), with ten or even more countries controlling the nuclear bomb, including North Korea and attempts in Iran;

iv/ Post-Fukushima (2011) is characterized by the implosion of nuclear power in Western capitalist market economies, and the closure of nuclear power plants, often before reaching technical lifetimes, due to economic reasons; many of the newbuild projects were abandoned, too. This leaves the development of nuclear power to “other”, non-market systems, where countries hang on to nuclear development, for political, military-strategic, or other reasons, mainly the nuclear superpowers China and Russia. “Nuclear diplomacy”, i.e. attempts to attract partner countries by providing them reactor technology more or less for free, is gaining ground in particular in China, Russia, and—to a lesser extent—the U.S.

The analysis of the diffusion of nuclear power on a country-by-country basis reveals different patterns: we distinguish “economies-of-scope” trajectories, recipient countries of nuclear technologies with and without subsequent indigenous technology catch-up, and “other”

countries; we also identify current trends in potential newcomer countries, such as Turkey, Bangladesh, and Sudan.

Initial hopes placed on “Generation IV” and/or small modular reactors (SMRs) have not been fulfilled. Although some Gen IV research reactors are developed, no technology has any perspective of becoming economically competitive, neither with current nuclear technologies, nor with conventional fossil or renewable generation in combination with storage. Most SMRs are based on designs that are several decades old, and none of them is close to attaining any sort of commercial availability.

The Data Documentation fills a research gap in the literature, in that it provides bottom-up, evidence-based proof that nuclear power follows no economic rationale, but some other logic linked to “science and warfare”. None of the 674 reactors analysed in the text and documented in the appendix, has been developed based on what is generally considered “economic” grounds, i.e. the decision of private investors in the context of a market-based, competitive economic system. Given current technical and economic trends in the global energy industry, there is no reason to believe that this rule will be broken in the near- or longer-term future.



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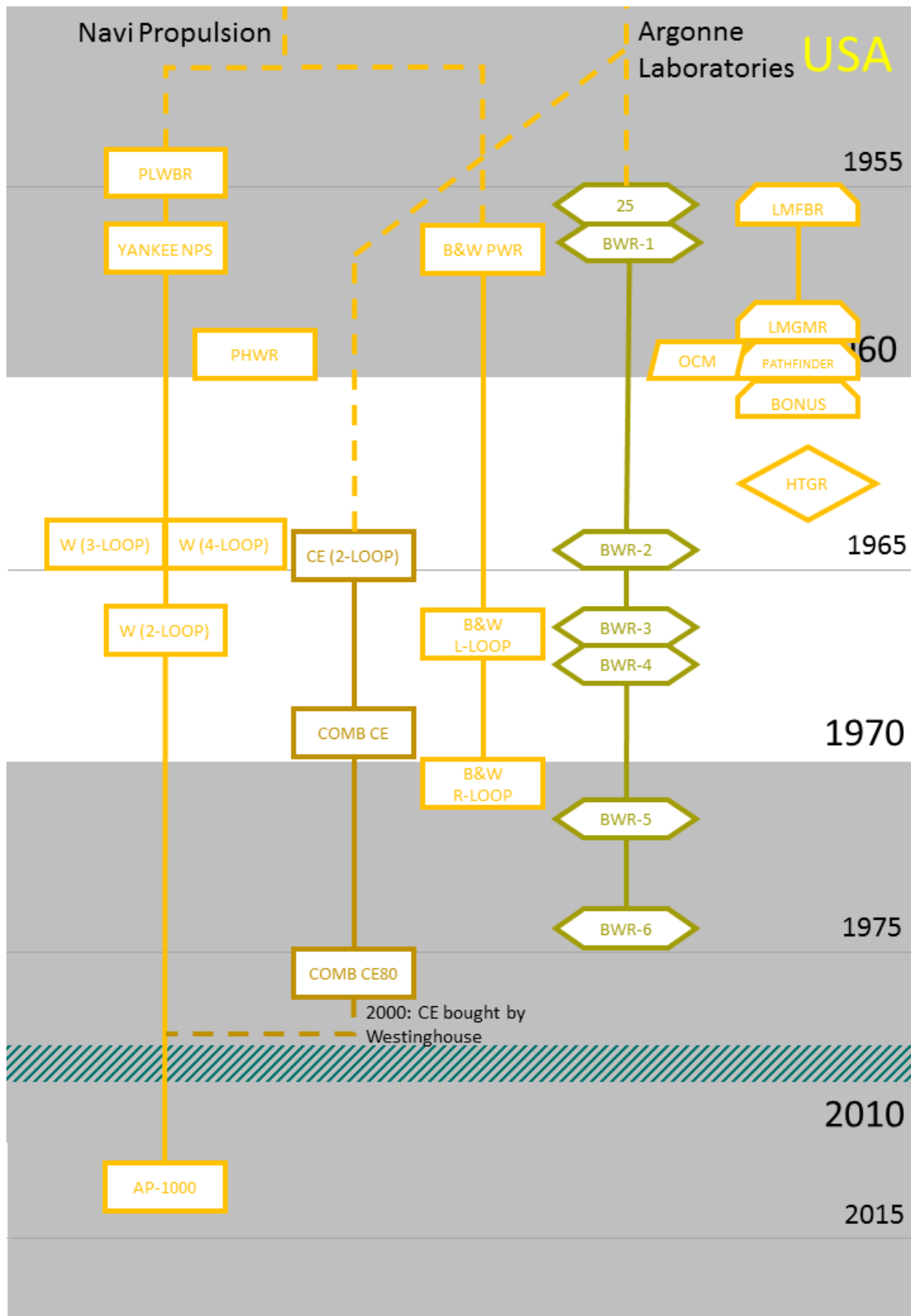
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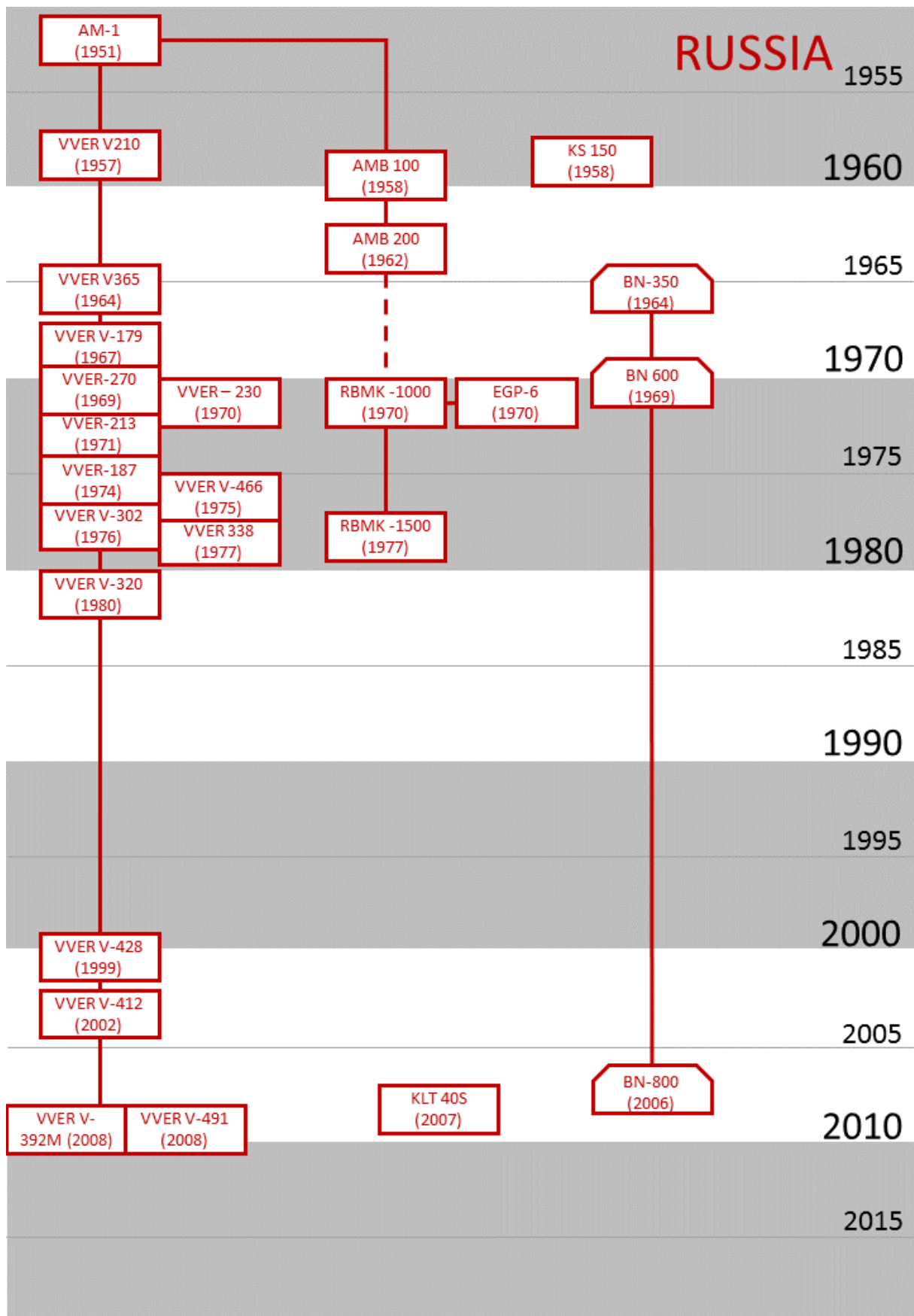


## Appendix

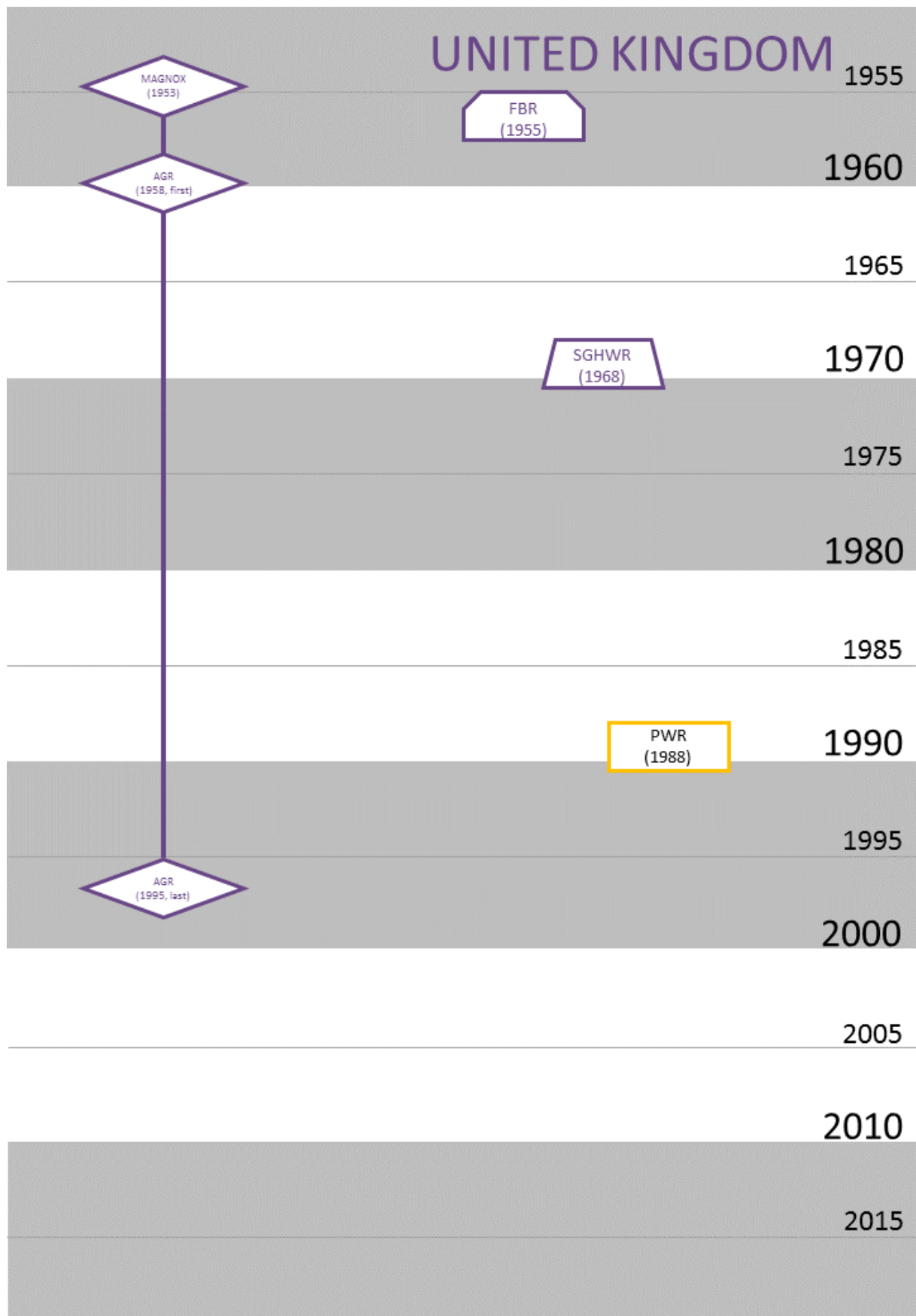
### Appendix 1: Families of nuclear reactors



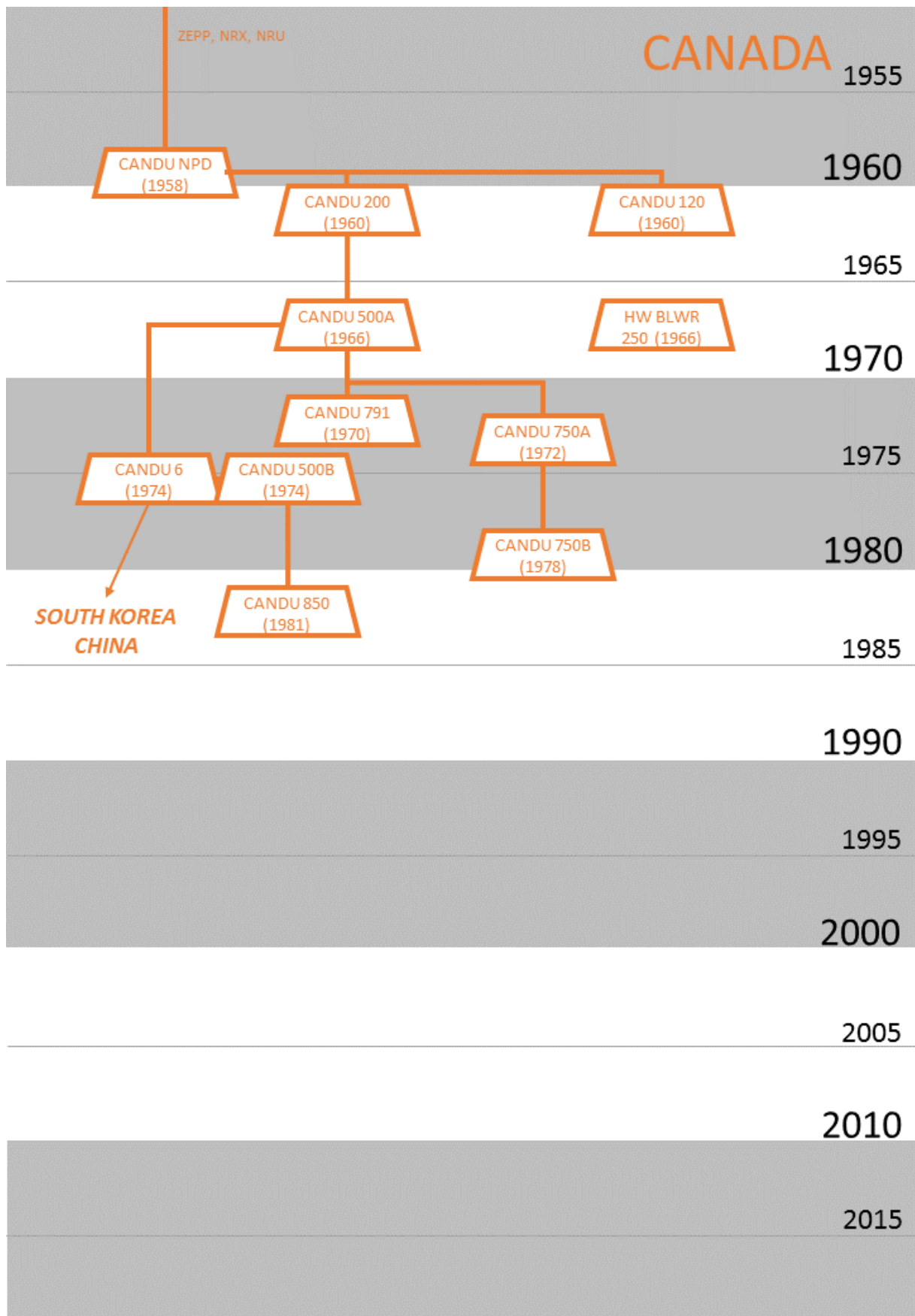
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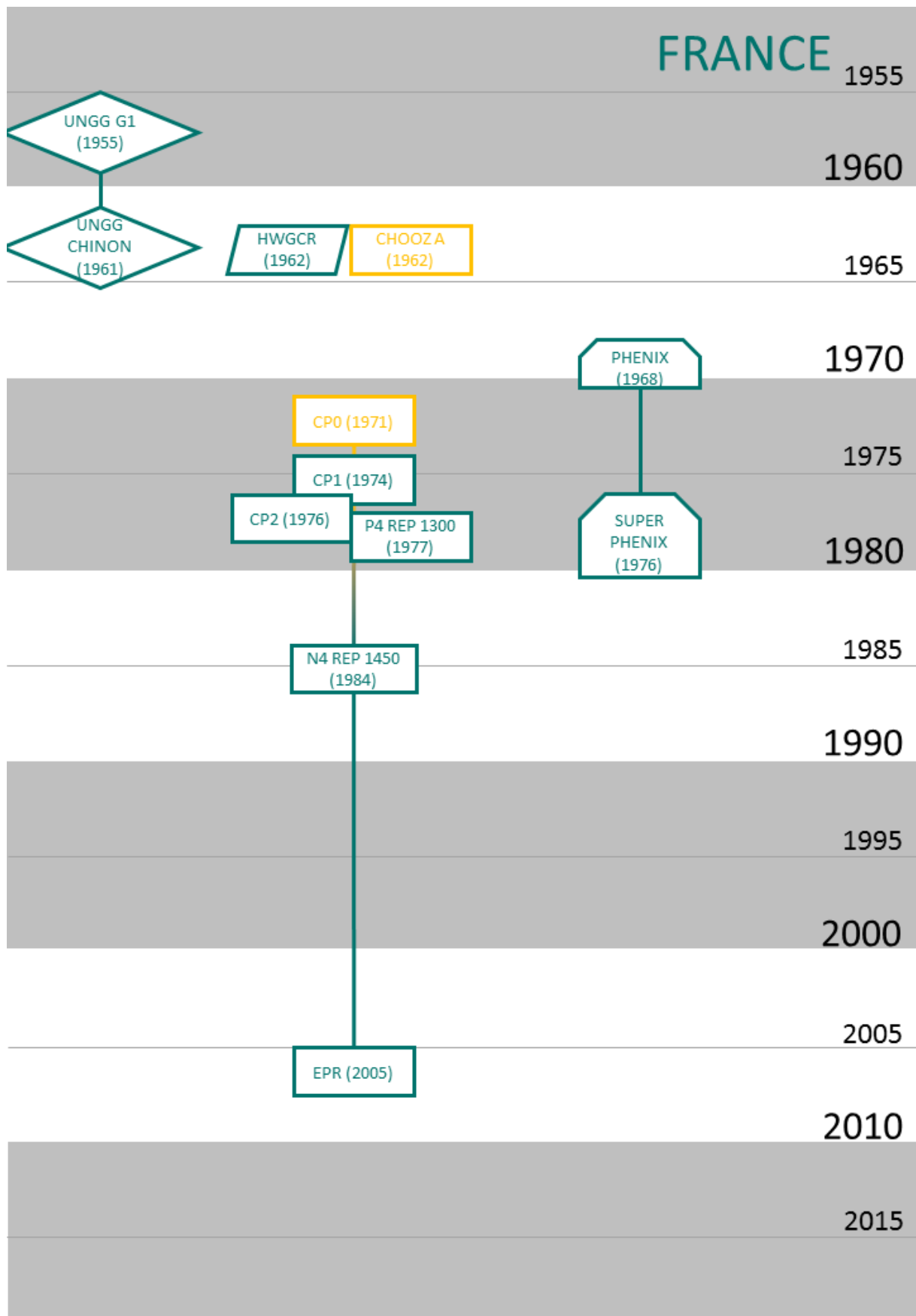
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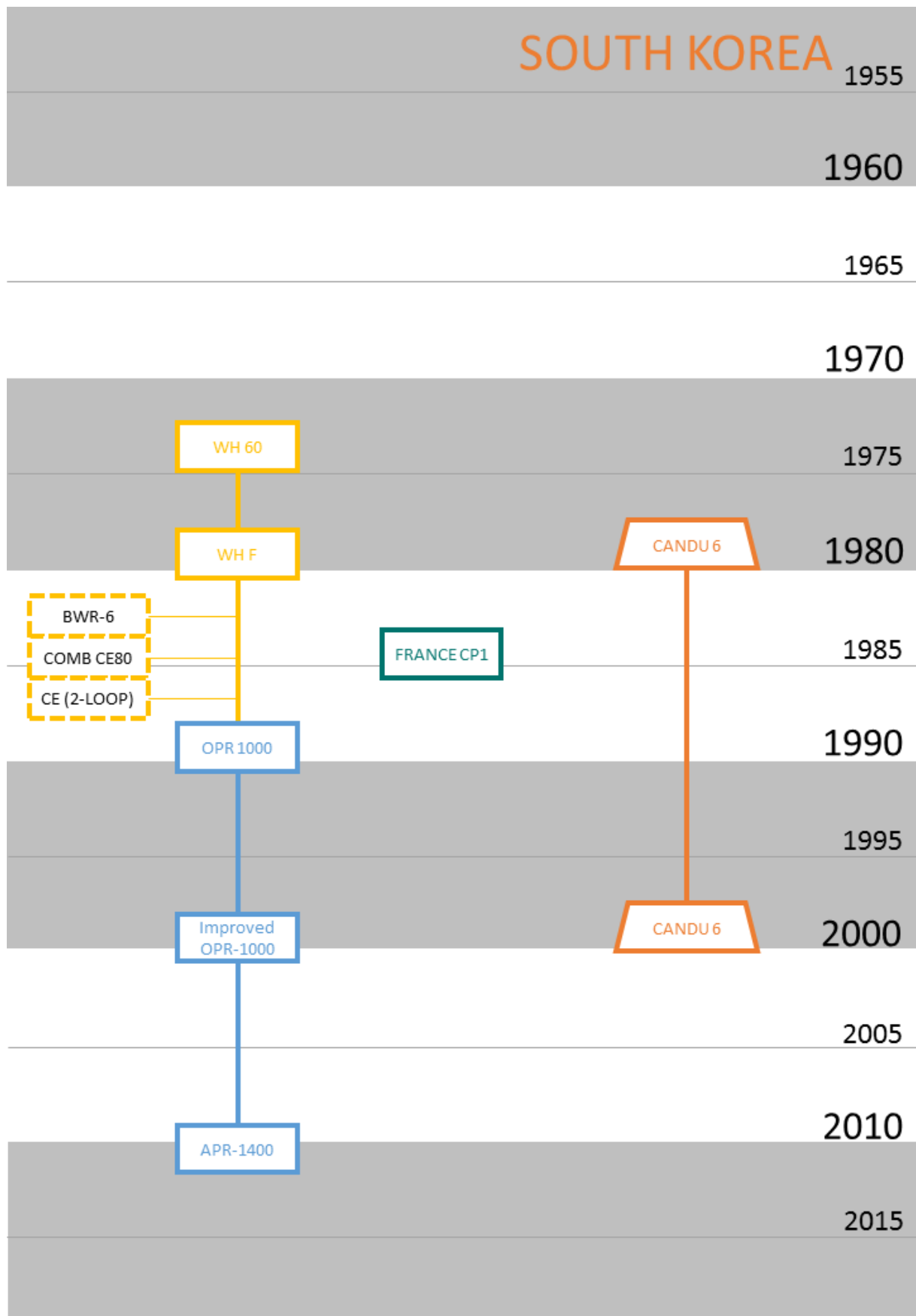


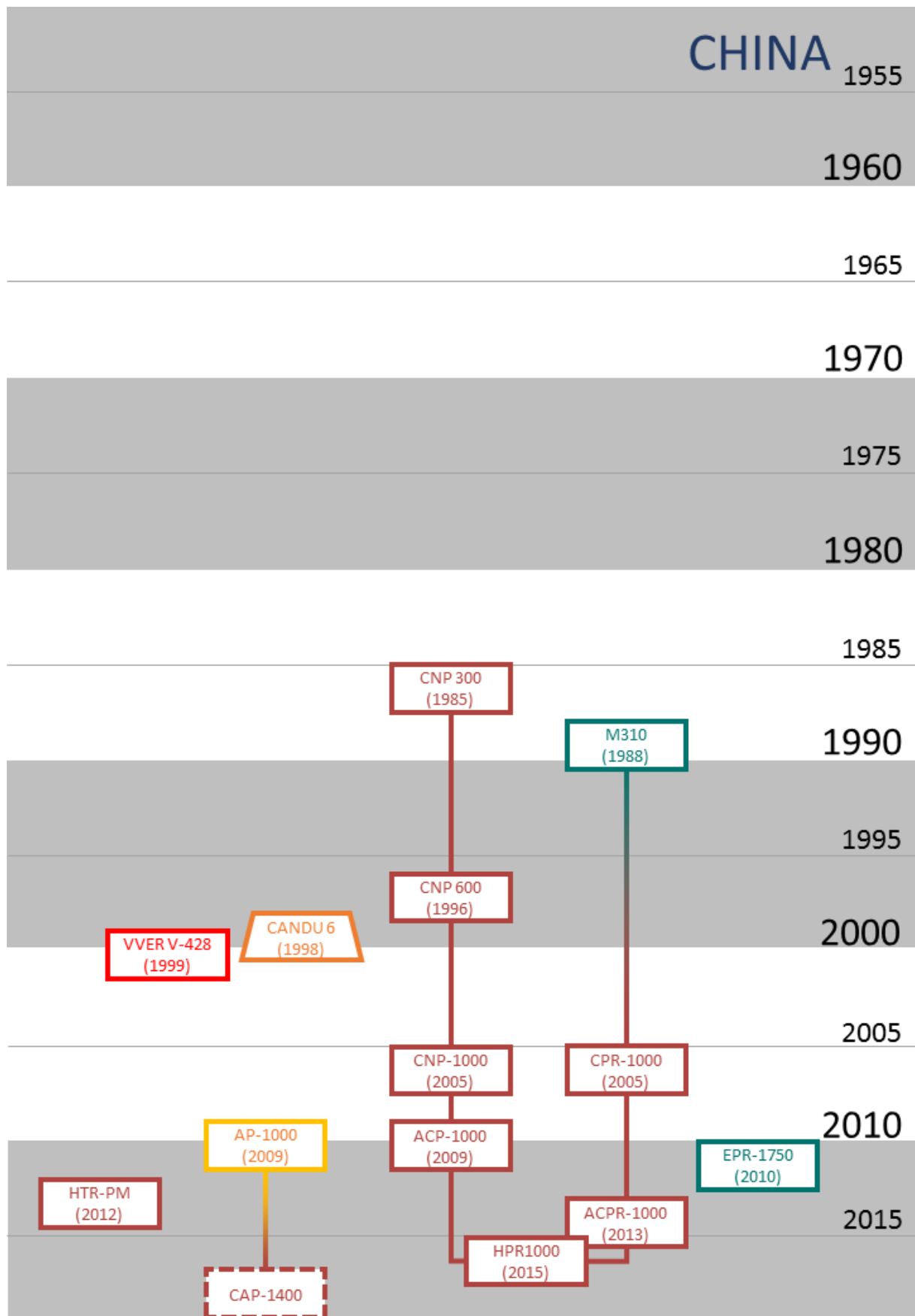
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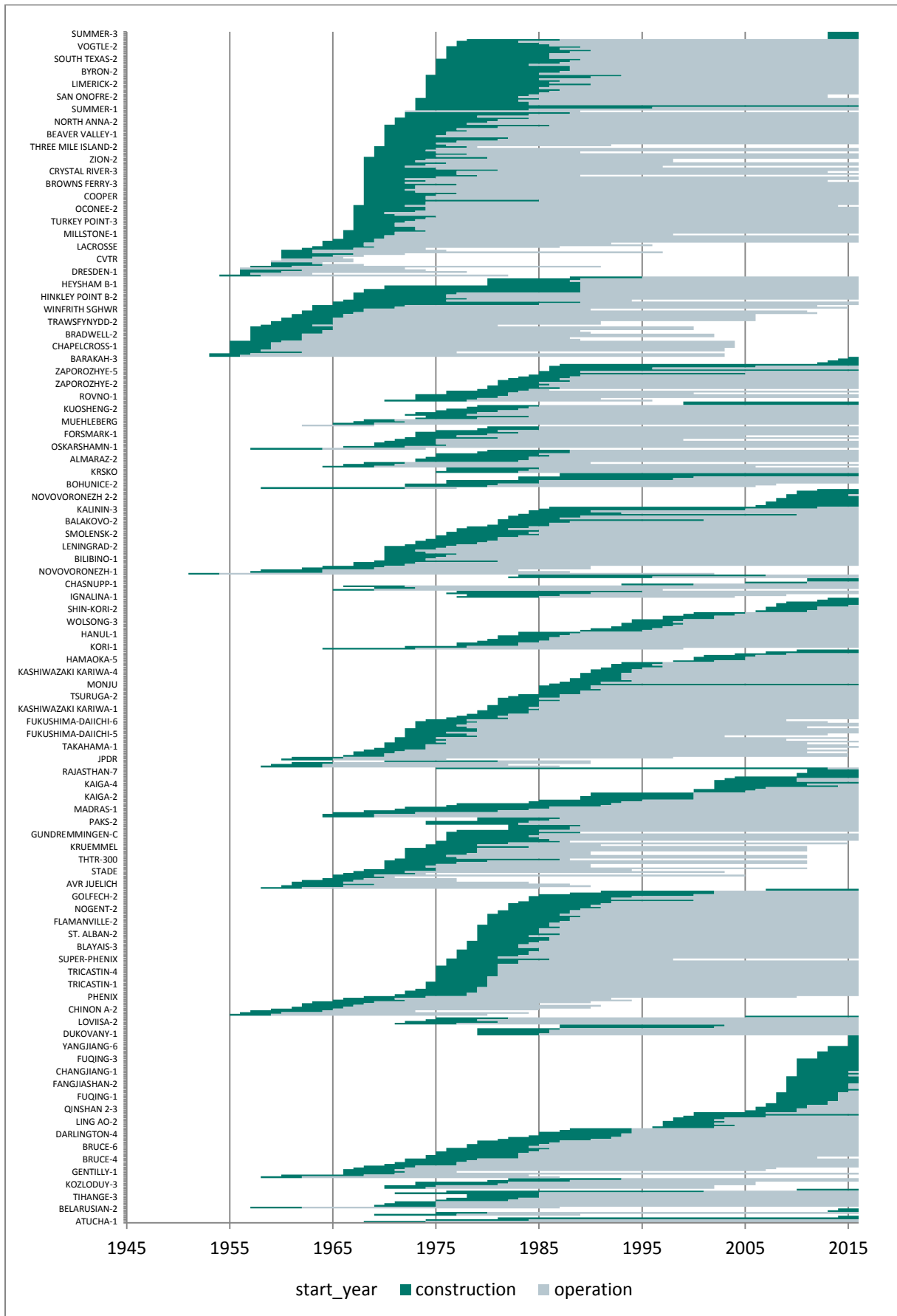
Appendix







**Appendix 2: Reactors per country**





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Appendix

Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
<b>ARGENTINA</b>								
ATUCHA-1	GERMANY	PHWR	PHWR KWU	319	01.06.1968	24.06.1974	operating	
EMBALSE	CANADA	PHWR	CANDU 6	600	01.04.1974	20.01.1984	operating	
ATUCHA-2	GERMANY	PHWR	PHWR KWU	692	14.07.1981	26.05.2016	operating	
CAREM25	ARGENTINA	PWR	CAREM Prototype	25	08.02.2014	-	-	under construction
<b>ARMENIA</b>								
ARMENIAN-1	RUSSIA	PWR	VVER V-270	376	01.07.1969	06.10.1977	25.02.1989	
ARMENIAN-2	RUSSIA	PWR	VVER V-270	375	01.07.1975	03.05.1980	operating	
<b>BELARUS</b>								
BELARUSIAN-1	RUSSIA	PWR	VVER V-491	1109	06.11.2013	-	-	under construction
BELARUSIAN-2	RUSSIA	PWR	VVER V-491	1109	26.04.2014	-	-	under construction
<b>BELGIUM</b>								
BR-3	USA	PWR	Prototype	11	01.11.1957	10.10.1962	30.06.1987	
DOEL-1	USA	PWR	W (2-loop)	392	01.07.1969	15.02.1975	operating	
TIHANGE-1	FRANCE	PWR	Framatome loops reactor <sup>3</sup>	870	01.06.1970	01.10.1975	operating	
DOEL-2	USA	PWR	W (2-loop)	392	01.09.1971	01.12.1975	operating	
DOEL-3	USA	PWR	W (3-loop)	890	01.01.1975	01.10.1982	operating	
TIHANGE-2	FRANCE	PWR	W (3-loop)	900	01.04.1976	01.06.1983	operating	
TIHANGE-3	USA	PWR	W (3-loop)	1020	01.11.1978	01.09.1985	operating	
DOEL-4	USA	PWR	W (3-loop)	1000	01.12.1978	01.07.1985	operating	
<b>BRAZIL</b>								
ANGRA-1	USA	PWR	2-loop WE	626	01.05.1971	01.01.1985	operating	
ANGRA-2	GERMANY	PWR	PRE KONVOI	1245	01.01.1976	01.02.2001	operating	
ANGRA-3	FRANCE	PWR	PRE KONVOI	1245	01.06.2010	-	-	under construction
<b>BULGARIA</b>								

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Appendix

Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
KOZLODUY-1	RUSSIA	PWR	VVER V-230	408	01.04.1970	28.10.1974	31.12.2002	
KOZLODUY-2	RUSSIA	PWR	VVER V-230	408	01.04.1970	10.11.1975	31.12.2002	
KOZLODUY-3	RUSSIA	PWR	VVER V-230	408	01.10.1973	20.01.1981	31.12.2006	
KOZLODUY-4	RUSSIA	PWR	VVER V-230	408	01.10.1973	20.06.1982	31.12.2006	
KOZLODUY-5	RUSSIA	PWR	VVER V-320	953	09.07.1980	23.12.1988	operating	
KOZLODUY-6	RUSSIA	PWR	VVER V-320	953	01.04.1982	30.12.1993	operating	
<b>CANADA</b>								
ROLPHTON NPD	CANADA	PHWR	CANDU	17	01.01.1958	01.10.1962	01.08.1987	
DOUGLAS POINT	CANADA	PHWR	CANDU 200	203	01.02.1960	26.09.1968	04.05.1984	
PICKERING-1	CANADA	PHWR	CANDU 500A	508	01.06.1966	29.07.1971	operating	
GENTILLY-1	CANADA	HWLWR	HW BLWR 250	250	01.09.1966	01.05.1972	01.06.1977	
PICKERING-2	CANADA	PHWR	CANDU 500A	508	01.09.1966	30.12.1971	28.05.2007	
PICKERING-3	CANADA	PHWR	CANDU 500A	508	01.12.1967	01.06.1972	31.10.2008	
PICKERING-4	CANADA	PHWR	CANDU 500A	508	01.05.1968	17.06.1973	operating	
BRUCE-2	CANADA	PHWR	CANDU 791	696	01.12.1970	01.09.1977	operating	
BRUCE-1	CANADA	PHWR	CANDU 791	732	01.06.1971	01.09.1977	operating	
BRUCE-3	CANADA	PHWR	CANDU 750A	750	01.07.1972	01.02.1978	operating	
BRUCE-4	CANADA	PHWR	CANDU 750A	750	01.09.1972	18.01.1979	operating	
GENTILLY-2	CANADA	PHWR	CANDU 6	645	01.04.1974	01.10.1983	28.12.2012	
PICKERING-5	CANADA	PHWR	CANDU 500B	516	01.11.1974	10.05.1983	operating	
POINT LEPREAU	CANADA	PHWR	CANDU 6	660	01.05.1975	01.02.1983	operating	
PICKERING-6	CANADA	PHWR	CANDU 500B	516	01.10.1975	01.02.1984	operating	
PICKERING-7	CANADA	PHWR	CANDU 500B	516	01.03.1976	01.01.1985	operating	
PICKERING-8	CANADA	PHWR	CANDU 500B	516	01.09.1976	28.02.1986	operating	
BRUCE-6	CANADA	PHWR	CANDU 750B	822	01.01.1978	14.09.1984	operating	

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Appendix

Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
BRUCE-5	CANADA	PHWR	CANDU 750B	822	01.06.1978	01.03.1985	operating	
BRUCE-7	CANADA	PHWR	CANDU 750B	822	01.05.1979	10.04.1986	operating	
BRUCE-8	CANADA	PHWR	CANDU 750B	795	01.08.1979	22.05.1987	operating	
DARLINGTON-2	CANADA	PHWR	CANDU 850	881	01.09.1981	09.10.1990	operating	
DARLINGTON-1	CANADA	PHWR	CANDU 850	881	01.04.1982	14.11.1992	operating	
DARLINGTON-3	CANADA	PHWR	CANDU 850	881	01.09.1984	14.02.1993	operating	
DARLINGTON-4	CANADA	PHWR	CANDU 850	881	01.07.1985	14.06.1993	operating	
<b>CHINA</b>								
QINSHAN-1	CANADA	PWR	CNP-300	288	20.03.1985	01.04.1994	operating	
DAYA BAY-1	CHINA	PWR	M310	930	07.08.1987	01.02.1994	operating	
DAYA BAY-2	FRANCE	PWR	M310	930	07.04.1988	06.05.1994	operating	
QINSHAN 2-1	CHINA	PWR	CNP-600	610	02.06.1996	15.04.2002	operating	
QINSHAN 2-2	CHINA	PWR	CNP-600	610	01.04.1997	03.05.2004	operating	
LING AO-1	CHINA	PWR	M310	950	15.05.1997	28.05.2002	operating	
LING AO-2	FRANCE	PWR	M310	950	28.11.1997	08.01.2003	operating	
QINSHAN 3-1	CHINA	PHWR	CANDU 6	677	08.06.1998	31.12.2002	operating	
QINSHAN 3-2	CANADA	PHWR	CANDU 6	677	25.09.1998	24.07.2003	operating	
TIANWAN-1	FRANCE	PWR	VVER V-428	990	20.10.1999	17.05.2007	operating	
CEFR	CANADA	FBR	BN-20	20	10.05.2000	-	-	under construction
TIANWAN-2	RUSSIA	PWR	VVER V-428	990	20.09.2000	16.08.2007	operating	
LING AO-3	FRANCE	PWR	CPR-1000	1007	15.12.2005	15.09.2010	operating	
QINSHAN 2-3	CHINA	PWR	CNP-600	619	28.04.2006	05.10.2010	operating	
<b>Reactor</b>	<b>License</b>	<b>Type</b>	<b>Model</b>	<b>Capacity (MW<sub>e</sub>)</b>	<b>Start of Construction</b>	<b>Start of Operation</b>	<b>Permanent Shutdown</b>	<b>Comments</b>
LING AO-4	CHINA	PWR	CPR-1000	1007	15.06.2006	07.08.2011	operating	

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Appendix

Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
QINSHAN 2-4	CHINA	PWR	CNP-600	619	28.01.2007	30.12.2011	operating	
HONGYANHE-1	USA	PWR	CPR-1000	1061	18.08.2007	06.06.2013	operating	
NINGDE-1	CHINA	PWR	CPR-1000	1018	18.02.2008	15.04.2013	operating	
HONGYANHE-2	CHINA	PWR	CPR-1000	1061	28.03.2008	13.05.2014	operating	
NINGDE-2	CHINA	PWR	CPR-1000	1018	12.11.2008	04.05.2014	operating	
FUQING-1	CHINA	PWR	CNP-1000	1000	21.11.2008	22.11.2014	operating	
YANGJIANG-1	CHINA	PWR	CPR-1000	1021	16.12.2008	25.03.2014	operating	
FANGJIASHAN-1	CHINA	PWR	CPR-1000	1000	26.12.2008	15.12.2014	operating	
HONGYANHE-3	CHINA	PWR	CPR-1000	1000	07.03.2009	16.08.2015	operating	
SANMEN-1	CHINA	PWR	AP1000	1000	19.04.2009	-	-	under construction
YANGJIANG-2	CHINA	PWR	CPR-1000	1000	04.06.2009	05.06.2015	operating	
FUQING-2	CHINA	PWR	CNP-1000	1000	17.06.2009	16.10.2015	operating	
FANGJIASHAN-2	CHINA	PWR	CPR-1000	1000	17.07.2009	12.02.2015	operating	
HONGYANHE-4	CHINA	PWR	CPR-1000	1000	15.08.2009	-	-	under construction
HAIYANG-1	CHINA	PWR	AP1000	1000	24.09.2009	-	-	under construction
TAISHAN-1	CHINA	PWR	EPR-1750	1660	18.11.2009	-	-	under construction
SANMEN-2	USA	PWR	AP1000	1000	15.12.2009	-	-	under construction
NINGDE-3	CHINA	PWR	CPR-1000	1018	08.01.2010	10.06.2015	operating	
TAISHAN-2	FRANCE	PWR	EPR-1750	1660	15.04.2010	-	-	under construction
CHANGJIANG-1	CHINA	PWR	CNP-600	610	25.04.2010	25.12.2015	operating	
HAIYANG-2	USA	PWR	AP1000	1000	20.06.2010	-	-	under construction
FANGCHENG-GANG-1	FRANCE	PWR	CPR-1000	1000	30.07.2010	01.01.2016	operating	
NINGDE-4	CHINA	PWR	CPR-1000	1018	29.09.2010	-	-	under construction
YANGJIANG-3	CHINA	PWR	CPR-1000	1000	15.11.2010	01.01.2016	operating	
CHANGJIANG-2	CHINA	PWR	CNP-600	610	21.11.2010	-	-	under construction

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Appendix

Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
FANGCHENG-GANG-2	CHINA	PWR	CPR-1000	1000	23.12.2010	-	-	under construction
FUQING-3	CHINA	PWR	CPR-1000	1000	31.12.2010	-	-	under construction
FUQING-4	CHINA	PWR	CNP-1000	1000	17.11.2012	-	-	under construction
YANGJIANG-4	CHINA	PWR	CPR-1000	1000	17.11.2012	-	-	under construction
SHIDAO BAY-1	USA	HTGR	HTR-PM	200	09.12.2012	-	-	under construction
TIANWAN-3	RUSSIA	PWR	VVER V-428M	990	27.12.2012	-	-	under construction
YANGJIANG-5	CHINA	PWR	ACPR-1000	1000	18.09.2013	-	-	under construction
TIANWAN-4	RUSSIA	PWR	VVER V-428M	990	27.09.2013	-	-	under construction
YANGJIANG-6	CHINA	PWR	ACPR-1000	1000	23.12.2013	-	-	under construction
HONGYANHE-5	CHINA	PWR	ACPR-1000	1000	29.03.2015	-	-	under construction
FUQING-5	CHINA	PWR	HPR1000	1000	07.05.2015	-	-	under construction
HONGYANHE-6	CHINA	PWR	ACPR-1000	1000	24.07.2015	-	-	under construction
FUQING-6	CHINA	PWR	HPR1000	1000	22.12.2015	-	-	under construction
FANGCHENG-GANG-3	CHINA	PWR	HPR1000	1000	24.12.2015	-	-	under construction
TIANWAN-5	RUSSIA	PWR	CNP-1000	1000	27.12.2015	-	-	under construction
<b>CZECH REPUBLIC</b>								
DUKOVANY-1	RUSSIA	PWR	VVER V-213	420	01.01.1979	03.05.1985	operating	
DUKOVANY-2	RUSSIA	PWR	VVER V-213	420	01.01.1979	21.03.1986	operating	
DUKOVANY-3	RUSSIA	PWR	VVER V-213	420	01.03.1979	20.12.1986	operating	
DUKOVANY-4	RUSSIA	PWR	VVER V-213	420	01.03.1979	19.07.1987	operating	
TEMELIN-1	RUSSIA	PWR	VVER V-320	912	01.02.1987	10.06.2002	operating	
TEMELIN-2	RUSSIA	PWR	VVER V-320	912	01.02.1987	18.04.2003	operating	
<b>FINLAND</b>								
LOVIISA-1	RUSSIA	PWR	VVER V-213	420	01.05.1971	09.05.1977	operating	

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Appendix

Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
LOVIISA-2	RUSSIA	PWR	VVER V-213	420	01.08.1972	05.01.1981	operating	
OLKILUOTO-1	RUSSIA	BWR	ABB-III, BWR-2500	660	01.02.1974	10.10.1979	operating	
OLKILUOTO-2	SWEDEN	BWR	ABB-III, BWR-2500	660	01.11.1975	10.07.1982	operating	
OLKILUOTO-3	SWEDEN	PWR	EPR	1600	12.08.2005	-	-	under construction
<b>FRANCE</b>								
G-2 (MARCOULE)	FRANCE	GCR	UNGG	36	01.03.1955	22.04.1959	02.02.1980	
G-3 (MARCOULE)	FRANCE	GCR	UNGG	36	01.03.1956	04.04.1960	20.06.1984	
CHINON A-1	FRANCE	GCR	UNGG	68	01.02.1957	01.02.1964	16.04.1973	
CHINON A-2	FRANCE	GCR	UNGG	170	01.08.1959	24.02.1965	14.06.1985	
CHINON A-3	FRANCE	GCR	UNGG	480	01.03.1961	04.08.1966	15.06.1990	
CHOOZ-A (ARDENNES)	USA	PWR	CHOOZ-A	280	01.01.1962	15.04.1967	30.10.1991	
EL-4 (MONTS D'ARREE)	FRANCE	HWGCR	MONTS-D'ARREE	70	01.07.1962	01.06.1968	31.07.1985	
ST. LAURENT A-1	FRANCE	GCR	UNGG	480	01.10.1963	01.06.1969	18.04.1990	
BUGEY-1	FRANCE	GCR	UNGG	540	01.12.1965	01.07.1972	27.05.1994	
ST. LAURENT A-2	FRANCE	GCR	UNGG	515	01.01.1966	01.11.1971	27.05.1992	
PHENIX	FRANCE	FBR	PH-250	233	01.11.1968	14.07.1974	01.02.2010	
FESSENHEIM-1	USA	PWR	CP0	880	01.09.1971	01.01.1978	operating	
FESSENHEIM-2	USA	PWR	CP0	880	01.02.1972	01.04.1978	operating	
BUGEY-2	USA	PWR	CP0	920	01.11.1972	01.03.1979	operating	
BUGEY-3	USA	PWR	CP0	920	01.09.1973	01.03.1979	operating	
BUGEY-4	USA	PWR	CP0	900	01.06.1974	01.07.1979	operating	
BUGEY-5	USA	PWR	CP0	900	01.07.1974	03.01.1980	operating	
TRICASTIN-1	USA	PWR	CP1	915	01.11.1974	01.12.1980	operating	
TRICASTIN-2	USA	PWR	CP1	915	01.12.1974	01.12.1980	operating	

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Appendix

Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
DAMPIERRE-1	USA	PWR	CP1	890	01.02.1975	10.09.1980	operating	
GRAVELINES-1	USA	PWR	CP1	910	01.02.1975	25.11.1980	operating	
GRAVELINES-2	USA	PWR	CP1	910	01.03.1975	01.12.1980	operating	
DAMPIERRE-2	USA	PWR	CP1	890	01.04.1975	16.02.1981	operating	
TRICASTIN-3	USA	PWR	CP1	915	01.04.1975	11.05.1981	operating	
TRICASTIN-4	USA	PWR	CP1	915	01.05.1975	01.11.1981	operating	
DAMPIERRE-3	USA	PWR	CP1	890	01.09.1975	27.05.1981	operating	
GRAVELINES-3	USA	PWR	CP1	910	01.12.1975	01.06.1981	operating	
DAMPIERRE-4	USA	PWR	CP1	890	01.12.1975	20.11.1981	operating	
GRAVELINES-4	USA	PWR	CP1	910	01.04.1976	01.10.1981	operating	
ST. LAURENT B-1	USA	PWR	CP2	915	01.05.1976	01.08.1983	operating	
ST. LAURENT B-2	USA	PWR	CP2	880	01.07.1976	01.08.1983	operating	
SUPER-PHENIX	FRANCE	FBR	Na-1200	1200	13.12.1976	01.12.1986	31.12.1998	
BLAYAIS-1	USA	PWR	CP1	910	01.01.1977	01.12.1981	operating	
BLAYAIS-2	USA	PWR	CP1	910	01.01.1977	01.02.1983	operating	
CHINON B-1	USA	PWR	CP2	870	01.03.1977	01.02.1984	operating	
CHINON B-2	USA	PWR	CP2	870	01.03.1977	01.08.1984	operating	
PALUEL-1	USA	PWR	P4 REP 1300	1330	15.08.1977	01.12.1985	operating	
PALUEL-2	USA	PWR	P4 REP 1300	1330	01.01.1978	01.12.1985	operating	
BLAYAIS-3	USA	PWR	CP1	910	01.04.1978	14.11.1983	operating	
BLAYAIS-4	USA	PWR	CP1	910	01.04.1978	01.10.1983	operating	
CRUAS-1	USA	PWR	CP2	880	01.08.1978	02.04.1984	operating	
CRUAS-2	USA	PWR	CP2	915	15.11.1978	01.04.1985	operating	
ST. ALBAN-1	USA	PWR	P4 REP 1300	1335	29.01.1979	01.05.1986	operating	
PALUEL-3	USA	PWR	P4 REP 1300	1330	01.02.1979	01.02.1986	operating	

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Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
CRUAS-3	USA	PWR	CP2	880	15.04.1979	10.09.1984	operating	
ST. ALBAN-2	USA	PWR	P4 REP 1300	1335	31.07.1979	01.03.1987	operating	
CRUAS-4	USA	PWR	CP2	880	01.10.1979	11.02.1985	operating	
GRAVELINES-5	USA	PWR	CP1	910	01.10.1979	15.01.1985	operating	
GRAVELINES-6	USA	PWR	CP1	910	01.10.1979	25.10.1985	operating	
CATTENOM-1	USA	PWR	P4 REP 1300	1300	29.10.1979	01.04.1987	operating	
FLAMANVILLE-1	USA	PWR	P4 REP 1300	1330	01.12.1979	01.12.1986	operating	
PALUEL-4	USA	PWR	P4 REP 1300	1330	01.02.1980	01.06.1986	operating	
FLAMANVILLE-2	USA	PWR	P4 REP 1300	1330	01.05.1980	09.03.1987	operating	
BELLEVILLE-1	USA	PWR	P4 REP 1300	1310	01.05.1980	01.06.1988	operating	
CATTENOM-2	USA	PWR	P4 REP 1300	1300	28.07.1980	01.02.1988	operating	
BELLEVILLE-2	USA	PWR	P4 REP 1300	1310	01.08.1980	01.01.1989	operating	
CHINON B-3	USA	PWR	CP2	905	01.10.1980	04.03.1987	operating	
CHINON B-4	USA	PWR	CP2	905	01.02.1981	01.04.1988	operating	
NOGENT-1	USA	PWR	P4 REP 1300	1310	26.05.1981	24.02.1988	operating	
NOGENT-2	USA	PWR	P4 REP 1300	1310	01.01.1982	01.05.1989	operating	
CATTENOM-3	USA	PWR	P4 REP 1300	1300	15.06.1982	01.02.1991	operating	
PENLY-1	USA	PWR	P4 REP 1300	1330	01.09.1982	01.12.1990	operating	
GOLFECH-1	USA	PWR	P4 REP 1300	1310	17.11.1982	01.02.1991	operating	
CATTENOM-4	FRANCE	PWR	P4 REP 1300	1300	28.09.1983	01.01.1992	operating	
CHOOZ B-1	FRANCE	PWR	N4 REP 1450	1455	01.01.1984	15.05.2000	operating	
PENLY-2	FRANCE	PWR	P4 REP 1300	1330	01.08.1984	01.11.1992	operating	
GOLFECH-2	FRANCE	PWR	P4 REP 1300	1310	01.10.1984	04.03.1994	operating	
CHOOZ B-2	FRANCE	PWR	N4 REP 1450	1455	31.12.1985	29.09.2000	operating	
CIVAUX-1	FRANCE	PWR	N4 REP 1450	1450	15.10.1988	29.01.2002	operating	



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Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
CIVAUX-2	FRANCE	PWR	N4 REP 1450	1450	01.04.1991	23.04.2002	operating	
FLAMANVILLE-3	FRANCE	PWR	EPR	1630	03.12.2007	-	-	under construction
<b>GERMANY</b>								
VAK KAHL	USA	BWR	BWR	15	01.07.1958	01.02.1962	25.11.1985	
RHEINSBERG	RUSSIA	PWR	VVER-70	62	01.01.1960	11.10.1966	01.06.1990	
AVR JUELICH	GERMANY	HTGR	Pebble bed prototype	13	01.08.1961	19.05.1969	31.12.1988	
MZFR	GERMANY	PHWR	NA	50	01.12.1961	19.12.1966	03.05.1984	
GUNDREMMINGEN-A	USA	BWR	NA	237	12.12.1962	12.04.1967	13.01.1977	
LINGEN	USA	BWR	BWR	240	01.10.1964	01.10.1968	05.01.1977	fossil fuel-fired superheater
HDR GROSSWELZHEIM	USA	BWR	Superheated steam	23	01.01.1965	02.08.1970	20.04.1971	
OBRIGHEIM	USA	PWR	NA	283	15.03.1965	31.03.1969	11.05.2005	
NIEDERAICHBACH	GERMANY	HWGCR	pressure tube reactor	100	01.06.1966	01.01.1973	31.07.1974	
STADE	USA	PWR	NA	630	01.12.1967	19.05.1972	14.11.2003	
WUERGASSEN	USA	BWR	NA	640	26.01.1968	11.11.1975	26.08.1994	
BIBLIS-A	GERMANY	PWR	PWR	1146	01.01.1970	26.02.1975	06.08.2011	
GREIFSWALD-1	RUSSIA	PWR	VVER V-230	440	01.03.1970	12.07.1974	14.02.1990	
GREIFSWALD-2	RUSSIA	PWR	VVER V-230	408	01.03.1970	16.04.1975	14.02.1990	
BRUNSBUETTEL	USA	BWR	BWR-69	770	15.04.1970	09.02.1977	06.08.2011	
PHILIPPSBURG-1	GERMANY	BWR	BWR-69	864	01.10.1970	26.03.1980	06.08.2011	
THTR-300	GERMANY	HTGR	Pebble bed reactor	296	03.05.1971	01.06.1987	29.09.1988	

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BIBLIS-B	GERMANY	PWR	PWR	1178	01.02.1972	31.01.1977	06.08.2011	
NECKARWEST-HEIM-1	GERMANY	PWR	PWR	805	01.02.1972	01.12.1976	06.08.2011	
GREIFSWALD-3	RUSSIA	PWR	VVER V-230	408	01.04.1972	01.05.1978	28.02.1990	
GREIFSWALD-4	RUSSIA	PWR	VVER V-230	408	01.04.1972	01.11.1979	22.07.1990	
ISAR-1	GERMANY	BWR	BWR-69	870	01.05.1972	21.03.1979	06.08.2011	
UNTERWESER	GERMANY	PWR	PWR	1230	01.07.1972	06.09.1979	06.08.2011	
KRUEMMEL	GERMANY	BWR	BWR-69	1260	05.04.1974	28.03.1984	06.08.2011	
KNK II	GERMANY	FBR	Prototype	18	01.09.1974	03.03.1979	23.08.1991	
GRAFENRHEINFELD	GERMANY	PWR	PWR	1225	01.01.1975	17.06.1982	27.06.2015	
MUELHEIM-KAERLICH	USA	PWR	PWR	1219	15.01.1975	18.08.1987	09.09.1988	
BROKDORF	GERMANY	PWR	PWR	1307	01.01.1976	22.12.1986	operating	
GROHNDE	GERMANY	PWR	PWR	1289	01.06.1976	01.02.1985	operating	
GUNDREMMINGEN-B	GERMANY	BWR	BWR-72	1244	20.07.1976	19.07.1984	operating	
GUNDREMMINGEN-C	GERMANY	BWR	BWR-72	1249	20.07.1976	18.01.1985	operating	
GREIFSWALD-5	RUSSIA	PWR	VVER V-213	408	01.12.1976	01.11.1989	24.11.1989	
PHILIPPSBURG-2	GERMANY	PWR	PWR	1268	07.07.1977	18.04.1985	operating	
EMSLAND	GERMANY	PWR	Konvoi	1242	10.08.1982	20.06.1988	operating	
ISAR-2	GERMANY	PWR	Konvoi	1285	15.09.1982	09.04.1988	operating	
NECKARWEST-HEIM-2	GERMANY	PWR	Konvoi	1225	09.11.1982	15.04.1989	operating	
<b>HUNGARY</b>								

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Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
PAKS-1	RUSSIA	PWR	VVER V-213	408	01.08.1974	10.08.1983	operating	
PAKS-2	RUSSIA	PWR	VVER V-213	410	01.08.1974	14.11.1984	operating	
PAKS-3	RUSSIA	PWR	VVER V-213	410	01.10.1979	01.12.1986	operating	
PAKS-4	RUSSIA	PWR	VVER V-213	410	01.10.1979	01.11.1987	operating	
<b>INDIA</b>								
TARAPUR-1	USA	BWR	BWR-1 (Mark 2)	200	01.10.1964	28.10.1969	operating	
TARAPUR-2	USA	BWR	BWR-1 (Mark 2)	200	01.10.1964	28.10.1969	operating	
RAJASTHAN-1	CANADA	PHWR	Horizontal Pressure Tube	207	01.08.1965	16.12.1973	operating	
RAJASTHAN-2	CANADA	PHWR	Horizontal Pressure Tube	207	01.04.1968	01.04.1981	operating	
MADRAS-1	RUSSIA	PHWR	Horizontal Pressure Tube	202	01.01.1971	27.01.1984	operating	
MADRAS-2	INDIA	PHWR	Horizontal Pressure Tube	202	01.10.1972	21.03.1986	operating	
NARORA-1	INDIA	PHWR	Horizontal Pressure Tube	202	01.12.1976	01.01.1991	operating	
NARORA-2	INDIA	PHWR	Horizontal Pressure Tube	202	01.11.1977	01.07.1992	operating	
KAKRAPAR-1	INDIA	PHWR	Horizontal Pressure Tube	202	01.12.1984	06.05.1993	operating	
KAKRAPAR-2	INDIA	PHWR	Horizontal Pressure Tube	202	01.04.1985	01.09.1995	operating	
KAIGA-1	USA	PHWR	Horizontal Pressure Tube	202	01.09.1989	16.11.2000	operating	
KAIGA-2	INDIA	PHWR	Horizontal Pressure Tube	202	01.12.1989	16.03.2000	operating	

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Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
			sure Tube					
RAJASTHAN-3	CANADA	PHWR	Horizontal Pressure Tube	202	01.02.1990	01.06.2000	operating	
RAJASTHAN-4	INDIA	PHWR	Horizontal Pressure Tube	202	01.10.1990	23.12.2000	operating	
TARAPUR-4	INDIA	PHWR	Horizontal Pressure Tube	502	08.03.2000	12.09.2005	operating	
TARAPUR-3	USA	PHWR	Horizontal Pressure Tube	502	12.05.2000	18.08.2006	operating	
KAIGA-3	INDIA	PHWR	Horizontal Pressure Tube	202	30.03.2002	06.05.2007	operating	
KUDANKULAM-1	INDIA	PWR	VVER V-412	917	31.03.2002	31.12.2014	operating	
KAIGA-4	INDIA	PHWR	Horizontal Pressure Tube	202	10.05.2002	20.01.2011	operating	
KUDANKULAM-2	RUSSIA	PWR	VVER V-412	917	04.07.2002	-	-	under construction
RAJASTHAN-5	INDIA	PHWR	Horizontal Pressure Tube	202	18.09.2002	04.02.2010	operating	
RAJASTHAN-6	INDIA	PHWR	Horizontal Pressure Tube	202	20.01.2003	31.03.2010	operating	
PFBR	INDIA	FBR	Prototype	470	23.10.2004	-	-	under construction
KAKRAPAR-3	INDIA	PHWR	PHWR-700	630	22.11.2010	-	-	under construction
KAKRAPAR-4	INDIA	PHWR	PHWR-700	630	22.11.2010	-	-	under construction
RAJASTHAN-7	INDIA	PHWR	Horizontal Pressure Tube	630	18.07.2011	-	-	under construction
RAJASTHAN-8	INDIA	PHWR	Horizontal Pressure Tube	630	30.09.2011	-	-	under construction

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Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
<b>IRAN</b>								
BUSHEHR-1	INDIA	PWR	VVER V-446	915	01.05.1975	23.09.2013	operating	
<b>ITALY</b>								
LATINA	UNITED KING-DOM	GCR	MAGNOX	200	01.11.1958	01.01.1964	01.12.1987	
GARIGLIANO	USA	BWR	BWR-1	150	01.11.1959	01.06.1964	01.03.1982	
ENRICO FERMI	USA	PWR	W (4-loop)	247	01.07.1961	01.01.1965	01.07.1990	
CAORSO	USA	BWR	BWR-4 (Mark 2)	840	01.01.1970	01.12.1981	01.07.1990	
<b>JAPAN</b>								
JPDR	JAPAN	BWR	BWR-1	10	01.12.1960	15.03.1965	18.03.1976	
TOKAI-1	UNITED KING-DOM	GCR	MAGNOX	159	01.03.1961	25.07.1966	31.03.1998	
TSURUGA-1	USA	BWR	BWR-2	341	24.11.1966	14.03.1970	27.04.2015	
MIHAMA-1	USA	PWR	W (2-loop)	320	01.02.1967	28.11.1970	27.04.2015	
FUKUSHIMA-DAIICHI-1	USA	BWR	BWR-3	439	25.07.1967	26.03.1971	19.05.2011	
MIHAMA-2	JAPAN	PWR	M (2-loop)	470	29.05.1968	25.07.1972	27.04.2015	
FUKUSHIMA-DAIICHI-2	USA	BWR	BWR-4	760	09.06.1969	18.07.1974	19.05.2011	
TAKAHAMA-1	USA	PWR	M (3-loop)	780	25.04.1970	14.11.1974	operating	Offline since 2011
SHIMANE-1	USA	BWR	BWR-3	439	02.07.1970	29.03.1974	30.04.2015	
FUKUSHIMA-DAIICHI-3	USA	BWR	BWR-4	760	28.12.1970	27.03.1976	19.05.2011	
TAKAHAMA-2	JAPAN	PWR	M (3-loop)	780	09.03.1971	14.11.1975	operating	Offline since 2011
HAMAOKA-1	USA	BWR	BWR-4	516	10.06.1971	17.03.1976	30.01.2009	
GENKAI-1	JAPAN	PWR	M (2-loop)	529	15.09.1971	15.10.1975	27.04.2015	

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FUGEN ATR	JAPAN	HWLWR	ATR	148	10.05.1972	20.03.1979	29.03.2003	
FUKUSHIMA-DAIICHI-5	USA	BWR	BWR-4	760	22.05.1972	18.04.1978	17.12.2013	
MIHAMA-3	JAPAN	PWR	M (3-loop)	780	07.08.1972	01.12.1976	operating	Offline since 2011
OHI-1	USA	PWR	W (4-loop)	1120	26.10.1972	27.03.1979	operating	Offline since 2011
OHI-2	USA	PWR	W (4-loop)	1120	08.12.1972	05.12.1979	operating	Offline since 2011
FUKUSHIMA-DAIICHI-4	JAPAN	BWR	BWR-4	760	12.02.1973	12.10.1978	19.05.2011	
IKATA-1	JAPAN	PWR	M (2-loop)	538	01.09.1973	30.09.1977	operating	Offline since 2011
TOKAI-2	JAPAN	BWR	BWR-5	1056	03.10.1973	28.11.1978	operating	Offline since 2011
FUKUSHIMA-DAIICHI-6	JAPAN	BWR	BWR-5	1067	26.10.1973	24.10.1979	17.12.2013	
HAMAOKA-2	JAPAN	BWR	BWR-4	814	14.06.1974	29.11.1978	30.01.2009	
FUKUSHIMA-DAINI-1	JAPAN	BWR	BWR-5	1067	16.03.1976	20.04.1982	operating	Offline since 2011
GENKAI-2	JAPAN	PWR	M (2-loop)	529	01.02.1977	30.03.1981	operating	Offline since 2011
IKATA-2	JAPAN	PWR	M (2-loop)	538	01.08.1978	19.03.1982	operating	Offline since 2011
FUKUSHIMA-DAINI-2	JAPAN	BWR	BWR-5	1067	25.05.1979	03.02.1984	operating	Offline since 2011
SENDAI-1	JAPAN	PWR	M (3-loop)	846	15.12.1979	04.07.1984	operating	Offline since 2011
KASHIWAZAKI KARIWA-1	JAPAN	BWR	BWR-5	1067	05.06.1980	18.09.1985	operating	Offline since 2011
ONAGAWA-1	JAPAN	BWR	BWR-4	496	08.07.1980	01.06.1984	operating	Offline since 2011
TAKAHAMA-3	JAPAN	PWR	M (3-loop)	830	12.12.1980	17.01.1985	operating	Offline since 2011
TAKAHAMA-4	JAPAN	PWR	M (3-loop)	830	19.03.1981	05.06.1985	operating	Offline since 2011
FUKUSHIMA-	JAPAN	BWR	BWR-5	1067	23.03.1981	21.06.1985	operating	Offline since 2011

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DAINI-3								
FUKUSHIMA-DAINI-4	JAPAN	BWR	BWR-5	1067	28.05.1981	25.08.1987	operating	Offline since 2011
SENDAI-2	JAPAN	PWR	M (3-loop)	846	12.10.1981	28.11.1985	operating	Offline since 2011
TSURUGA-2	JAPAN	PWR	M (4-loop)	1115	06.11.1982	17.02.1987	operating	Offline since 2011
HAMAOKA-3	JAPAN	BWR	BWR-5	1056	18.04.1983	28.08.1987	operating	Offline since 2011
SHIMANE-2	JAPAN	BWR	BWR-5	789	02.02.1985	10.02.1989	operating	Offline since 2011
TOMARI-1	JAPAN	PWR	M (2-loop)	550	18.04.1985	22.06.1989	operating	Offline since 2011
TOMARI-2	JAPAN	PWR	M (2-loop)	550	13.06.1985	12.04.1991	operating	Offline since 2011
KASHIWAZAKI KARIWA-5	JAPAN	BWR	BWR-5	1067	20.06.1985	10.04.1990	operating	Offline since 2011
KASHIWAZAKI KARIWA-2	JAPAN	BWR	BWR-5	1067	18.11.1985	28.09.1990	operating	Offline since 2011
MONJU	JAPAN	FBR	-	246	10.05.1986	-	-	under construction
OHI-3	JAPAN	PWR	M (4-loop)	1127	03.10.1987	18.12.1991	operating	Offline since 2011
GENKAI-3	JAPAN	PWR	M (4-loop)	1127	01.06.1988	18.03.1994	operating	Offline since 2011
OHI-4	JAPAN	PWR	M (4-loop)	1127	13.06.1988	02.02.1993	operating	Offline since 2011
KASHIWAZAKI KARIWA-3	JAPAN	BWR	BWR-5	1067	07.03.1989	11.08.1993	operating	Offline since 2011
SHIKA-1	JAPAN	BWR	BWR-5	505	01.07.1989	30.07.1993	operating	Offline since 2011
HAMAOKA-4	JAPAN	BWR	BWR-5	1092	13.10.1989	03.09.1993	operating	Offline since 2011
KASHIWAZAKI KARIWA-4	JAPAN	BWR	BWR-5	1067	05.03.1990	11.08.1994	operating	Offline since 2011
IKATA-3	JAPAN	PWR	M (3-loop)	846	01.10.1990	15.12.1994	operating	Offline since 2011
ONAGAWA-2	JAPAN	BWR	BWR-5	796	12.04.1991	28.07.1995	operating	Offline since 2011
GENKAI-4	JAPAN	PWR	M (4-loop)	1127	15.07.1992	25.07.1997	operating	Offline since 2011

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Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
KASHIWAZAKI KARIWA-6	USA	BWR	ABWR	1315	03.11.1992	07.11.1996	operating	Offline since 2011
KASHIWAZAKI KARIWA-7	USA	BWR	ABWR	1315	01.07.1993	02.07.1997	operating	Offline since 2011
ONAGAWA-3	JAPAN	BWR	BWR-5	796	23.01.1998	30.01.2002	operating	Offline since 2011
HAMAOKA-5	USA	BWR	ABWR	1325	12.07.2000	18.01.2005	operating	Offline since 2011
HIGASHI DORI-1	JAPAN	BWR	BWR-5	1067	07.11.2000	08.12.2005	operating	Offline since 2011
SHIKA-2	USA	BWR	ABWR	1304	20.08.2001	15.03.2006	operating	Offline since 2011
TOMARI-3	JAPAN	PWR	M (3-loop)	866	18.11.2004	22.12.2009	operating	Offline since 2011
SHIMANE-3	USA	BWR	ABWR	1325	12.10.2007	-	-	under construction
OHMA	USA	BWR	ABWR	1325	07.05.2010	-	-	under construction
<b>KAZAKHSTAN</b>								
AKTAU	RUSSIA	FBR	BN-350	135	01.10.1964	16.07.1973	22.04.1999	
<b>REPUBLIC OF KOREA</b>								
KORI-1	USA	PWR	W â <sup>-3</sup> 60	558	27.04.1972	29.04.1978	operating	
WOLSONG-1	CANADA	PHWR	CANDU 6	670	30.10.1977	22.04.1983	operating	
KORI-2	USA	PWR	WH F	618	04.12.1977	25.07.1983	operating	
KORI-3	USA	PWR	WH F	1001	01.10.1979	30.09.1985	operating	
KORI-4	USA	PWR	WH F	903	01.04.1980	29.04.1986	operating	
HANBIT-1	USA	PWR	WH F	903	04.06.1981	25.08.1986	operating	
HANBIT-2	USA	PWR	WH F	903	10.12.1981	10.06.1987	operating	
HANUL-1	FRANCE	PWR	France CPI	903	26.01.1983	10.09.1988	operating	
HANUL-2	FRANCE	PWR	France CPI	903	05.07.1983	30.09.1989	operating	
HANBIT-3	REPUBLIC OF KOREA	PWR	OPR1000	950	23.12.1989	31.03.1995	operating	
HANBIT-4	REPUBLIC OF KOREA	PWR	OPR1000	950	26.05.1990	01.01.1996	operating	



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	KOREA							
WOLSONG-2	CANADA	PHWR	CANDU 6	652	22.06.1992	01.07.1997	operating	
HANUL-3	REPUBLIC OF KOREA	PWR	OPR1000	950	21.07.1993	11.08.1998	operating	
HANUL-4	REPUBLIC OF KOREA	PWR	OPR1000	950	01.11.1993	31.12.1999	operating	
WOLSONG-3	CANADA	PHWR	CANDU 6	665	17.03.1994	01.07.1998	operating	
WOLSONG-4	CANADA	PHWR	CANDU 6	669	22.07.1994	01.10.1999	operating	
HANBIT-5	REPUBLIC OF KOREA	PWR	OPR1000	950	29.06.1997	21.05.2002	operating	
HANBIT-6	REPUBLIC OF KOREA	PWR	OPR1000	950	20.11.1997	24.12.2002	operating	
HANUL-5	REPUBLIC OF KOREA	PWR	OPR1000	950	01.10.1999	29.07.2004	operating	
HANUL-6	REPUBLIC OF KOREA	PWR	OPR1000	950	29.09.2000	22.04.2005	operating	
SHIN-KORI-1	REPUBLIC OF KOREA	PWR	OPR1000	998	16.06.2006	28.02.2011	operating	
SHIN-KORI-2	REPUBLIC OF KOREA	PWR	OPR1000	995	05.06.2007	20.07.2012	operating	
SHIN-WOLSONG-1	REPUBLIC OF KOREA	PWR	OPR1000	950	20.11.2007	31.07.2012	operating	
SHIN-WOLSONG-2	REPUBLIC OF KOREA	PWR	OPR1000	950	23.09.2008	24.07.2015	operating	
SHIN-KORI-3	REPUBLIC OF KOREA	PWR	APR-1400	1400	16.10.2008	-	-	under construction

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Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
SHIN-KORI-4	REPUBLIC OF KOREA	PWR	APR-1400	1340	19.08.2009	-	-	under construction
SHIN-HANUL-1	REPUBLIC OF KOREA	PWR	APR-1400	1340	10.07.2012	-	-	under construction
SHIN-HANUL-2	REPUBLIC OF KOREA	PWR	APR-1400	1340	19.06.2013	-	-	under construction
<b>LITHUANIA</b>								
IGNALINA-1	RUSSIA	LWGR	RBMK-1500	1500	01.05.1977	01.05.1985	31.12.2004	
IGNALINA-2	RUSSIA	LWGR	RBMK-1500	1500	01.01.1978	01.12.1987	31.12.2009	
<b>MEXICO</b>								
LAGUNA VERDE-1	USA	BWR	BWR-5	803	01.10.1976	29.07.1990	operating	
LAGUNA VERDE-2	USA	BWR	BWR-5	780	01.06.1977	10.04.1995	operating	
<b>NETHERLANDS</b>								
DODEWAARD	USA	BWR	GE design	54	01.05.1965	26.03.1969	26.03.1997	
BORSSELE	GERMANY	PWR	2-loops KWU	495	01.07.1969	26.10.1973	operating	
<b>PAKISTAN</b>								
KANUPP	CANADA	PHWR	CANDU-137 MW	125	01.08.1966	07.12.1972	operating	
CHASNUPP-1	CHINA	PWR	CNP-300	300	01.08.1993	15.09.2000	operating	
CHASNUPP-2	CHINA	PWR	CNP-300	300	28.12.2005	18.05.2011	operating	
CHASNUPP-3	CHINA	PWR	CNP-300	315	28.05.2011	-	-	under construction
CHASNUPP-4	CHINA	PWR	CNP-300	315	18.12.2011	-	-	under construction
<b>ROMANIA</b>								
CERNAVODA-1	CANADA	PHWR	CANDU 6	650	01.07.1982	02.12.1996	operating	
CERNAVODA-2	CANADA	PHWR	CANDU 6	650	01.07.1983	31.10.2007	operating	

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Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
<b>RUSSIA</b>								
APS-1 OBNINSK	RUSSIA	LWGR	AM-1	5	01.01.1951	01.12.1954	29.04.2002	
NOVOVOR-ONEZH-1	RUSSIA	PWR	VVER V-120	197	01.07.1957	31.12.1964	16.02.1988	
BELOYARSK-1	RUSSIA	LWGR	AMB-100	102	01.06.1958	26.04.1964	01.01.1983	
BELOYARSK-2	RUSSIA	LWGR	AMB-200	146	01.01.1962	01.12.1969	01.01.1990	
NOVOVOR-ONEZH-2	RUSSIA	PWR	VVER V-120	336	01.06.1964	14.04.1970	29.08.1990	
NOVOVOR-ONEZH-3	RUSSIA	PWR	VVER V-179	385	01.07.1967	29.06.1972	operating	
NOVOVOR-ONEZH-4	RUSSIA	PWR	VVER V-179	385	01.07.1967	24.03.1973	operating	
BELOYARSK-3	RUSSIA	FBR	BN-600	560	01.01.1969	01.11.1981	operating	
BILIBINO-1	RUSSIA	LWGR	EGP-6	11	01.01.1970	01.04.1974	operating	
BILIBINO-2	RUSSIA	LWGR	EGP-6	11	01.01.1970	01.02.1975	operating	
BILIBINO-3	RUSSIA	LWGR	EGP-6	11	01.01.1970	01.02.1976	operating	
BILIBINO-4	RUSSIA	LWGR	EGP-6	11	01.01.1970	01.01.1977	operating	
LENINGRAD-1	RUSSIA	LWGR	RBMK-1000	925	01.03.1970	01.11.1974	operating	
KOLA-1	RUSSIA	PWR	VVER V-230	411	01.05.1970	28.12.1973	operating	
KOLA-2	RUSSIA	PWR	VVER V-230	411	01.05.1970	21.02.1975	operating	
LENINGRAD-2	RUSSIA	LWGR	RBMK-1000	925	01.06.1970	11.02.1976	operating	
KURSK-1	RUSSIA	LWGR	RBMK-1000	925	01.06.1972	12.10.1977	operating	
KURSK-2	RUSSIA	LWGR	RBMK-1000	925	01.01.1973	17.08.1979	operating	
LENINGRAD-3	RUSSIA	LWGR	RBMK-1000	925	01.12.1973	29.06.1980	operating	
NOVOVOR-ONEZH-5	RUSSIA	PWR	VVER V-187	950	01.03.1974	20.02.1981	operating	

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Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
LENINGRAD-4	RUSSIA	LWGR	RBMK-1000	925	01.02.1975	29.08.1981	operating	
SMOLENSK-1	RUSSIA	LWGR	RBMK-1000	925	01.10.1975	30.09.1983	operating	
SMOLENSK-2	RUSSIA	LWGR	RBMK-1000	925	01.06.1976	02.07.1985	operating	
KOLA-4	RUSSIA	PWR	VVER V-213	411	01.08.1976	06.12.1984	operating	
KALININ-1	RUSSIA	PWR	VVER V-338	950	01.02.1977	12.06.1985	operating	
KOLA-3	RUSSIA	PWR	VVER V-213	411	01.04.1977	03.12.1982	operating	
KURSK-3	RUSSIA	LWGR	RBMK-1000	925	01.04.1978	30.03.1984	operating	
BALAKOVO-1	RUSSIA	PWR	VVER V-320	950	01.12.1980	23.05.1986	operating	
KURSK-4	RUSSIA	LWGR	RBMK-1000	925	01.05.1981	05.02.1986	operating	
BALAKOVO-2	RUSSIA	PWR	VVER V-320	950	01.08.1981	18.01.1988	operating	
ROSTOV-1	RUSSIA	PWR	VVER V-320	950	01.09.1981	25.12.2001	operating	
KALININ-2	RUSSIA	PWR	VVER V-338	950	01.02.1982	03.03.1987	operating	
BALAKOVO-3	RUSSIA	PWR	VVER V-320	950	01.11.1982	08.04.1989	operating	
ROSTOV-2	RUSSIA	PWR	VVER V-320	950	01.05.1983	10.12.2010	operating	
BALAKOVO-4	RUSSIA	PWR	VVER V-320	950	01.04.1984	22.12.1993	operating	
SMOLENSK-3	RUSSIA	LWGR	RBMK-1000	925	01.05.1984	12.10.1990	operating	
KALININ-3	RUSSIA	PWR	VVER V-320	950	01.10.1985	08.11.2005	operating	
KALININ-4	RUSSIA	PWR	VVER V-320	950	01.08.1986	25.12.2012	operating	
BELOYARSK-4	RUSSIA	FBR	BN-800	789	18.07.2006	-	-	under construction
AKADEMIK LO-MONOSOV-1	RUSSIA	PWR	KLT-40S 'Floating'	32	15.04.2007	-	-	under construction
AKADEMIK LO-MONOSOV-2	RUSSIA	PWR	KLT-40S 'Floating'	32	15.04.2007	-	-	under construction
NOVOVOR-ONEZH 2-1	RUSSIA	PWR	VVER V-392M	1114	24.06.2008	-	-	under construction
LENINGRAD 2-1	RUSSIA	PWR	VVER V-491	1085	25.10.2008	-	-	under construction

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Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
NOVOVOR-ONEZH 2-2	RUSSIA	PWR	VVER V-392M	1114	12.07.2009	-	-	under construction
ROSTOV-3	RUSSIA	PWR	VVER V-320	1011	15.09.2009	17.09.2015	operating	
LENINGRAD 2-2	RUSSIA	PWR	VVER V-491	1085	15.04.2010	-	-	under construction
ROSTOV-4	RUSSIA	PWR	VVER V-320	1011	16.06.2010	-	-	under construction
BALTIC-1	RUSSIA	PWR	VVER V-491	1109	22.02.2012	-	-	under construction
<b>SLOVAKIA</b>								
BOHUNICE A1	RUSSIA	HWGCR	KS 150	110	01.08.1958	25.12.1972	22.02.1977	
BOHUNICE-1	RUSSIA	PWR	VVER V-230	408	24.04.1972	01.04.1980	31.12.2006	
BOHUNICE-2	RUSSIA	PWR	VVER V-230	408	24.04.1972	01.01.1981	31.12.2008	
BOHUNICE-3	RUSSIA	PWR	VVER V-213	408	01.12.1976	14.02.1985	operating	
BOHUNICE-4	RUSSIA	PWR	VVER V-213	408	01.12.1976	18.12.1985	operating	
MOCHOVCE-1	RUSSIA	PWR	VVER V-213	408	13.10.1983	29.10.1998	operating	
MOCHOVCE-2	RUSSIA	PWR	VVER V-213	408	13.10.1983	11.04.2000	operating	
MOCHOVCE-3	RUSSIA	PWR	VVER V-213	440	27.01.1987	-	-	under construction
MOCHOVCE-4	RUSSIA	PWR	VVER V-213	440	27.01.1987	-	-	under construction
<b>SLOVENIA</b>								
KRSKO	USA	PWR	W (2-loop)	632	30.03.1975	01.01.1983	operating	
<b>SOUTH AFRICA</b>								
KOEBERG-1	FRANCE	PWR	CP1	921	01.07.1976	21.07.1984	operating	
KOEBERG-2	FRANCE	PWR	CP1	921	01.07.1976	09.11.1985	operating	
<b>SPAIN</b>								
JOSE CABRERA-1	USA	PWR	W (1-loop)	153	24.06.1964	13.08.1969	30.04.2006	
SANTA MARIA DE GARONA	USA	BWR	BWR-3	440	01.09.1966	11.05.1971	operating	
VANDELLOS-1	USA	GCR	NA	480	21.06.1968	02.08.1972	31.07.1990	

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Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
ALMARAZ-1	USA	PWR	W (3-loop)	900	03.07.1973	01.09.1983	operating	
ALMARAZ-2	USA	PWR	W (3-loop)	930	03.07.1973	01.07.1984	operating	
ASCO-1	USA	PWR	W (3-loop)	888	16.05.1974	10.12.1984	operating	
ASCO-2	USA	PWR	W (3-loop)	888	07.03.1975	31.03.1986	operating	
COFRENTES	USA	BWR	BWR-6	939	09.09.1975	11.03.1985	operating	
TRILLO-1	GERMANY	PWR	PWR 3 loops	990	17.08.1979	06.08.1988	operating	
VANDELLOS-2	USA	PWR	W (3-loop)	930	29.12.1980	08.03.1988	operating	
<b>SWEDEN</b>								
AGESTA	SWEDEN	PHWR	NA	9	01.12.1957	01.05.1964	02.06.1974	
OSKARSHAMN-1	SWEDEN	BWR	ABB-I	440	01.08.1966	06.02.1972	operating	
RINGHALS-1	SWEDEN	BWR	ABB-I	760	01.02.1969	01.01.1976	operating	
OSKARSHAMN-2	SWEDEN	BWR	ABB-II	580	01.09.1969	01.01.1975	operating	
RINGHALS-2	USA	PWR	W (3-loops)	820	01.10.1970	01.05.1975	operating	
BARSEBACK-1	SWEDEN	BWR	ABB-II	570	01.02.1971	01.07.1975	30.11.1999	
RINGHALS-3	USA	PWR	W (3-loops)	915	01.09.1972	09.09.1981	operating	
BARSEBACK-2	SWEDEN	BWR	ABB-II	570	01.01.1973	01.07.1977	31.05.2005	
FORSMARK-1	SWEDEN	BWR	ABB-III, BWR-2500	900	01.06.1973	10.12.1980	operating	
RINGHALS-4	USA	PWR	W (3-loops)	915	01.11.1973	21.11.1983	operating	
FORSMARK-2	SWEDEN	BWR	ABB-III, BWR-2500	900	01.01.1975	07.07.1981	operating	
FORSMARK-3	SWEDEN	BWR	ABB-III, BWR-3000	1050	01.01.1979	18.08.1985	operating	
OSKARSHAMN-3	SWEDEN	BWR	ABB-III, BWR-3000	1050	01.05.1980	15.08.1985	operating	
<b>SWITZERLAND</b>								
LUCENS	SWITZERLAND	HWGCR	HWGCR: 2-loops	6	01.04.1962	never connected	21.01.1969	
BEZNAU-1	USA	PWR	W (2-loop)	350	01.09.1965	01.09.1969	operating	
MUEHLEBERG	USA	BWR	BWR-4	306	01.03.1967	06.11.1972	operating	

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Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
BEZNAU-2	USA	PWR	W (2-loop)	350	01.01.1968	01.12.1971	operating	
GOESGEN	GERMANY	PWR	PWR 3 Loop	920	01.12.1973	01.11.1979	operating	
LEIBSTADT	USA	BWR	BWR-6	960	01.01.1974	15.12.1984	operating	
<b>TAIWAN</b>								
CHINSHAN-1	CHINA	BWR	BWR-4	604	02.06.1972	10.12.1978	operating	
CHINSHAN-2	USA	BWR	BWR-4	604	07.12.1973	15.07.1979	operating	
KUOSHENG-1	USA	BWR	BWR-6	951	19.11.1975	28.12.1981	operating	
KUOSHENG-2	USA	BWR	BWR-6	951	15.03.1976	16.03.1983	operating	
MAANSHAN-1	USA	PWR	WE 312 (3 loop-12 foot)	890	21.08.1978	27.07.1984	operating	
MAANSHAN-2	USA	PWR	WE 312 (3 loop-12 foot)	890	21.02.1979	18.05.1985	operating	
LUNG MEN 1	USA	BWR	ABWR	1300	31.03.1999	-	-	under construction
LUNG MEN 2	USA	BWR	ABWR	1300	30.08.1999	-	-	under construction
<b>UKRAINE</b>								
CHERNOBYL-1	RUSSIA	LWGR	RBMK	925	01.03.1970	27.05.1978	30.11.1996	
CHERNOBYL-2	RUSSIA	LWGR	RBMK	925	01.02.1973	28.05.1979	11.10.1991	
ROVNO-1	RUSSIA	PWR	VVER V-213	361	01.08.1973	22.09.1981	operating	
ROVNO-2	RUSSIA	PWR	VVER V-213	384	01.10.1973	29.07.1982	operating	
CHERNOBYL-3	RUSSIA	LWGR	RBMK	925	01.03.1976	08.06.1982	15.12.2000	
SOUTH UKRAINE-1	RUSSIA	PWR	VVER V-302	950	01.08.1976	02.12.1983	operating	
CHERNOBYL-4	RUSSIA	LWGR	RBMK	925	01.04.1979	26.03.1984	26.04.1986	
ROVNO-3	RUSSIA	PWR	VVER V-320	950	01.02.1980	16.05.1987	operating	
ZAPOROZHYE-1	RUSSIA	PWR	VVER V-320	950	01.04.1980	25.12.1985	operating	
ZAPOROZHYE-2	RUSSIA	PWR	VVER V-320	950	01.01.1981	15.02.1986	operating	

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Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
SOUTH UKRAINE-2	RUSSIA	PWR	VVER V-338	950	01.07.1981	06.04.1985	operating	
KHMELNITSKI-1	RUSSIA	PWR	VVER V-320	950	01.11.1981	13.08.1988	operating	
ZAPOROZHYE-3	RUSSIA	PWR	VVER V-320	950	01.04.1982	05.03.1987	operating	
ZAPOROZHYE-4	RUSSIA	PWR	VVER V-320	950	01.04.1983	14.04.1988	operating	
SOUTH UKRAINE-3	RUSSIA	PWR	VVER V-320	950	01.11.1984	29.12.1989	operating	
KHMELNITSKI-2	RUSSIA	PWR	VVER V-320	950	01.02.1985	15.12.2005	operating	
ZAPOROZHYE-5	RUSSIA	PWR	VVER V-320	950	01.11.1985	27.10.1989	operating	
KHMELNITSKI-3	RUSSIA	PWR	VVER V-392B	950	01.03.1986	-	-	under construction
ZAPOROZHYE-6	RUSSIA	PWR	VVER V-320	950	01.06.1986	17.09.1996	operating	
ROVNO-4	RUSSIA	PWR	VVER V-320	950	01.08.1986	06.04.2006	operating	
KHMELNITSKI-4	RUSSIA	PWR	VVER V-392B	950	01.02.1987	-	-	under construction
<b>UAE</b>								
BARAKAH-1	KOREA, PUBLIC OF	RE-PWR	APR-1400	1345	19.07.2012	-	-	under construction
BARAKAH-2	KOREA, PUBLIC OF	RE-PWR	APR-1400	1345	16.04.2013	-	-	under construction
BARAKAH-3	KOREA, PUBLIC OF	RE-PWR	APR-1400	1345	24.09.2014	-	-	under construction
BARAKAH-4	KOREA, PUBLIC OF	RE-PWR	APR-1400	1345	30.07.2015	-	-	under construction
<b>UNITED KINGDOM</b>								
CALDER HALL-1	UNITED KINGDOM	GCR	MAGNOX	35	01.08.1953	01.10.1956	31.03.2003	
CALDER HALL-2	UNITED KINGDOM	GCR	MAGNOX	35	01.08.1953	01.02.1957	31.03.2003	



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Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
	DOM							
DOUNREAY DFR	UNITED KING- DOM	FBR	NA	14	01.03.1955	01.10.1962	01.03.1977	
CALDER HALL-3	UNITED KING- DOM	GCR	MAGNOX	35	01.08.1955	01.05.1958	31.03.2003	
CALDER HALL-4	UNITED KING- DOM	GCR	MAGNOX	35	01.08.1955	01.04.1959	31.03.2003	
CHAPELCROSS-1	UNITED KING- DOM	GCR	MAGNOX	35	01.10.1955	01.03.1959	29.06.2004	
CHAPELCROSS-2	UNITED KING- DOM	GCR	MAGNOX	35	01.10.1955	01.08.1959	29.06.2004	
CHAPELCROSS-3	UNITED KING- DOM	GCR	MAGNOX	35	01.10.1955	01.12.1959	29.06.2004	
CHAPELCROSS-4	UNITED KING- DOM	GCR	MAGNOX	35	01.10.1955	01.03.1960	29.06.2004	
BERKELEY-1	UNITED KING- DOM	GCR	MAGNOX	138	01.01.1957	12.06.1962	31.03.1989	
BERKELEY-2	UNITED KING- DOM	GCR	MAGNOX	138	01.01.1957	20.10.1962	26.10.1988	
BRADWELL-1	UNITED KING- DOM	GCR	MAGNOX	150	01.01.1957	01.07.1962	31.03.2002	
BRADWELL-2	UNITED KING- DOM	GCR	MAGNOX	150	01.01.1957	12.11.1962	30.03.2002	
HUNTERSTON A-1	UNITED KING- DOM	GCR	MAGNOX	150	01.10.1957	05.02.1964	30.03.1990	
HUNTERSTON A-2	UNITED KING- DOM	GCR	MAGNOX	150	01.10.1957	01.07.1964	31.12.1989	

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Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
HINKLEY POINT A-1	UNITED KING-DOM	GCR	MAGNOX	250	01.11.1957	30.03.1965	23.05.2000	
HINKLEY POINT A-2	UNITED KING-DOM	GCR	MAGNOX	250	01.11.1957	05.05.1965	23.05.2000	
WINDSCALE AGR	UNITED KING-DOM	GCR	AGR	32	01.11.1958	01.03.1963	03.04.1981	
TRAWSFYNYDD-1	UNITED KING-DOM	GCR	MAGNOX	250	01.07.1959	24.03.1965	06.02.1991	
TRAWSFYNYDD-2	UNITED KING-DOM	GCR	MAGNOX	250	01.07.1959	24.03.1965	04.02.1991	
DUNGENESS A-1	UNITED KING-DOM	GCR	MAGNOX	275	01.07.1960	28.10.1965	31.12.2006	
DUNGENESS A-2	UNITED KING-DOM	GCR	MAGNOX	275	01.07.1960	30.12.1965	31.12.2006	
SIZEWELL A-1	UNITED KING-DOM	GCR	MAGNOX	290	01.04.1961	25.03.1966	31.12.2006	
SIZEWELL A-2	UNITED KING-DOM	GCR	MAGNOX	290	01.04.1961	15.09.1966	31.12.2006	
OLDBURY A-1	UNITED KING-DOM	GCR	MAGNOX	300	01.05.1962	31.12.1967	29.02.2012	
OLDBURY A-2	UNITED KING-DOM	GCR	MAGNOX	300	01.05.1962	30.09.1968	30.06.2011	
WINFRITH SGHWR	UNITED KING-DOM	SGHWR	NA	92	01.05.1963	01.01.1968	11.09.1990	
WYLFA-1	UNITED KING-DOM	GCR	MAGNOX	550	01.09.1963	01.11.1971	30.12.2015	
WYLFA-2	UNITED KING-DOM	GCR	MAGNOX	550	01.09.1963	03.01.1972	25.04.2012	

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Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
	DOM							
DUNGENESS B-1	UNITED KING- DOM	GCR	AGR	607	01.10.1965	01.04.1985	operating	
DUNGENESS B-2	UNITED KING- DOM	GCR	AGR	607	01.10.1965	01.04.1989	operating	
DOUNREAY PFR	UNITED KING- DOM	FBR	NA	234	01.01.1966	01.07.1976	31.03.1994	
HINKLEY POINT B-1	UNITED KING- DOM	GCR	AGR	625	01.09.1967	02.10.1978	operating	
HINKLEY POINT B-2	UNITED KING- DOM	GCR	AGR	625	01.09.1967	27.09.1976	operating	
HUNTERSTON B-1	UNITED KING- DOM	GCR	AGR	624	01.11.1967	06.02.1976	operating	
HUNTERSTON B-2	UNITED KING- DOM	GCR	AGR	624	01.11.1967	31.03.1977	operating	
HARTLEPOOL A-1	UNITED KING- DOM	GCR	AGR	625	01.10.1968	01.04.1989	operating	
HARTLEPOOL A-2	UNITED KING- DOM	GCR	AGR	600	01.10.1968	01.04.1989	operating	
HEYSHAM A-1	UNITED KING- DOM	GCR	AGR	611	01.12.1970	01.04.1989	operating	
HEYSHAM A-2	UNITED KING- DOM	GCR	AGR	611	01.12.1970	01.04.1989	operating	
HEYSHAM B-1	UNITED KING- DOM	GCR	AGR	615	01.08.1980	01.04.1989	operating	
HEYSHAM B-2	UNITED KING- DOM	GCR	AGR	615	01.08.1980	01.04.1989	operating	

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Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
TORNESS-1	UNITED KING-DOM	GCR	AGR	645	01.08.1980	25.05.1988	operating	
TORNESS-2	UNITED KING-DOM	GCR	AGR	645	01.08.1980	03.02.1989	operating	
SIZEWELL B	USA	PWR	SNUPPS	1188	18.07.1988	22.09.1995	operating	
<b>UNITED STATES OF AMERICA</b>								
SHIPPINGPORT	USA	PWR	PLWBR	60	01.01.1954	26.05.1958	01.10.1982	
GE VALLECITOS	USA	BWR	25	24	01.01.1956	19.10.1957	09.12.1963	
DRESDEN-1	USA	BWR	NA	192	01.05.1956	04.07.1960	31.10.1978	
INDIAN POINT-1	USA	PWR	PWR	265	01.05.1956	01.10.1962	31.10.1974	
FERMI-1	USA	FBR	Liquid Metal FBR	60	01.12.1956	never connected	29.11.1972	
YANKEE NPS	USA	PWR	PWR	175	01.11.1957	01.07.1961	01.10.1991	
ELK RIVER	USA	BWR	-	22	01.01.1959	01.07.1964	01.02.1968	
HALLAM	USA	X	LMGMR	75	01.01.1959	01.11.1963	01.09.1964	
PATHFINDER	USA	BWR	NA	59	01.01.1959	never connected	01.10.1967	
CVTR	USA	PHWR	Prototype	17	01.01.1960	never connected	10.01.1967	
PIQUA	USA	X	OCM	11	01.01.1960	01.11.1963	01.01.1966	
BONUS	USA	BWR	Superheater	17	01.01.1960	01.09.1965	01.06.1968	
SAXTON	USA	PWR	25	3	01.01.1960	01.03.1967	01.05.1972	
BIG ROCK POINT	USA	BWR	-	72	01.05.1960	29.03.1963	29.08.1997	
HUMBOLDT BAY	USA	BWR	Natural cir.	65	01.11.1960	01.08.1963	02.07.1976	
PEACH BOTTOM-1	USA	HTGR	NA	40	01.02.1962	01.06.1967	01.11.1974	

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Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
LACROSSE	USA	BWR	NA	50	01.03.1963	07.11.1969	30.04.1987	
HADDAM NECK	USA	PWR	-	582	01.05.1964	01.01.1968	05.12.1996	
SAN ONOFRE-1	USA	PWR	NA	436	01.05.1964	01.01.1968	30.11.1992	
OYSTER CREEK	USA	BWR	BWR-2 (Mark 1)	650	15.12.1964	01.12.1969	operating	
NINE MILE POINT-1	USA	BWR	BWR-2 (Mark 1)	620	12.04.1965	01.12.1969	operating	
DRESDEN-2	USA	BWR	BWR-3 (Mark 1)	794	10.01.1966	09.06.1970	operating	
GINNA	USA	PWR	W (2-loop)	470	25.04.1966	01.07.1970	operating	
MILLSTONE-1	USA	BWR	NA	660	01.05.1966	01.03.1971	01.07.1998	
DRESDEN-3	USA	BWR	BWR-3 (Mark 1)	794	14.10.1966	16.11.1971	operating	
INDIAN POINT-2	USA	PWR	W (4-loop) DRY-AMB	873	14.10.1966	01.08.1974	operating	
QUAD CITIES-1	USA	BWR	BWR-3 (Mark 1)	789	15.02.1967	18.02.1973	operating	
QUAD CITIES-2	USA	BWR	BWR-3 (Mark 1)	789	15.02.1967	10.03.1973	operating	
PALISADES	USA	PWR	CE (2-loop) DRY-AMB	805	14.03.1967	31.12.1971	operating	
ROBINSON-2	USA	PWR	W (3-loop) DRY-AMB	700	13.04.1967	07.03.1971	operating	
TURKEY POINT-3	USA	PWR	W (3-loop) DRY-AMB	693	27.04.1967	14.12.1972	operating	
TURKEY POINT-4	USA	PWR	W (3-loop) DRY-AMB	693	27.04.1967	07.09.1973	operating	
BROWNS FERRY-1	USA	BWR	BWR-4 (Mark 1)	1065	01.05.1967	01.08.1974	operating	
BROWNS FERRY-2	USA	BWR	BWR-4 (Mark 1)	1065	01.05.1967	01.03.1975	operating	

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Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
MONTICELLO	USA	BWR	BWR-3	545	19.06.1967	30.06.1971	operating	
POINT BEACH-1	USA	PWR	W (2-loop) DRY-AMB	497	19.07.1967	21.12.1970	operating	
OCONEE-1	USA	PWR	B&W (L-loop)	887	06.11.1967	15.07.1973	operating	
OCONEE-2	USA	PWR	B&W (L-loop)	887	06.11.1967	09.09.1974	operating	
OCONEE-3	USA	PWR	B&W (L-loop)	887	06.11.1967	16.12.1974	operating	
VERMONT YAN-KEE	USA	BWR	BWR-4 (Mark 1)	514	11.12.1967	30.11.1972	29.12.2014	
PEACH BOTTOM-2	USA	BWR	BWR-4 (Mark 1)	1065	31.01.1968	05.07.1974	operating	
PEACH BOTTOM-3	USA	BWR	BWR-4 (Mark 1)	1065	31.01.1968	23.12.1974	operating	
DIABLO CANYON-1	USA	PWR	W (4-loop)	1084	23.04.1968	07.05.1985	operating	
THREE MILE ISLAND-1	USA	PWR	B&W (L-loop)	819	18.05.1968	02.09.1974	operating	
COOPER	USA	BWR	BWR-4 (Mark 1)	778	01.06.1968	01.07.1974	operating	
CALVERT CLIFFS-1	USA	PWR	CE (2-loop) DRY-AMB	845	01.06.1968	08.05.1975	operating	
CALVERT CLIFFS-2	USA	PWR	CE (2-loop) DRY-AMB	845	01.06.1968	01.04.1977	operating	
FORT CALHOUN-1	USA	PWR	CE (2-loop)	478	07.06.1968	26.09.1973	24.10.2016	
SURRY-1	USA	PWR	W (3-loop) DRY-SUB	788	25.06.1968	22.12.1972	operating	
PRAIRIE ISLAND-	USA	PWR	W (2-loop) DRY-	530	25.06.1968	16.12.1973	operating	

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Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
1			AMB					
SURRY-2	USA	PWR	W (3-loop) DRY-SUB	788	25.06.1968	01.05.1973	operating	
BROWNS FERRY-3	USA	BWR	BWR-4 (Mark 1)	1065	01.07.1968	01.03.1977	operating	
POINT BEACH-2	USA	PWR	W (2-loop) DRY-AMB	497	25.07.1968	01.10.1972	operating	
KEWAUNEE	USA	PWR	W (2-loop) DRY-AMB	535	06.08.1968	16.06.1974	07.05.2013	
PILGRIM-1	USA	BWR	BWR-3 (Mark 1)	655	26.08.1968	01.12.1972	operating	
FITZPATRICK	USA	BWR	BWR-4 (Mark 1)	821	01.09.1968	28.07.1975	operating	
FORT ST. VRAIN	USA	HTGR	NA	330	01.09.1968	01.07.1979	29.08.1989	
SALEM-1	USA	PWR	W (4-loop) DRY-AMB	1090	25.09.1968	30.06.1977	operating	
CRYSTAL RIVER-3	USA	PWR	B&W (L-loop)	825	25.09.1968	13.03.1977	05.02.2013	
SALEM-2	USA	PWR	W (4-loop) DRY-AMB	1115	25.09.1968	13.10.1981	operating	
HATCH-1	USA	BWR	BWR-4 (Mark 1)	777	30.09.1968	31.12.1975	operating	
MAINE YANKEE	USA	PWR	NA	825	01.10.1968	28.12.1972	01.08.1997	
ANO-1	UNITED KINGDOM	PWR	B&W (L-loop) DRYAMB	850	01.10.1968	19.12.1974	operating	
INDIAN POINT-3	USA	PWR	W (4-loop) DRY-AMB	965	01.11.1968	30.08.1976	operating	
ZION-1	USA	PWR	W (4-loop)	1040	01.12.1968	31.12.1973	13.02.1998	
ZION-2	USA	PWR	W (4-loop)	1040	01.12.1968	17.09.1974	13.02.1998	
ANO-2	USA	PWR	CE (2-loop) DRY-	912	06.12.1968	26.03.1980	operating	

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Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
			AMB					
COOK-1	USA	PWR	W (4-loop) ICECDN	1030	25.03.1969	28.08.1975	operating	
COOK-2	USA	PWR	W (4-loop) ICECND	1100	25.03.1969	01.07.1978	operating	
RANCHO SECO-1	USA	PWR	NA	918	01.04.1969	17.04.1975	07.06.1989	
PRAIRIE ISLAND-2	USA	PWR	W (2-loop) DRY-AMB	530	25.06.1969	21.12.1974	operating	
MILLSTONE-2	USA	PWR	COMB CE DRY-AMB	870	01.11.1969	26.12.1975	operating	
THREE MILE ISLAND-2	USA	PWR	NA	906	01.11.1969	30.12.1978	28.03.1979	
TROJAN	USA	PWR	NA	1130	01.02.1970	20.05.1976	09.11.1992	
BRUNSWICK-2	USA	BWR	BWR-4 (Mark 1)	821	07.02.1970	03.11.1975	operating	
BRUNSWICK-1	USA	BWR	BWR-4 (Mark 1)	821	07.02.1970	18.03.1977	operating	
SEQUOYAH-1	USA	PWR	W (4-loop) ICECND	1148	27.05.1970	01.07.1981	operating	
SEQUOYAH-2	USA	PWR	W (4-loop) (ICECND)	1148	27.05.1970	01.06.1982	operating	
DUANE ARNOLD-1	USA	BWR	BWR-4 (Mark 1)	538	22.06.1970	01.02.1975	operating	
BEAVER VALLEY-1	USA	PWR	W (3-loop)	835	26.06.1970	01.10.1976	operating	
ST. LUCIE-1	USA	PWR	COMB CE DRY-AMB	830	01.07.1970	21.12.1976	operating	
DAVIS BESSE-1	USA	PWR	B&W (R-loop)	906	01.09.1970	31.07.1978	operating	
FARLEY-1	USA	PWR	W (3-loop)	829	01.10.1970	01.12.1977	operating	
FARLEY-2	USA	PWR	W (3-loop) DRY-AMB	829	01.10.1970	30.07.1981	operating	



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Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
DIABLO CANYON-2	USA	PWR	W (4-loop)	1106	09.12.1970	13.03.1986	operating	
NORTH ANNA-1	USA	PWR	W (3-loop)	907	19.02.1971	06.06.1978	operating	
NORTH ANNA-2	USA	PWR	W (3-loop)	907	19.02.1971	14.12.1980	operating	
MCGUIRE-1	USA	PWR	W (4-loop) ICECND	1180	01.04.1971	01.12.1981	operating	
MCGUIRE-2	USA	PWR	W (4-loop) (ICECND)	1180	01.04.1971	01.03.1984	operating	
HATCH-2	USA	BWR	BWR-4 (Mark 1)	784	01.02.1972	05.09.1979	operating	
COLUMBIA	USA	BWR	BWR-5 (Mark 2)	1100	01.08.1972	13.12.1984	operating	
FERMI-2	USA	BWR	BWR-4 (Mark 1)	1093	26.09.1972	23.01.1988	operating	
SHOREHAM	USA	BWR	-	809	01.11.1972	never connected	01.05.1989	
SUMMER-1	USA	PWR	W (3-loop) DRY-AMB	900	21.03.1973	01.01.1984	operating	
WATTS BAR-1	USA	PWR	W (4-loop) (ICECND)	1218	20.07.1973	27.05.1996	operating	
WATTS BAR-2	USA	PWR	W (4-loop) (ICECND)	1165	01.09.1973	03.06.2016	-	
LASALLE-1	USA	BWR	BWR-5 (Mark 2)	1078	10.09.1973	01.01.1984	operating	
LASALLE-2	USA	BWR	BWR-5 (Mark 2)	1078	10.09.1973	19.10.1984	operating	
SUSQUEHANNA-1	USA	BWR	BWR-4 (Mark 2)	1065	02.11.1973	08.06.1983	operating	
SUSQUEHANNA-2	USA	BWR	BWR-4 (Mark 2)	1065	02.11.1973	12.02.1985	operating	
SAN ONOFRE-2	USA	PWR	CE (2-loop) DRY-AMB	1070	01.03.1974	08.08.1983	07.06.2013	

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Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
SAN ONOFRE-3	USA	PWR	CE (2-loop) DRY-AMB	1070	01.03.1974	01.04.1984	07.06.2013	
CATAWBA-1	USA	PWR	W (4-loop) (ICECND)	1145	01.05.1974	29.06.1985	operating	
CATAWBA-2	USA	PWR	W (4-loop) (ICECND)	1145	01.05.1974	19.08.1986	operating	
BEAVER VALLEY-2	USA	PWR	W (3-loop)	836	03.05.1974	17.11.1987	operating	
GRAND GULF-1	USA	BWR	BWR-6 (Mark 3)	1250	04.05.1974	01.07.1985	operating	
LIMERICK-1	USA	BWR	BWR-4 (Mark 2)	1055	19.06.1974	01.02.1986	operating	
LIMERICK-2	USA	BWR	BWR-4 (Mark 2)	1055	19.06.1974	08.01.1990	operating	
MILLSTONE-3	USA	PWR	W (4-loop) DRY-SUB	1159	09.08.1974	23.04.1986	operating	
PERRY-1	USA	BWR	BWR-6 (Mark 3)	1205	01.10.1974	18.11.1987	operating	
WATERFORD-3	USA	PWR	CE (2-loop)	1104	14.11.1974	24.09.1985	operating	
COMANCHE PEAK-1	USA	PWR	W (4-loop) DRY-AMB	1150	19.12.1974	13.08.1990	operating	
COMANCHE PEAK-2	USA	PWR	W (4-loop) DRY-AMB	1150	19.12.1974	03.08.1993	operating	
BYRON-1	USA	PWR	W (4-loop) (DRY-AMB)	1120	01.04.1975	16.09.1985	operating	
BYRON-2	USA	PWR	W (4-Loop) (DRY-AMB)	1120	01.04.1975	02.08.1987	operating	
BRAIDWOOD-1	USA	PWR	W (4-loop)	1120	01.08.1975	29.07.1988	operating	
NINE MILE POINT-2	USA	BWR	BWR-5 (Mark 2)	1100	01.08.1975	11.03.1988	operating	

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Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
BRAIDWOOD-2	USA	PWR	W (4-loop) DRY-AMB	1120	01.08.1975	17.10.1988	operating	
CALLAWAY-1	USA	PWR	W (4-loop) DRY-AMB	1171	01.09.1975	19.12.1984	operating	
CLINTON-1	USA	BWR	BWR-6 (Mark 3)	950	01.10.1975	24.11.1987	operating	
SOUTH TEXAS-1	USA	PWR	W (4-loop)	1250	22.12.1975	25.08.1988	operating	
SOUTH TEXAS-2	USA	PWR	W (4-loop) DRY-AMB	1250	22.12.1975	19.06.1989	operating	
HOPE CREEK-1	USA	BWR	BWR-4 (Mark 1)	1067	01.03.1976	20.12.1986	operating	
PALO VERDE-1	USA	PWR	CE (2-loop) DRY-AMB	1221	25.05.1976	28.01.1986	operating	
PALO VERDE-2	USA	PWR	COMB CE80 DRY-AMB	1304	01.06.1976	19.09.1986	operating	
PALO VERDE-3	USA	PWR	COMB CE80 DRY-AMB	1304	01.06.1976	08.01.1988	operating	
SEABROOK-1	USA	PWR	W (4-loop) DRY-AMB	1149	07.07.1976	19.08.1990	operating	
VOGTLE-1	USA	PWR	W (4-loop) DRY-AMB	1122	01.08.1976	01.06.1987	operating	
VOGTLE-2	USA	PWR	W (4-loop) DRY-AMB	1101	01.08.1976	20.05.1989	operating	
RIVER BEND-1	USA	BWR	BWR-6 (Mark 3)	966	25.03.1977	16.06.1986	operating	
WOLF CREEK	USA	PWR	W (4-loop)	1170	31.05.1977	03.09.1985	operating	
ST. LUCIE-2	USA	PWR	COMB CE DRY-AMB	830	02.06.1977	08.08.1983	operating	
HARRIS-1	USA	PWR	W (3-loop) DRY-	900	28.01.1978	02.05.1987	operating	

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Reactor	License	Type	Model	Capacity (MW <sub>e</sub> )	Start of Construction	Start of Operation	Permanent Shutdown	Comments
			AMB					
SUMMER-2	USA	PWR	AP1000	1117	09.03.2013	-	-	under construction
VOGTLE-3	USA	PWR	AP1000	1117	12.03.2013	-	-	under construction
SUMMER-3	USA	PWR	AP1000	1117	02.11.2013	-	-	under construction

