The decline of civil nuclear power programs:

Why state-owned enterprises hold the key to success in the Post-Fukushima Era.

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Abstract

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Civil nuclear power is declining in Canada, Germany, Japan, the United Kingdom, and the United States, and rapidly expanding in China, France, India, Russia, and South Korea. The disaster at the Fukushima-Daiichi nuclear power plant changed the future of nuclear power. For some states that means drastic shifts away from nuclear, and for others it means that the future of nuclear just became more difficult and expensive. This paper seeks to examine the role that state-owned enterprises play in advancing nuclear programs, and the difficulties that states without state-owned enterprises will face in this new future. A state-owned enterprise is a corporation that conducts the business of the state, and is either wholly owned by the government, or controlled by a government ownership of majority shares in a private corporation. (e.g., Amtrak, Freddie Mac, etc.) I posit that the presence of state-owned enterprises, or a government's controlling interest in a private nuclear energy corporation, enables governments to advance their state's civil nuclear power programs. This will be analyzed by examining nuclear power plant construction times, and completion rates for states that operate nuclear state-owned enterprises against those of private corporations. The results show that states operating state-owned enterprises have higher completion rates and quicker completion times.

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Introduction

Three Mile Island. Chernobyl. Fukushima. No matter which generation you grew up in, one of these three names has become synonymous with civil nuclear power[1]. For Baby Boomers it is Three Mile Island, for GenXers it is Chernobyl, and for Millennials it is Fukushima. These three events have shaped nations' energy policies, as well as the world nuclear energy industry. The long-standing effects of the Three Mile Island accident of 1979 can be seen in the United States' de jure and de facto moratorium on building new nuclear power plants. The effects of the 1986 Chernobyl accident can be readily seen in the strong anti-nuclear movements present in Germany and western Europe. On March 11, 2011, disaster struck at the Fukushima civil nuclear power plant.

In 2021, the effects of the Fukushima disaster are still being felt around the world. Anti-nuclear sentiment heightened once again. Legislation has been passed, tighter regulations imposed, and in some cases, drastic shifts in energy policy have been made. The Japanese government responded to Fukushima by shutting down fifty-four nuclear reactors. [2] Anti-nuclear movements, capitalizing on the media attention, organized massive political protests in cities across the country. Sixty-thousand citizens took to the streets of Tokyo to march against civil nuclear power plants.[3] German citizens organized and formed a forty-five-kilometer human chain of 60,000 anti-nuclear protesters stretching between the Stuttgart and Neckarwestheim nuclear power plants.[4] States, politicians, and corporations attempted to distance themselves

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[1] Note: To draw a distinction between nuclear power programs and nuclear weapons programs, this paper will use the terms 'civil nuclear power' or 'nuclear energy' to refer to electrical power generated from nuclear fission—with one exception. 'Nuclear power plant', being the accepted industry nomenclature for nuclear plants, will continue to be used. 'Nuclear power' will refer to a nuclear weapons program, and 'nuclear state' will refer to states with 'civil nuclear power plants'.

[2] Martin Fackler, "Japan's Nuclear Energy Industry Nears Shutdown, at Least for Now", *New York Times*, March 8, 2012, https://www.nytimes.com/2012/03/09/world/asia/japan-shutting-down-its-nuclear-power-industry.html

[3]"Sayonara, nukes, but not yet; An anti-nuclear protest in Japan." The Economist, September 24, 2011, 52(US). https://www.economist.com/asia/2011/09/24/sayonara-nukes-but-not-yet

[4] "Thousands protest against Germany's nuclear plants", *BBC News*, Mar 12, 2011, https://www.bbc.com/news/world-europe-12724981

from nuclear energy to avoid the bad press or a stroke of financial misfortune. Civil nuclear power projects that were once in discussion have now been put aside. Even large engineering corporations preemptively exited the nuclear industry—thinking they had seen the writing on the wall. Germany's largest nuclear engineering company, Siemens, left the nuclear industry following the events of Fukushima.[5]

Japan and Germany were not alone in their strong reactions to the events of Fukushima. South Korea's then-President elect Moon Jae-in stated that the events of Fukushima would lead South Korea to shift its energy policy and begin phasing-out nuclear power plants.[6] Western European states that had previously committed to distant benchmarks for civil nuclear power phase-outs, reaffirmed their stance or had advanced the phase-out timelines following Fukushima. Germany's Chancellor, Angela Merkel, shifted from a pro-nuclear stance to an anti-nuclear stance immediately following the events of Fukushima.[7] This took the phase-out deadline for civil nuclear plants from 2036 (for plants that had come online after 1980) to the originally proposed 2022 from the Red-Green phaseout law.[8]

Based on reactions to the events of Three Mile Island and Chernobyl, a similar reaction towards the events of Fukushima would be expected from states operating civil nuclear power plants. More states would follow in Germany and Japan's footsteps—holding massive anti-nuclear protests, calling for a nuclear moratorium, or an immediate and complete phase out

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[5] "Siemens to Exit Nuclear Energy Business", *Der Spiegel*, September 19, 2011, https://www.spiegel.de/international/business/response-to-fukushima-siemens-to-exit-nuclear-energy-business-a-787020.html.

[6] Christine Kim, "South Korea's president says will continue phasing out nuclear power", *Reuters*, October 21, 2017, https://www.reuters.com/article/us-southkorea-nuclear-moon/south-koreas-president-says-will-continue-phasing-out-nuclear-power-idUSKBN1CR04U.
Chloe Sang-Hun, "South Korea Will Resume Reactor Work, Defying Nuclear Opponents", *New York Times*, October 20, 2017, https://www.nytimes.com/2017/10/20/world/asia/south-korea-nuclear-plants.html.

[7] "Merkel Gambles Credibility with Nuclear U-Turn", *Der Spiegel*, March 21, 2011, *Der* Spiegel, https://www.spiegel.de/international/germany/out-of-control-merkel-gambles-credibility-with-nuclear-u-turn-a-752163.html.

[8] Craig Morris, and Arne Jungjohann, *Energy Democracy: Germany's ENERGIEWENDE to Renewables* (New York: Palgrave MacMillan, 2016), 280.

existing civil nuclear power plants. Governments would halt the construction of ongoing nuclear power plant projects, and then ultimately abandon them. Energy policy shifts in developed nuclear states such as China, South Korea, and Japan would occur; and growing nuclear markets such as India, and Pakistan; as well as emerging markets in the Middle East such as Bangladesh, Iran, Turkey, and UAE; would also observe shifts in their state's energy policy. Energy policy would also be expected to shift in mature nuclear states with aging nuclear fleets such as France, the United Kingdom, and the United States, who have all experienced decades-long intermissions of nuclear plant construction and were discussing a return to building more civil nuclear plants on their soil. However, those expectations were not met.

Instead, half of the states reacted adversely to the events of Fukushima, while the other states were seemingly undeterred. Geographic proximity to the event was not a determinate, neither was cultural proximity. China is closer to Japan than Germany is to Japan, yet the anti-nuclear reactions of German citizens were more similar to those of Japan. The possibility of a link between states that had themselves experienced a nuclear disaster—e.g., the United States, and the former Soviet Union states—was a possibility. The New York Times reported that polling conducted on public support for building more nuclear power plants in the United States was polled at 43 percent following the events of Fukushima, as compared to 57 percent approval in 2008 at the height of the 'Nuclear Renaissance'. This decline of public support was experienced in the U.S. before—following the events of Three Mile Island. The polls showed a 69 percent approval of nuclear power plants prior to Three Mile Island, and a 46 percent approval afterwards [9] The events of Chernobyl took a much larger toll on public support for nuclear power plants. One poll has the approval rating in the United states at 34 percent following Chernobyl.[10] The U.S. polls do not indicate the same level of disapproval for nuclear

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[9] Michael Cooper and Dalia Sussman, "Nuclear Power Loses Support in New Poll", *New York Times*, March 22, 2011, https://www.nytimes.com/2011/03/23/us/23poll.html.

[10] Ibid.

energy following Fukushima as it had following Chernobyl. It did not appear there was a strong link for Russia's case either. Russia's actions did not indicate that its state was experiencing a decline in civil nuclear power. Russia's nuclear exporter, Atomstroyexport, was still building nuclear plants in India, and China during and following the events of Fukushima. Multiple states in Europe, the Americas, and Asia, that operated civil nuclear power had varied responses to the events of Fukushima as well. To find the answer to the phenomenon of certain states' civil nuclear power programs declining as a result of the events of Fukushima, while other states programs advancing, a new approach was taken.

Quantitative research has two basic approaches: deductive reasoning--top-down, starting with a hypothesis then drilling for data to confirm; and inductive reasoning—bottom up, starting with data/observations and then developing a theory. The deductive reasoning approach to researching this phenomenon was not bearing any fruit. In the pursuit of the answer, data points were collected on all states that operate, have operated, or aspire to operate (near future), civil nuclear power plants. The question then became which points of data *would* inform a theory. Data points were collected on various aspects of each state that operated civil nuclear power—quantity of reactors/plants, which years the reactors/plants were constructed, construction times, types and capacities of reactor designs, and who constructed and financed the nuclear construction project. After much research, collection, and graphing of data, the observations indicated one data point in common for states that are currently advancing their civil nuclear programs, and one point in common for states whose programs are on the decline. The research question then became: In the Post-Fukushima era, what factors indicate whether a state's civil nuclear power programs would advance, decline, or stall.

Hypothesis:

I posit that the presence of state-owned enterprises, or a government's controlling interest in a private nuclear energy corporation, enables governments to advance their state's civil nuclear power programs.

Literature review

The current academic studies on state-owned enterprises are focused mainly on China. Having 150,000 state-owned enterprises, China offers academics a wealth of material to write on.[11] Studies on state-owned enterprises, pertaining to China as well as a minority written on other states, focus mainly on state-owned enterprises' effects on the economy, principle/agent relationships, and public accountability/corruption. Notably, Lin et al. *State-owned enterprises in China: A review of 40 years of research and practice* (2019) offers valuable insight into the advantages of operating state-owned enterprises. The discussion of governmental interventions in the market, as well as the 'commanding heights' approach a state may employ to control the critical areas of the economy is applicable to the phenomenon addressed in this paper.

There were two standout books that addressed the factors behind declining U.S. civil nuclear power programs: Scott Montgomery and Thomas Graham Jr.'s *Seeing the Light: The case for nuclear power in the 21st Century*; and a book produced by two Fellows from the Hoover Institute--Jeremy Carl and David Fedor's *Keeping the Lights on at America's Nuclear Power Plants*.[12] Carl and Fedor's economic analysis and discussion on nuclear plant cost diversity, and the nuclear industry supply chain helped inform the argument of this paper.

No studies were located during the literature review that focused on the relationship between state-owned enterprises and the nuclear energy industry. To that end, the approach taken was to source business articles written about recent industry activity pertaining to nuclear corporations, nuclear power projects, and energy sector mergers and acquisitions. Newspaper articles from Reuters, Forbes, Bloomberg, New York Times, Wall Street Journal, and the Times

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[11] Karen Jingrong Lin et al., "State-owned enterprises in China: A review of 40 years of research and practice", *China Journal of Accounting Research*, (March 2020), https://www.sciencedirect.com/science/article/pii/S1755309119300437

[12] Scott Montgomery and Thomas Graham Jr., *Seeing the Light: The case for nuclear power in the 21st Century,* (Cambridge: Cambridge University Press, 2017).
Jeremy Carl and David Fedor, *Keeping the Lights on at America's Nuclear Power* Plants, (Standford: Hoover Institute Press, 2017).

(UK) were sourced and the information from articles verified through corporation or government websites when available. Government websites were also sourced for information on legislative and/or regulatory changes that have occurred since the events of Fukushima.

Recent legislative support for small modular reactor technology (fortuitously) occurred during the writing process. Due to the recency of the events, news articles from newspapers, Popular Mechanics, and other sources devoted to technology were sourced to present the most updated information.

Nuclear technology studies and journals were also used to present indicators of future nuclear industry direction. With the current industry development of small modular reactors and a projected plant cost of three to four billion dollars, strong financial incentives exist for private corporations to invest in nuclear energy infrastructure projects. Private corporations would likely be able to compete with state-owned enterprises, and state enterprises may opt to focus only on large-scale nuclear plants. Future research could be conducted on the impact of SMRs on the nuclear energy industry—specifically large electric utility corporations and state-owned enterprises. Two additional studies in this vein: study on the impact of potential nuclear hybrid energy systems using molten-salt energy storage systems and their effects on the nuclear energy industry; and a study on the ability of private firms to compete against state-owned enterprises on small-distributed power projects.

Roadmap

This paper will address the roles that state-owned enterprises (SOE), and nuclear corporations that a state has controlling interest in, have in the nuclear energy industry. This paper will demonstrate how the presence or absence of SOEs are the strongest explanatory variable for why a state's civil nuclear program is advancing, declining, or stalling.

Chapter 1 provides a brief background on civil nuclear power to provide the necessary historical context for an examination of the merits of the argument presented in this paper. This chapter is written for those unfamiliar with the history of nuclear weapons programs and its evolution into civil nuclear power programs (electricity).

Chapter 2 presents the argument for state-owned enterprises (SOE) driving advancement of the civil nuclear field. Note that the term SOE covers both wholly-owned, and majority-owned government enterprises. Specific reactor designs will be touched on throughout this chapter for the purpose of demonstrating the logic of the argument. These reactor designs will be explained in further detail in each state's case study. Additionally, the Appendices include reactor design diagrams—both simplified as well as cutaways—for reference. Chapter 2 also contains a section on nuclear regulators and their relationship to the SOEs. This chapter introduces the names of state-owned enterprises and nuclear exporters. These will be discussed again in the case studies.

Chapter 3 presents the ten case studies. Each case study gives a brief historical background of each state's civil nuclear power program, followed by analysis of each state's reactor construction projects and relevant explanatory variables such as economics, political voice, and environmental movements that affect the civil nuclear power industry.
The order of case studies is as follows: United States, Russia, Canada, United Kingdom, France, Germany, China, Japan, South Korea, and India.

Chapter 4 presents the findings from across all the case studies. The conclusion will address any limitations of SOEs operating in the Post-Fukushima era, and discuss possible ways forward for the advancement of the civil nuclear power industry.

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Chapter 1: The path to civil nuclear power

States follow similar paths in their development of civil nuclear power. States begin with a research reactor to gain understanding of the scientific and technical aspects of the achieving nuclear fission. Afterwards, a full-scale nuclear power plant is constructed. (See Appendix A.) [13] Another path that states may take is the nuclear weapons path. In this variation, the state builds a research reactor; and later builds a full-scale reactor, as before. The reactor is not connected to systems that generate and supply electrical power to the commercial grid. Instead, the reactor's purpose is to produce Plutonium. The state uses the Plutonium for the creation of nuclear weapons. Later, the state applies its mastery of the nuclear fuel cycle towards building nuclear reactors for commercial applications. As the focus of this paper is solely on commercial applications of nuclear energy, the former path will be discussed. The development of civil nuclear power can be split into three groups: indigenous, foreign assistance, and isolation.

Group 1: Indigenous development

The first group is indigenous development—when a country uses its own design, technology, personnel, and know-how to master the nuclear fuel cycle, and achieve a self-sustaining fission chain reaction. The United States, Soviet Union/Russia, Canada, the United Kingdom, France, and Germany fall under this category.

The United States was the first nation of this group to build a nuclear reactor. The process of developing nuclear weapons requires the construction of a full-scale nuclear reactor in order to obtain fissionable material for use in nuclear weapons. The U.S. nuclear power program began in 1939 during the lead up to World War II with the creation of the Manhattan Project. The first-ever nuclear chain reaction took place on December 2nd, 1942, in a squash court under the football stadium at the University of Chicago. The United States later built a full-scale (DoD) nuclear reactor at Hanford, which went critical on September 26, 1944. The Soviet

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[13] Note: Basic nuclear power plant diagrams from the U.S. NRC are included in Appendices A, B, and C.

Union followed on December 25, 1946 with the F-1 reactor; Canada introduced their ZEEP reactor on July 22, 1947; and two months later the United Kingdom went critical with their GLEEP reactor on August 15, 1947.[14] France was the fifth to achieve criticality with their Zoé EL-1 reactor on Dec 15, 1948. Germany's Atomic Egg went critical on October 31st,1957.

Following World War II, and in the early years of the Cold War, states possessing nuclear technology did not allow commercial ventures in nuclear energy. In 1954, the Soviet Union was the first state to use nuclear power to supply electricity to the commercial grid, followed by the United Kingdom in 1956, the United States in 1958, Canada in 1962, France in 1964, and Germany in 1969.

Group 2: Development through foreign assistance

The second group is development through foreign assistance—a nuclear nation from the above group transfers nuclear technology to a non-nuclear state. This path can be traced back to a speech made to the UN on Dec 8, 1953 by President Dwight D. Eisenhower:

> "The more important responsibility of this atomic energy agency would be to devise methods whereby this fissionable material would be allocated to serve the peaceful pursuits of mankind. Experts would be mobilized to apply atomic energy to the needs of agriculture, medicine, and other peaceful activities. A special purpose would be to provide abundant electrical energy in the power-starved areas of the world." [15]

This section from President Dwight D. Eisenhower's *Atoms for Peace* speech references an atomic energy agency that had yet to be created. Four years later, the International Atomic Energy Agency (IAEA) came into existence—its motto: 'Atoms for Peace and Development'. Within a year, the United States was supplying research reactors and transferring nuclear technology to member states of the IAEA. At the time of writing, there have been over 850

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[14] Note: Even though the United Kingdom had helped the U.S. during the Manhattan project, the McMahon Act of 1946 prevented the U.S. from disseminating nuclear information or technology. This Act was in effect until 1958.

[15] Dwight D. Eisenhower, "Atom for Peace", December 8, 1953, IAEA, accessed February 12, 2021, https://www.iaea.org/about/history/atoms-for-peace-speech.

research reactors constructed worldwide.[16] Austria, Brazil, Columbia, India, Israel, Italy, Japan, Pakistan, North Korea, Philippines, Slovenia, South Africa, Sweden, Switzerland, Turkey, Uruguay, Venezuela, and Vietnam are some of the beneficiaries of nuclear technology transfer agreements. The United States was not the only state offering nuclear technology transfers. Those early years of Atoms for Peace saw Canada, France, the UK, and the USSR offering technical assistance to foreign nations as well.

Nuclear technology transfers historically start with an advanced-nuclear state supplying a nuclear research reactor to a non-nuclear state. Research reactors were the means for a nascent nuclear state to develop the necessary experience with the nuclear plant operations prior to progressing to civil nuclear plants. The nascent nuclear state would then either master the technology and pursue an indigenous nuclear program, or contract with the advanced nuclear state to provide a turnkey commercial power reactor to be built.

Non-nuclear states in Asia were among the first to take advantage of the Atoms for Peace movement and the technological expertise being offered by IAEA member states. India's first nuclear research reactor, Apsara, was built with help from the United Kingdom in 1956, and its second nuclear research reactor, CIRUS, was supplied by Canada and filled with heavy water supplied by the United States .[17] Japan's JRR-1 reactor was built with assistance from the United States in 1957, as was South Korea's TRIGA reactor in 1962.[18] States as far away as South Africa, Uruguay, and the Philippines were also party to technology transfers. The Philippines' PRR-1 was constructed by General Atomics (General Dynamics atomic division) in

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[16] "Research Reactor Database RRDB", IAEA, accessed February 13, 2021, https://www.iaea.org/resources/databases/research-reactor-database-rrdb.

[17] Perkovich, George*, India's Nuclear Bomb: The Impact on Global Proliferation* (Berkeley: University of California Press, 1999), 27.

[18] Kiyonobu Yamashita, "History of Nuclear Technology Development in Japan*", AIP conference proceedings*, 1659, no. 1, (April 2015), accessed February 7, 2021, https://aip.scitation.org/doi/pdf/10.1063/1.4916842.
Phillip Andrews-Speed, "South Korea's nuclear power industry: Recovering from scandal*", Journal of World Energy Law and Business*, 13, no. 1, (March 2020): 48, https://watermark.silverchair.com/jwaa010.pdfs.

1963, and South Africa’s Safari-1 and Uruguay’s RU-1 reactors were also built by the US in 1965.[19]

The Cold War

The early years of Atoms for Peace were also the early years of the Cold War. The Cold War saw both the Soviet Union and the United States vying for hegemonic influence in non-nuclear states. Nuclear technology transfers became a diplomatic mechanism for strengthening ties with neutral foreign states. States in Asia and the Middle East were being diplomatically courted by both the Soviets and the Americans with offers of nuclear technology due to their strategic significance to the Cold War. States considering offers of nuclear assistance from the Soviets or the United States were placed in a position of choosing to align themselves with one of the two hegemonic powers. In 1961, Egypt, Ghana, India, Indonesia, and Yugoslavia chose not to pick sides, and created the Non-Aligned Movement.[20] Many developing states in Africa, Asia, Central and South America also joined the movement. Non-nuclear states had other options for attaining nuclear power. Canada’s AECL exported CANDU reactors during the Cold War to Argentina, India, Pakistan, Romania, and South Korea.

Group 3: Isolation

The third group is defined by their isolation from the international nuclear community. This group is comprised of states that obtained early, limited assistance from other nations, and were supplied with research reactors. The state’s later pursuit of nuclear weapons isolated them from the international nuclear community, and the state had to rely on indigenous development thereafter. India, Israel, North Korea, and Pakistan are examples of states in this group.

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[19] “The History of Safari 1”, NTP, accessed on 13 February 2021, https://www.ntp.co.za/history//, “Research Reactor Database RRDB”, IAEA, accessed February 13, 2021, https://www.iaea.org/resources/databases/research-reactor-database-rrdb#.

[20] “History and Evolution of Non-Aligned Movement”, Ministry of External Affairs, Government of India, August 22, 2012, accessed February 13, 2021, https://mea.gov.in/in-focus-article.htm?20349/History+and+Evolution+of+NonAligned+Movement.

Nuclear weapons proliferation

While the ideology behind the Atoms for Peace program was to promote peaceful use of nuclear energy, and aimed at mitigating the proliferation of nuclear weapons, many states pursued nuclear technology as a means to develop nuclear weapons capabilities. Nuclear technology transfers during Atoms for Peace enabled states to master the nuclear fuel cycle, and with that knowledge and experience, access to plutonium. Obtaining plutonium from research reactors is possible through chemically removing plutonium from spent fuel rods at a reprocessing facility. An example of this occurred with India. Their research reactor, CIRUS, made it possible to obtain the plutonium used for India's first nuclear weapons test—*Smiling Buddha*.[21] This was possible due to the type of reactor India was supplied with—a heavy water reactor. Heavy water reactors use natural Uranium (U-238) instead of enriched Uranium (U-235). The usage of U-238 allows it to capture one extra neutron, which after a series of radioactive decays, transforms the U-238 into Plutonium (Pu-239). This element can later be extracted from the reactor after the fuel is 'spent' (used up) and used in the construction of nuclear weapons. The 1950s and 1960s saw nuclear weapons develop in five additional states—Russia (1949), UK (1952), France (1960), China (1964)[22], and (allegedly) Israel in (1967).[23]

The Nuclear non-proliferation treaty (NPT) was drafted on July 1, 1968 to address the proliferation of nuclear weapons. The NPT includes eleven articles, of which the first four are pertinent to events described in this paper. The NPT is briefly summarized as follows: Article I,

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[21] Scott L. Montgomery and Thomas Graham Jr., *Seeing the Light: The case for nuclear power in the 21st century* (Cambridge: Cambridge University Press, 2017), 323-324.

[22] Note: In the 1960s, China had constructed nuclear facilities in secret to produce fissile material for building an atomic bomb. "China's Bomb", *New York Times*, October 18, 1964, https://www.nytimes.com/1964/10/18/archives/chinas-bomb.html

[23] Avner Cohen, *Israel and the Bomb*, (New York: Columbia University Press, 1998), 342.
Phillipp C. Bleek, *When did (and didn't) States Proliferate?* (Cambridge: Harvard Kennedy School, 2017), 8, 13-14 https://www.belfercenter.org/sites/default/files/files/publication/When%20Did%20%28and%20Didn%27t%29%20States%20Proliferate%3F_1.pdf

is the most important text with regard to non-proliferation: “Each nuclear-weapon State Party to the Treaty undertakes not to transfer to any recipient whatsoever nuclear weapons or other nuclear explosive devices…” Article II states the same concept but from the receiving state’s point of view and is aimed at non-nuclear weapon states. Article III obligates non-nuclear weapon states to accept ‘safeguards’—a verification system put in place to ensure that no nuclear materials (Plutonium or enriched Uranium) are diverted from operation of civil nuclear power. Article IV is the ‘carrot’ to Article I, II, and III’s ‘stick’. The text of Article IV provides the incentive to non-nuclear states—technology transfers: “All the Parties to the Treaty undertake to facilitate, and have the right to participate in, the fullest possible exchange of equipment, materials and scientific and technological information for the peaceful uses of nuclear energy…”[24] The prominent signatories of the NPT include all states mentioned in this paper save for three notable exceptions: India, Israel, and Pakistan. To emphasize the import of this treaty--every other state in the *world* has signed the NPT, with the exception of India, Israel, Pakistan and South Sudan. (North Korea, a signatory, withdrew in 2003.) Despite the efforts of the NPT, the 1970s saw two additional states added to ranks of nuclear states: India (1974), and South Africa (1977).[25] (South Africa later gave up its nuclear arsenal in 1989-1991.[26]) The 1990s and 2000s saw the addition of the last two states to join the ranks of nuclear statehood: Pakistan (1998), and North Korea (2006).

Israel’s early nuclear program trajectory was similar to states in the second group. They obtained a 5 MWt pool-type research reactor through the U.S. Atoms for Peace program. The Soreq research reactor was constructed by American Machine and Foundry (AMF) and went critical in 1960. Israel’s refusal to become a signatory of the Nuclear Non-Proliferation Treaty (NPT) and the US discovery of their secret nuclear facility at Dimona—which signaled Israel’s

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[24] “Treaty on the Non-Proliferation of Nuclear Weapons (NPT)”, United Nations Office for Disarmament Affairs, accessed on April 13, 2021, https://www.un.org/disarmament/wmd/nuclear/npt/text.
[25] George Perkovich, *India’s Nuclear Bomb*, 27
[26] Thomas Graham Jr., *Disarmament Sketches* (Seattle: University of Washington Press, 2002), 327.

intentions to develop nuclear weapons—halted further foreign assistance from the United States and other members of the international nuclear community.[27]

Pakistan's early nuclear program trajectory began much like those in the second group. They obtained early foreign assistance from the United States, and were supplied with a research reactor, PARR-1, which attained criticality on December 21, 1965. Pakistan was later cut-off from the nuclear supply chain after the United States discovered Pakistan's intention to develop nuclear weapons following a comment from A.Q. Khan, the head of Pakistan's nuclear enrichment program, to an Indian member of the press.[28] Once isolated from the international nuclear community, Pakistan proceeded to develop both their nuclear power and civil nuclear energy programs indigenously.

North Korea followed a similar path as Pakistan. The Soviet Union supplied North Korea with a pool-type IRT-2000 research reactor which was installed at Yongbyon in 1963. Following the fall of the Soviet Union, North Korea requested that Russia supply them with a light-water reactor for commercial purposes but was not able to afford the cost of the project. Later, at the Six Party Talks in 2003, North Korea offered to trade its nascent nuclear weapons program in exchange for a light-water reactor and other concessions, however, the United States and other parties did not come to an agreement on the matter.[29] North Korea continued its pursuit of nuclear weapons and remained cut off from the international nuclear community.

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[27] Avner Cohen, *The Worst Kept Secret*, (New York: Columbia University Press, 2010), 57, 71, 75.

[28] Feroz Khan, *Eating Grass: The Making of the Pakistani Bomb*, (Stanford: Stanford University Press, 2012),225-226.

Perkovich, 308. Note: Pressler Agreement

[29] Victor Cha, *The Impossible State: North Korea past and future*, (New York: Harper Collins, 2013), 261.

Chapter 2: The role of state-owned enterprises in nuclear infrastructure

Why is it that Canada, China, France, and South Korea have higher completion rates and faster average nuclear plant construction times than the United States, United Kingdom, and other European states? The answer: **SOEs**, or state-owned Enterprises.[30]

A state-owned enterprise is a corporation that is owned by the government of a state. The treatment of the term ‘state-owned enterprise’ has been interpreted in publications as either wholly owned, or partially owned by a government. This paper’s usage of the term will interpret both majority ownership, and whole ownership, of a corporation by a government as state-owned enterprises. State-owned enterprises operate across many sectors such as the airline industry, banking, broadcasting, electricity production, housing, health care, manufacturing, postal service, prison systems, telecommunications, and transportation.[31] The terminology a state uses for its SOEs differs from state to state. State-owned enterprises have descriptors such as: state corporation, state enterprise, Crown corporation, Republican Unitary enterprise, State participation agency, statutory corporation, and government ‘authority’. Examples of SOEs can be found throughout the world. There are many state-owned enterprises that readers may be familiar with: Air France, Amtrak, Bank of Canada, British Broadcasting Corporation (BBC), Deutsche Bahn AG (German rail), DHL, Freddie Mac, and the Tennessee Valley Authority. [32]

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[30] Note: Canada (6.59 years), China (5.4 years, indigenous), France (6.25 years), South Korea (5.16 years), United States (8 years), United Kingdom (7.5 years). Source: IAEE PRIS database. Author’s own calculations. Source: “Power Reactor Information System (PRIS), IAEA, accessed October 2020-April 2021. Author’s own calculations. https://pris.iaea.org/PRIS/CountryStatistics/CountryStatisticsLandingPage.aspx.

[31] Michael A. Crew and R. Richard Geddes, “A business model for USPS” in *The Role of the Postal and Delivery Sector in a Digital Age*, eds., Michael A. Crew and Timothy J Brennan (Cheltenham: Edward Elgar, 2014), 16. Note: Referencing the French postal service, La Poste, and not the U.S. Postal Service-- which, although wholly owned by the government, is not an SOE.

[32] Note: Air France was nationalized from 1945-1999, then was privatized and merged with the Netherland’s KLM; “Our History”, TVA website, accessed February 04, 2021, https://www.tva.com/about-tva/our-history.

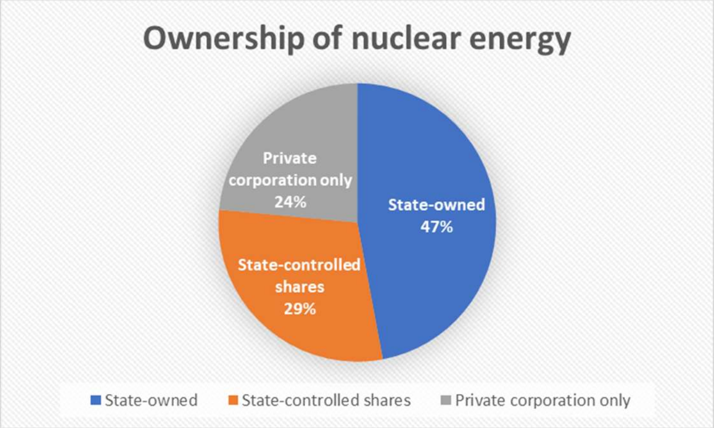

Figure 1-- Chart: Ownership of nuclear energy. Author's own chart.

At the time of writing, there are 444 nuclear reactors operating in thirty-three states.[33] Roughly half—forty seven percent—of states operate their civil nuclear programs through state-owned enterprises that are wholly owned by the government.[34] The repeated inclusion of the word 'wholly' is due to an added layer of complexity in the world of nuclear state-owned enterprises. In the 1990s and early 2000s, energy market deregulations and SOE privatizations occurred in many states that operate civil nuclear power—mostly in Western Europe and North America. In addition to the forty-seven percent above, twenty-nine percent of states have privatized their previously government-held nuclear energy corporations. Examples of this can be seen in Canada (AECL), and the United Kingdom (British Energy). During the privatization process, most states opt to retain a simple majority of shares—fifty one percent. If a state opted to sell its controlling interest, it was often critical of whom the shares were sold to—especially if the interested party was a foreign state corporation. This strategy enables states to control their civil nuclear projects while resourcing private funding (at onset of stock sale). This leaves twenty-four percent of states that have civil nuclear programs funded by private energy firms.

There are some notable outliers to the three (percentage-based) groups represented above. There are several instances of states privatizing their SOEs in which ***another*** state SOE acquired the shares of the first. This can be seen in the cases of Belgium (who owns a 'golden

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[33] Source: IAEA PRIS database. Author's own calculations.
Note: 34 states have operating nuclear power plants across 33 countries. Source: IAEA PRIS database. Author's own calculations.
Note: Croatia and Slovenia have a joint venture at the Krsko nuclear plant in Krsko, Slovenia—just 34 miles northwest of Zagreb, Croatia.

[34] Author's own calculation.

share' of Électricité de France S.A. (EDF)/Electrabel), Spain, and the United Kingdom. The multi-billion-dollar deals to obtain controlling shares of privatized energy firms can be difficult to follow, but usually entail a state wanting to divest itself of its majority shares of an energy corporation operating at a loss, and a second state wanting to expand its portfolio to take advantage of economies of scale. France's Électricité de France S.A. (EDF), Italy's ENEL, and Sweden's Vattenfall A.B. are the largest players on the board in this regard. Italy's ENEL, a government majority-owned energy SOE, purchased Spain's nuclear SOE, Empresa/Endesa, in 2008.[35] Sweden's nuclear SOE, Vattenfall A.B., bought the Netherland's energy firm Nuon.[36] France's EDF purchased bought the United Kingdom's nuclear SOE, British Energy in 2008.[37]

In addition to SOEs building nuclear infrastructure on foreign soil, there are also private multinational corporations like Westinghouse, RWE, Siemens, and Toshiba.

As noted in the hypothesis, I posit that the presence of state-owned enterprises leads to the advancement of civil nuclear power programs. The reason for this advancement is the number of advantages that being an SOE provides. The benefits of a state operating an SOE are fully realized in the front-end of civil nuclear power plant projects—from the design phase to the reactor achieving first criticality. The largest benefits of SOE-led projects are secure financing, standardized design, experience, and minimizing project delays.

Secure Financing

When a state with an SOE plans to build a civil nuclear power plant, there is no question as to where the financial backing will come from—the answer is the state. Front-end project financing is where the largest obstacles to infrastructure projects are found. Not being able to

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[35] David Lawsky and William Schomberg, "EU clears "Enel-Acciona bid for Endesa", Reuters, June 16, 2008, https://www.reuters.com/article/innovationNews/idUKL164379920080616?edition-redirect=uk

[36] Catherine Hornby and Quentin Webb, "Vattenfall to buy Nuon unit for $13.3 billion", *Reuters,* February 23, 2009, Note: Nuon is involved in gas, not nuclear.

[37] Vanessa Walters and John Bowker, "France's EDF agrees $23 billion bid for British Energy", *Reuters*, September 24, 2008. https://www.reuters.com/article/us-britishenergy-edfma/frances-edf-agrees-23-billion-bid-for-british-energy-idUSTRE48N27920080924

secure financing prevents civil nuclear power plant projects from breaking ground. Even when a project does break ground, the possibility of delays midway through construction can cause projects to fall through. There is a term in circulation inside the project management industry—'The Iron Law of Megaprojects.'[38] It is derived from the title of a book by an Oxford Professor, Bent Flyvbjerg. The Iron Law of Megaprojects states: "Over budget, over time, under benefits, over and over again." [39] This is true of large infrastructure projects, and certainly true of large civil nuclear plant construction projects. Rarely, if ever, do nuclear plant projects come in *under* budget. Nor do they typically complete on time. For first-of-its-kind design builds, as seen in the AP1000 design builds, time delays and cost overruns are not limited to a one-time occurrence per project. It is typically several delays, and several unexpected financial bumps in the road. These financial hurdles encountered mid-project can lead to a project stalling until further funding is allocated. Recent examples of stalled projects can be seen in the UK's Wylfa Newydd and Moorside[40]. A recent example of an abandoned project—meaning the construction had already begun and then the project was terminated—is the Summer 2 and Summer 3 AP1000 project in South Carolina, United States.[41]

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NEW YORK, MO

15,000 Protest L.I. Atom Plant; 600 Seized

Protester lies on ground after fence he tried to scale gave way during demonstration at nuclear plant in Shoreham, L.I.

Shoreham Action Is One of Largest Held Worldwide

By JOHN T. McQUISTON

U.S. Oil Outlook Called Fragile; Further Spot Shortages Foreseen

By STEVEN RATTNER

Figure 2-- Shoreham protest. Source: New York Times, June 4, 1979, https://www.nytimes.com/1979/06/04/archives/shoreham-action-is-one-of-largest-held-worldwide-15000-protest-li.html

Financing for a project of this size and duration is a difficult undertaking. Project managers, utility companies, voters, and politicians need to understand the risks involved. There are political

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[38] Note: Any projects that cost $1B or more is considered a 'megaproject'. (See following footnote.)

[39] Bent Flyvbjerg, "Introduction: The Iron Law of Megaproject Management," in *The Oxford Handbook of Megaproject Management*, ed. Bent Flyvbjerg, (Oxford: Oxford University Press, 2017), 1-18; http://bit.ly/2bctWZt.

[40] Stephen Stapczyinski "Hitachi Poised to Exit U.K. Nuclear Power Project Wednesday", *Bloomberg*, September 14, 2020, https://www.bloomberg.com/news/articles/2020-09-15/hitachi-plans-to-exit-u-k-nuclear-power-project-mainichi-says.
Note for the curious: Wylfa Newydd is a Welsh site and pronounced 'wilva newith'.

[41] Brad Plumer, "U.S. Nuclear Comeback Stalls as Two Reactors Are Abandoned", *New York Times*, July 31, 2017, https://www.nytimes.com/2017/07/31/climate/nuclear-power-project-canceled-in-south-carolina.html#.

risks—will the state/government/voters actively prevent the project from starting/completing? The Shoreham plant in the United States is an example of political risk—even though the $6B plant was completed, the state of New York prevented the plant from going online in response to massive citizen protests.[42] (See image right.) The corporate project financers concern themselves with capital costs, where to secure the capital, rate of return, and financial risks--if the project will be profitable in the long run. Project managers are concerned with timelines. This aspect of finance will be discussed in the Project Delays section below.

Standardized design

Construction projects on civil nuclear power plants are costly and span several years—seven years on average.[43] (Calculation performed for all civil nuclear reactors completed in the world.) In addition to the financial risks addressed above, the World Nuclear Association lists design change as a major project management risk.[44] When a nuclear energy firm innovates to compete with another firm's designs, it creates barriers to completing the project on time and on budget. Innovation in the nuclear industry necessitates new design plans, new components, new links in the supply chain, and obtaining a new regulatory license.[45] SOEs, and states with majority shares in a nuclear corporation, are better equipped to handle these issues, in part, due to the absence of competing firms. Unlike non-SOE states such as: Germany, Japan, and the United States, who each have several firms producing different nuclear plant designs; SOE states typically have one state-approved design—what is known as a *standardized design*.

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[42] John Rather, "Planning the Fate of a Nuclear Plant's Land", *New York Times*, January 1, 2009, https://www.nytimes.com/2009/01/04/nyregion/long-island/04shorehamli.html.

[43] Note: Seven years on average for civil nuclear projects completed from 1954 to present. Based on author's own research. Data collected from IAEA PRIS and the World Nuclear Association.

[44] "Structuring Nuclear Projects for Success: An analytical framework", *World Nuclear Association*, Sep 2012, pg. 7, table 1, http://www.world-nuclear.org/uploadedFiles/org/WNA/Publications/Working_Group_Reports/Structuring%20Projects%20Report.pdf

[45] Note: These obstacles are also encountered by those revisiting an old design after a decades-long period between builds.

Standardizing design provides several advantages to large-scale nuclear infrastructure projects by reducing license application timelines, increasing project efficiency, and maintaining supply chain efficiency. States have saved time and money by using a standardized design for all their domestic power plant construction projects.[46] Examples of states that use standardized design are France's EDF, Russia's Rosatom, and South Korea's KEPCO.

France built its domestic (non-export) nuclear reactors using standardized design: six CP0 reactors from 1971-1974; eighteen CP1 reactors from 1974-1979; ten CP2 reactors from 1976-1980; twenty N4 REP 1300s from 1977-1984; and four N4 REP 1450s from 1984-1991.[47] Russia's Rosatom also uses a standardized VVER reactor design, which was used extensively during the Soviet area as well as modern and contemporary usage. Russia's VVER design is employed for domestic builds as well as contract builds in other states.[48] From 1967 to the present, Russia has used a standardized VVER reactor designs in Russia, former Soviet Union states, and former Soviet satellite states. A recent example of its use can be found in the Akkuyu nuclear power plant project in Turkey where Russia's Rosatom corporation is constructing three VVER V-509 reactors.[49] Rosatom's director of the Akkuyu project states:

> "The standardized design saves several months of construction – not from the first project, of course…We estimate that construction of the first reactor will take 48 months. Other reactors will be built in just 40 months."[50]—Andrei Kuchumov

Russia, like many other states, builds several reactors of the same design at one site. This reduces the cost of building additional units (land procurement, site approval, etc.), thus achieving economies of scale. Another example of this can be seen at the United Arab Emirate

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[46] Jessica Lovering, Arthur Yip, and Ted Nordhaus, "Historical construction costs of global nuclear power reactors", *Energy Policy*, Vol. 91, (April 2016), 371-382, https://www.sciencedirect.com/science/article/pii/S0301421516300106

[47] IAEA PRIS database. Data collected from IAEA PRIS and the World Nuclear Association.

[48] Note: VVER stand for 'water-water energy reactor'. The 'V' comes from the Russian word for water-- вода, pronounced 'voda'.

[49] Note: A fourth civil nuclear power plant at Akkuyu is also planned.

[50] Andrei Kuchumov, "Rosatom newsletter 2016", Rosatom website, accessed January 21, 2021, https://rosatomnewsletter.com/2016/12/21/evolution-of-vver-reactors/

(UAE) Barakah nuclear power plant. South Korea's KEPCO, who is responsible for the design and construction of Barakah, is using a standardized design to build four APR1400 reactors at one site. South Korea has also paved the way for its APR1400 design to be used in the United States.[51]

Innovation in the nuclear sector comes at a cost—even for experienced SOEs. A first-of-its-kind design project takes longer than subsequent projects. France's EDF is currently building a new design called the European Pressurized Water Reactor (EPR). EDF is concurrently building this design at the Hinkley Point C nuclear power plant in Somerset, UK; Flamanville 3 in Normandy, France; and Olkiluoto 3 on Olkiluoto island, Finland. The first European attempt at the EPR design in Olkiluoto is twelve years behind schedule. [52] Flamanville 3 and Hinkley Point C plants are both behind schedule by seven years. Hinkley Point C, an £18 billion project, was scheduled to supply energy to the grid by 2017; however, it is now projected for completion in 2025.[53] The Olkiluoto will come online in late 2021 and $7 billion USD over budget.[54] Flamanville 3 will load fuel and come online mid to late 2024 and $10 billion USD over budget.[55] This same design reactor was also used at China's EPR project at Taishan 1 and Taishan 2—the first operational EPRs to come online. The successful Taishan nuclear power project was a

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[51] Note: In 2013, South Korea submitted its standardized design to the U.S. Nuclear Regulatory Commission (NRC) for approval. The APR1400 was approved and certified for use in the US in 2019.
"Korean reactor design certified for use in USA", *World Nuclear News*, August 27, 2019, https://www.world-nuclear-news.org/Articles/Korean-reactor-design-certified-for-use-in-USA

[52] Edwardes-Evans, Henry; "Generation at Finland's Olkiluoto-3 reactor delayed 11 months to Feb. 2022", *S&P Global*, August 28, 2020, https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/082820-generation-at-finlands-olkiluoto-3-reactor-delayed-11-months-to-feb-2022

[53] Sudip Kar-Gupta and Susanna Twidale, "EDF warns UK nuclear plant could cost extra $3.6 billion, see more delays", *Reuters*, September 25, 2019, https://www.reuters.com/article/us-britain-nuclear-hinkley-edf/edf-warns-uk-nuclear-plant-could-cost-extra-3-6-billion-see-more-delays-idUSKBN1WA0T0

[54] Henry Edwardes-Evans, "Generation at Finland's Olkiluoto-3 reactor delayed 11 months to Feb. 2022", *S&P Global*, August 28, 2020, https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/082820-generation-at-finlands-olkiluoto-3-reactor-delayed-11-months-to-feb-2022

[55] De Beaupuy, Francois, "EDF Cost Overrun at French Plant Piles Pressure on Nuclear Giant", *Bloomberg*, October 8, 2020, https://www.bloomberg.com/news/articles/2019-10-09/edf-lifts-cost-of-french-nuclear-reactor-by-14-to-13-6-billion?sref=RuowHo8w

joint venture between EDF (30% equity share) and China General Nuclear Corporation (70%). Both reactors were constructed in 2009 and 2010, respectively, and each were completed almost nine years later.[56] This project duration can be compared to China's six-year average construction time for its nuclear plants.[57] Taishan was originally scheduled to be completed in forty-six months, the project experienced delays and was not complete until the 105th month—nearly a five-year delay.[58] Taishan's five-year delay is relatively smaller than the delays experienced by the Olkiluoto project, and it is worth noting that those projects are still ongoing and may yet experience more delays. The answer to why China's EPR project met with different results than the Finnish, French, and UK projects will be discussed further in the proceeding chapter on nuclear regulators.

Experience

In addition to economies of scale and standardized design, knowledge and experience accrued from previous builds will benefit current projects. The French, who are hailed as the pioneers of nuclear standardized design, term this benefit 'return of experience'. (Similar to the term 'lessons learned'.) France's General Director of Energy and Raw Materials, Claude Mandil, explains that the return of experience is greater with states that use standardized designs compared to states that have competing designs.[59] States without nuclear SOEs have competing firms, each with a competing design, which means that the lessons learned during the construction of a Westinghouse-designed plant would not be directly applicable to a competing firm's construction of a Babcock & Wilcox (B&W) or a Combustion Engineering (CE) design. When a state uses the same design to build several nuclear reactors at one site, or at

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[56] IAEA-PRIS databases. Author's own research.

[57] Ibid.

[58] "A Double First for China as Taishan EPR and Sanmen AP1000 Connect to the Grid", *World Nuclear Industry Status Report*, July 2, 2018, https://www.worldnuclearreport.org/A-Double-First-for-China-as-Taishan-EPR-and-Sanmen-AP1000-Connect-to-the-Grid.html.

[59] Jon Palfreman, "Why the French like Nuclear Energy", *PBS Frontline,* October 2008, https://www.pbs.org/wgbh/pages/frontline/shows/reaction/readings/french.html

different project sites with short intervals of time in between, they can use information discovered during the previous plant's construction to avoid pitfalls on the current project. France's joint venture in Taishan has demonstrated that use of return of experience. The then-Chief Executive Officer of Areva (a French predecessor to EDF), Anne Lauvergeon, stated: "All of the lessons learned in Finland are being integrated into construction at Taishan. We are simplifying and improving."[60]

The return of experience concept extends beyond lessons learned from construction project obstacles, or solutions/preventative measures for equipment failures, operator errors, and reactor plant incidents—these all focus on data related to errors and failures. Standardized design also enables states to analyze performance across multiple plants running the same reactor plant design and identify the top-performing plants. These areas of optimal performance across an industry are termed 'bright spots.'[61] States and nuclear firms can analyze what the high performing plants are doing to set them apart from other plants running the same design. Then it is possible to multiply the return of experience, making that knowledge available to other plant managers in order to increase optimalization, reduce construction time, and avoid pitfalls.

Project Delays

In addition to increasing the likelihood of project completion, experience and secure financial backing also reduce the amount of time a project takes. While time is a major factor in all infrastructure projects, this is especially the case with infrastructure projects pertaining to commercial power. The sooner a plant is operable and connected to the commercial electric grid, the sooner it can provide electricity to consumers, generating the profits needed to pay for the debt servicing on the project capital interest.

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[60] Francois De Beaupuy and Tara Patel, "China Builds French Reactor for 40% Less, Areva Says", *Bloomberg,* November 24, 2010, https://www.bloomberg.com/news/articles/2010-11-24/china-builds-french-designed-nuclear-reactor-for-40-less-areva-ceo-says?sref=RuowHo8w

[61] Chip Heath and Dan Heath, *Switch: How to change things when change is hard*. (Waterville, ME: Thorndike Press, 2011), chap. 2.

Project managers are focused on impacts to construction timelines for this reason. Delays to the timeline equates to increases in financing costs. With nuclear infrastructure projects of this size, the amount of interest that is being generated off the capital borrowed will dictate the debt servicing required (your bill each month). The financial livelihood of the project is based on the reactor plant coming online as scheduled, and within budget. Schedule overruns delay the revenue stream used to pay for the debt servicing, which puts the project at risk.

Recent examples of delays impacting project costs can be found in the United Kingdom, and in India. The Hinkley Point C project in Somerset, England, was delayed by six months and left the project overbudget by $687M.[62] This first-of-its-kind EPR design project in the U.K. is experiencing long delays, and exposed EDF to greater financial risk of not realizing profit in the long run. The project is run by a state-owned enterprise—France's EDF. State-owned enterprises are better able to weather bumps in the road (even across three projects--Hinkley Point C, Flamanville 3, and Olkiluoto 3) due to their ability to source funds from the government if need be. The funds need only bolster the SOE long enough for it to begin collecting revenue.

State-owned enterprises are able to weather some bumps in the road because they have access to government funding and favorable terms, whereas private corporations are exposed to more financial risks with access only to their finite financial reserves. The Olkiluoto reactor plant delays caused the French government, a majority owner of Électricité de France S.A. (EDF), to provide billions of dollars to its SOE to ensure the project would have continued.[63] Had EDF not been a state-owned corporation, it would have suffered the same fate

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[62] Francois De Beaupuy and Rachel Morison, "British Hinkley Point Nuclear Plant Delayed with Higher Costs", *Bloomberg*, July 26, 2021, https://www.bloomberg.com/news/articles/2021-01-27/edf-sees-delay-and-rising-bill-in-british-nuclear-plant-project.

[63] "IEEFA Brief: U.K. Government at Risk in Over-Budget Nuclear Project That Stands Incomplete", Institute for Energy Economics and Financial Analysis, October 16, 2017, https://ieefa.org/ieefa-brief-u-k-government-risk-budget-half-finished-nuclear-project-may-never-come-online/

as Westinghouse—they filed for bankruptcy when they ran overbudget and went in debt by $9.8B on the Summer nuclear plant project.[64]

The Kudankulam nuclear power plant project in India is another example. It experienced a delay of 100 months (8.3 years) due to financing and political protests (political risk.) This resulted in the Kudankulam project being over budget by 4.5 billion *rupees*/449.92 *crore*, or $67 million dollars (2020 USD).[65] India's nuclear promoter, state-owned Nuclear Power Corporation of India Limited (NPCIL), while able to weather financial bumps in the road better than private corporations focused on financial risk, also had to navigate political risks.

Role of nuclear regulators

Nuclear regulation authorities are responsible for creating standards for radiation safety and regulating those standards at sites that use radioactive materials—civil nuclear power plants, medical, and industrial facilities. Nuclear regulators also approve nuclear power plant designs, issue licenses, and conduct site inspections to ensure compliance within standards. Regulators are often also responsible for conducting environmental reviews and inspections of nuclear sites to ensure that radiation is not affecting the environment adversely.

State nuclear regulatory bodies are located within different departments or ministries in each state. Some nuclear regulators are organized under economic, environmental, or health departments; however, most nuclear regulatory authorities are housed together with the nuclear promotion agency under an energy department, or an exclusively nuclear department. In the early stages of a state's nuclear program, it is frequently seen for the government agency

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[64] Diane Cardwell and Jonathan Soble, "Westinghouse Files for Bankruptcy, in Blow to Nuclear Power", *New York Times,* March 29, 2017, https://www.nytimes.com/2017/03/29/business/westinghouse-toshiba-nuclear-bankruptcy.html.

[65] Tamil Nadu, "Kudankulam: CAG faults NPCIL for plant delays, cost overruns", *The Hindu,* December 28, 2017, https://www.thehindu.com/news/national/tamil-nadu/kudankulam-cag-faults-npcil-for-plant-delays-cost-overruns/article22289052.ece

responsible for directing nuclear promotion to also regulate its civil nuclear power industry. States with nuclear regulatory bodies that are housed in, or under, the same organization as that of the nuclear promoter, may experience a loss of efficacy in licensing, regulations, and plant inspections. To redress that issue, the International Atomic Energy Agency (IAEA) drafted the IAEA Convention on Nuclear Safety (1994), which advises its members to separate its nuclear regulatory body from the agency responsible for promoting civil nuclear power generation. Article 8, section 2, states:

> Each Contracting Party shall take the appropriate steps to ensure an effective separation between the functions of the regulatory body and those of any other body or organization concerned with the promotion or utilization of nuclear energy.[66]

Prior to this convention, only a few states had separated their promotional and regulatory bodies. In 1974, the United States dissolved the Atomic Energy Commission and formed the U.S. Nuclear Regulatory Commission and the cabinet-level Department of Energy. The U.S. Congress saw the need to separate nuclear licensing from nuclear promotion.[67] Other examples of this separation can be seen in Canada and France. China and Russia have also made movement towards regulatory independence following the IAEA convention. The process for a state's nuclear regulatory agency to attain full independence and authority is sometimes less direct and involves several inter-departmental moves and/or legislative changes. Where IAEA conventions, and best practices from nuclear peers, fail to convince a state to sever the tie between nuclear promotion and nuclear regulation, nuclear disasters have acted as a catalyst for regulatory change.

The aftermath of the nuclear accident at Fukushima-Daiichi caused Japan to restructure their nuclear regulatory framework. The National Diet (Japan's legislature) issued an after-accident investigation report which stated that there was a conflict of interest with the Nuclear

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[66] "INFCIRC/449 *Convention on Nuclear Safety*", IAEA, July 5, 1994, accessed February 8, 2021, https://www.iaea.org/sites/default/files/infcirc449.pdf

[67] "Office of environment, health, safety and security", US Department of Energy, accessed February 8, 2021, https://www.energy.gov/ehss/atomic-energy-act-and-related-legislation

and Industrial Safety Agency (NISA) having been organized within the Ministry of Economy, Trade, and Industry (METI).[68] (The latter being a promoter of Japan's nuclear industry.) Subsequently, the Japanese government reorganized the newly formed Nuclear Regulation Authority (NRA) under the Ministry of the Environment.[69]

The Fukushima-Daiichi nuclear accident became a cautionary tale in the nuclear industry, and states paid close attention to the lessons learned by Japan. The Republic of Korea made changes to their regulatory structure in response to the Fukushima accident.[70] In October of 2011, the Nuclear Safety and Security Commission (NSSC) was established under the office of the President, whereas the nuclear promotion and research and development arms are located under the Prime Minister of South Korea.[71] The nuclear regulatory authorities of Bangladesh, the Netherlands, Turkey, and the United Kingdom also found independence in the years following Fukushima.

The proximity a nuclear regulator has to its state's nuclear promotion arm, as well as the strength of authority that it has been invested with by its government, determines the efficacy of its ability to regulate safety in nuclear plants. Regulatory bodies that are housed with the nuclear promotion arm reduces the efficacy of the regulator. While this proximity can be a driver for shorter approval times in states with SOEs/government's controlling interest in a corporation, nuclear safety and due diligence are put at risk.

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[68] "Fukushima Nuclear Accident Independent Investigation Commission", National Diet of Japan, updated 2012, 40, accessed February 11, 2021, https://www.nirs.org/wp-content/uploads/fukushima/naiic_report.pdf.
Ferguson, Charles D., and Mark Jansson, "Regulating Japanese Nuclear Power in the Wake of the Fukushima Daiichi Accident", *Federation of American Scientists*, (May 2013), pg. 10.
https://fas.org/wp-content/uploads/2013/05/Regulating_Japanese_Nuclear_13May131.pdf

[69] "New Japanese regulator takes over", *World Nuclear News*, September 19, 2012, https://www.world-nuclear-news.org/RS-New_Japanese_regulator_takes_over-1909125.html

[70] "Country Nuclear Power Profiles 2012: Republic of Korea", IAEA, accessed February 11, 2021, https://www-pub.iaea.org/MTCD/Publications/PDF/CNPP2012_CD/countryprofiles/KoreaRepublicof/KoreaRepublicof.htm

[71] "Republic of Korea: Country Nuclear Power Profile", IAEA, 2012, accessed February 11, 2021, https://www-pub.iaea.org/mtcd/publications/pdf/cnpp2012_cd/countryprofiles/KoreaRepublicof/KoreaRepublicof.htm

Nuclear regulation comparison

France, a nuclear exporter, is currently engaged in several concurrent nuclear infrastructure projects across four states using the *same design.* This provides an apples-to-apples comparison for analysis of how the same design is treated by different regulators, and what impact the presence of an SOE has on that process. The focus of this section will be on the time span between the contract bid acceptance/government agreement, to the day the construction broke ground. Once construction begins on a large infrastructure project, delays are more indicative of engineering or supply chain problems—not administrative or regulatory delays.

Et ceteris paribus (all things being equal), when the design approval process across the various states for the standardized EPR design is compared, it will provide data points from which to gauge if any potential advantage exists between SOE states over non-SOE states.

France's European Pressurized Water Reactor (EPR)

The EPR reactor designed by France's EDR has been used in several different countries with varying levels of success. This design was first used at the Olkiluoto nuclear power plant in Finland. (Previously discussed in the standardized design section.) The application-to-construction timeline spanned from 2000 to 2005. The EPR design was submitted to the Finnish Radiation and Nuclear Safety Authority --Säteilyturvakeskus (STUK) in Finland in December of 2000. In 2002, after public debate took place and a Decision in Principle (DIP) was awarded, the Finnish Parliament approved the design concept for Olkiluoto.[72] In 2004, the construction application was submitted; it was approved a year later in 2005.[73] Construction on the project started in July 2005—nearly five years after the administrative process began. (See timeline in Appendix M)

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[72] "Finnish EPR Olkiluoto 3 The world's first third-generation reactor now under construction", AREVA, accessed February 15, 2021, https://inis.iaea.org/collection/NCLCollectionStore/_Public/40/108/40108797.pdf?r=1,

[73] "Nuclear power plant Olkiluoto 3", Finnish Ministry of Employment and the Economy, Jan 26, 2012, accessed February 15, 2021, https://web.archive.org/web/20160304060734/http://www.tem.fi/index.phtml?l=en&s=187

The next place the EPR design was used was in Flamanville, France. The EPR design for Flamanville 3 was approved in October 2004.[74] The French government authorized construction to begin and the project broke ground in December 2007. The administrative and regulatory process in France took one year less than the project in Finland.

The coastal Chinese city of Taishan (100 miles/120 km west of Hong Kong) is home to the world's first operational EPR nuclear power plant. Given the timeline for both Olkiluoto and Flamanville above—which at the time of writing both are not operational—it may be surprising to learn that the Taishan project began five years *after* Finland's EPR project started, and two years after France's own EPR project started. The Taishan project began in December of 2006, and the partnership contract was awarded in 2007.[75] China front-end process took four years from the time it received France's proposal submittal to breaking ground on construction. Construction on the reactors began in 2009 and 2010, respectively, and were completed in 2018 and 2019, respectively.

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[74] "Safety Fears Raised at French Reactor", *New York Times,* July 26, 2010, https://www.nytimes.com/2010/07/27/business/global/27iht-renepr.html
Ann MacLachlan, "EPR wins design approval from French government Paris.", *Nucleonics Week*, October 14, 2004, https://advance-lexis-com/api/document?collection=news&id=urn:contentItem:4DN9-KM70-TWJ6-K2R5-00000-00&context=1516831.

[75] "EDF in China", EDF Press Pack, EDF website, January 2015, accessed February 11, 2021, https://www.edf.fr/sites/default/files/contrib/groupe-edf/espaces-dedies/espace-medias/dp/edf_in_china.pdf
Chen Aizhu, "France's Areva wins $5 billion nuke deal", *Reuters*, February 14, 2007, https://www.reuters.com/article/us-areva-china-nuclear/frances-areva-wins-5-billion-nuke-deal-idUSSP24762820070215?edition-redirect=ca
"Reactor vessel installed at Taishan", *Word Nuclear News*, June 6, 2012, https://www.world-nuclear-news.org/Articles/Reactor-vessel-installed-at-Taishan
"NPP under construction (2008)", China Guangdong nuclear power group website, accessed February 11, 2021, https://web.archive.org/web/20110102175631/http://www.cgnpc.com.cn/n2881959/n3075227/n3075259/n3075392/index.html

A final example of where the EPR design was implemented is in the United Kingdom. This example is considerably more complex than the previous three. Like the previous examples, Hinkley Point C nuclear power plant has the same designer—EDF—but at the onset of the project, EDF acquired controlling interest of the (former) state-owned nuclear energy corporation, British Energy. Financial complications arose during the application phase when a financial partner, the UK energy company Centrica, pulled out its 20% stake leaving EDF to search for other partners.[76] With the project in crisis, EDF turned to its Taishan project partner, the China General Nuclear Power Group (CGN), and offered them the 20% option. This offer was not only for future proceeds from the Hinkley Point C project, but also for future projects planned at Bradwell, Sizewell, and other possible sites.[77] (See Figure 3.) The Hinkley Point C project, much like the Flamanville and Olkiluoto projects, is years behind schedule—seven years at the time of writing. The application and approval process timelines contributed to this delay, as did external events. (See Appendix L: Hinkley Point C timeline graph.)

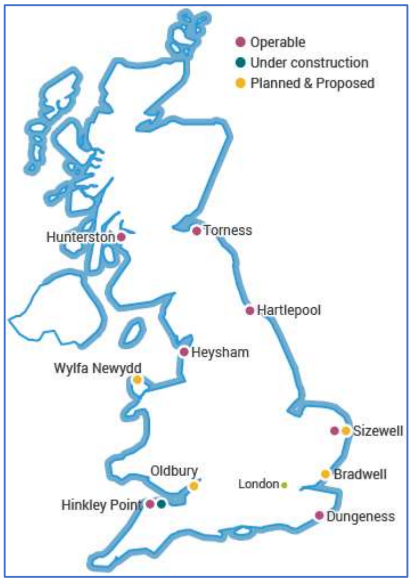

Figure 3- Nuclear Power plant sites in the UK- World Nuclear Association 2021

The application for Hinkley Point C was submitted to the Office for Nuclear Regulation (ONR) in August 2007. The 55,000-page planning application was submitted in October of 2011, and the reactor design was finally approved in December of 2012.[78] The construction at Hinkley Point C began in 2018 and 2019.

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[76] Damian Carrington, "Centrica withdraws from new UK nuclear project", *The Guardian*, February 4, 2013, accessed https://www.theguardian.com/environment/2013/feb/04/centrica-withdraw-new-nuclear-projects.

[77] Simon Jack, "UK government could take stake in Sizewell nuclear power station", *BBC News*, September 16, 2020, https://www.bbc.com/news/business-54181748

[78] "EPR reactor design meets UK approval", *World Nuclear News*, December 13, 2012, https://www.world-nuclear-news.org/NN-EPR_reactor_design_meets_UK_approval-1312127.html.
Luc Torres, "Hinkley Point C timeline: all the key moments", *The Guardian*, July 28, 2016 https://www.theguardian.com/environment/2016/jul/28/hinkley-point-c-timeline-all-the-key-moments

In addition to the examples provided where construction took place, there are also examples of the EPR design not moving past the application stage. EDF (then Areva) partnered with Constellation Energy, a subsidiary of Baltimore-based Exelon, to form the consortium--Areva/UniStar. Areva/UniStar also partnered with AmerenUE, an energy corporation based in Missouri. The intent of these partnerships was to build nuclear plants with EPR design in the United States. Designs were submitted to the U.S. Nuclear Regulatory Commission (U.S. NRC) in December of 2007. In 2015, after eight years of processing, Areva withdrew its application from the US NRC. The withdrawal was due to EDF's complete ownership of UniStar following Constellation Energy Group's departure from the project. (U.S. Federal Law prevents complete foreign ownership of a nuclear plant.) [79]

The regulatory approval process in many states was lengthened in the aftermath of both 9/11 and Fukushima. After 9/11, the IAEA recommended 'aircraft impact' assessments be added to the regulatory process.[80] Plant designers now had to ensure that reactor core temperatures and spent fuel pools would not be affected by commercial aircraft collisions.[81] Following the aftermath of Fukushima, regulatory bodies required extra safety measures to be put in place to mitigate "beyond design basis events" (large-scale natural disaster events that were not considered during plant design.)[82]

The nuclear plant applications for the Finnish, French, Chinese, and British sites all used the same basic French EPR design with power outputs between 1600-1660 MWe.[83] Even with

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[79] "US EPR plans suspended", *World Nuclear News*, March 6, 2015, https://www.world-nuclear-news.org/RS-US-EPR-plans-suspended-0603157.html.

[80] "NS-G-1.5 IAEA Safety Standards Series: External Events Excluding Earthquakes in the Design of Nuclear Power Plants Annex I", IAEA, January 12, 2021, accessed February 12, 2021, https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1159_web.pdf

[81] "§ 50.150 Aircraft impact assessment", U.S. NRC, August 29, 2017, accessed February 12, 2021, https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-0150.html

[82] "Post-Fukushima Safety Enhancements", U.S. NRC, March 11, 2020, accessed February 12, 2021, https://www.nrc.gov/reactors/operating/ops-experience/post-fukushima-safety-enhancements.html

[83] Patricia Brett, "Safety Fears Raised at French Reactor", *New York Times*, July 26, 2010, https://www.nytimes.com/2010/07/27/business/global/27iht-renepr.html
IAEA PRIS

standardized design, plans took a year longer to pass through the application and regulatory processes in Finland than it did in China and France. The United Kingdom approval process took almost three times longer to process than it did in China or France.

Given the apples-to-apples comparison of how different bureaucratic and regulatory processes for the same design, by the same corporation (Areva), it is fair to say that the success experienced by Taishan 1 & 2 projects compared to the delays experienced at both Olkiluoto and Hinkley Point C demonstrate that states with SOEs, or states that have controlling interest in a nuclear energy corporation, are able to navigate through the administrative and regulatory process quicker than states without SOEs or government controlling interest corporations —even on first-of-its-kind plant design and builds.

* * *

Chapter 3: Case Studies—Analysis of ten civil nuclear power states

The argument has been presented in this paper that the absence of state-owned enterprises, or absence of a government's controlling interest in a nuclear corporation, is the leading cause of decline in a state's civil nuclear power program. The case studies will examine factors that contribute to the success or decline of a state's civil nuclear power program—explanatory variables such as economics, legislation, political voice, nuclear regulation, and environmental stewardship. The following case studies are presented in the order each developed nuclear reactor technology: United States, Russia, Canada, United Kingdom, France, Germany, China, Japan, South Korea, and India. The selected states represent ten of the top thirteen states in several metrics—number of operational reactors, number of new reactors under construction, and total nuclear energy production (GWe).[84] Combined, these ten states own eighty percent of the nuclear reactors in the world. The differing level of nuclear technological advancement among the selected states also provides an excellent cross section of the nuclear industry stages—emerging, growing, advanced, as well as phasing out.

Methodology

The data used for case studies was primarily drawn from the IAEA Power Reactor Information System (PRIS). Seven data points (plant name, design, reactor type, net capacity MWe, construction start, first grid connection, and permanent shutdown dates) were collected for each civil nuclear reactor that began construction, completed, shutdown, stalled, or abandoned. Data was gathered from academic journals, foreign newspapers, government web pages, and corporate websites to locate missing data points or provide necessary context. All graphs and charts are the author's own, based on said compiled data.

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[84] IAEA PRIS, https://pris.iaea.org/PRIS/CountryStatistics/CountryStatisticsLandingPage.aspx

Analysis

The construction periods will be broken down differently in each case study according to the significance of the build periods. Different designs will be addressed, as well as explanations for any outliers related to construction times and whether the delays were owing to design, finance, political reasons, protests, or supply chain. Each state's nuclear promoter/engineering firm will be examined to determine if it is an SOE.

Future

The current direction of a state's research and development of nuclear technology will be presented to indicate the future direction of a state's nuclear industry.

Findings

The findings presented will address whether that state was able to take advantage of standardized design, economies of scale, secure financing, return of experience, and able to mitigate adverse effects of delays.

The findings section will also indicate whether a state's civil nuclear power program is advancing, declining, stalled, or phasing out.

Recommendations will be made on how to advance a state's civil nuclear program in the Post-Fukushima era. These recommendations will center on whether or not the state has a state-owned enterprise or not.

* * *

Case Study 1: United States

The United States was the first state to build a nuclear reactor as well as the first state to build and test a nuclear weapon. After the detonation of nuclear weapons at Hiroshima and Nagasaki, and the end of World War II, President Dwight D. Eisenhower delivered the Atoms for Peace speech to the United Nations. The implications of the speech were far-reaching, and the world's nuclear future looked bright. Knowledge of the atom would be harnessed for energy production.[85] The United States, having devoted its earlier nuclear efforts towards nuclear weapons, developed commercial nuclear power years later than both Russia and the United Kingdom. The Atoms for Peace speech prompted the Atomic Energy Commission (AEC) to accelerate the timeline for U.S. civil nuclear power. Shippingport, a reactor previously designed for aircraft carriers, was modified to be a civil nuclear reactor. It was connected to the electrical grid in 1958.[86] American manufacturing giants such as Westinghouse, General Electric (GE), and Combustion Engineering (CE) were among the first businesses to build civil nuclear power plants in the United States.

Within a decade of breaking ground on construction at Shippingport (1954), ten other nuclear reactors were operational. By 1970, a total of twenty-two nuclear power plants had come online. By 1979, the United States had built a total of eighty-one nuclear power plants that supplied electricity to the grid.[87] In the first twenty-five years of civil nuclear power in the United States, the average time to complete a nuclear power plant was 8.16 years.[88] The United States leads the world in both number of civil nuclear reactors (94), and civil nuclear power production.

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[85] Eisenhower, Dwight D., Atom for Peace speech

[86] Note: Shippingport's first connection to the grid was on December 02, 1957 but entered commercial operations on May 26, 1958. Source: IAEA PRIS

[87] IAEA PRIS database. Note: By 1979, fourteen nuclear reactors had been permanently shut down—bringing the total number of operating nuclear reactors in the U.S. down to sixty-seven.

[88] Authors own calculations based on data from IAEA PRIS database.

(809 TWh)[89] The United States' nuclear power output accounts for 30 percent of the world's nuclear power.[90]

The graph below depicts the number of years spent to construct a civil nuclear power plant in the United States, referenced to the year each plant's construction started. The X axis of the graph depicts the year construction started, and the Y axis depicts the length of time each reactor took to complete. The purpose of this graph, and of similar graphs provided in subsequent case studies, is to demonstrate trends in construction times during significant periods of the nuclear power industry's history.

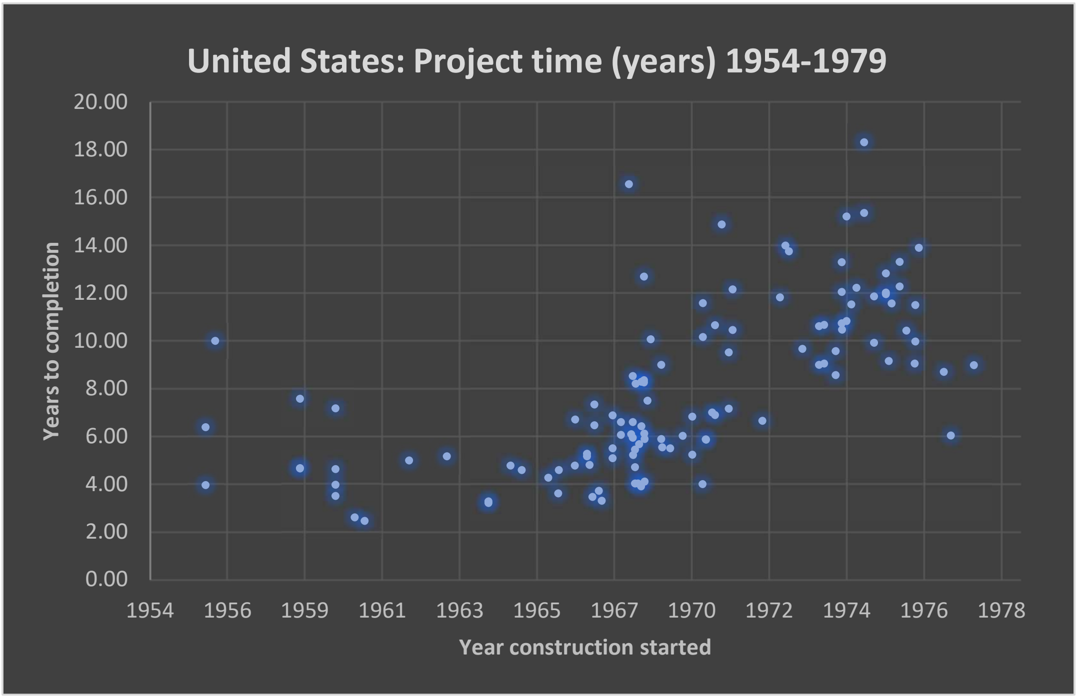

Figure 4- Nuclear power plant construction times 1954-1979. Source: IAEA PRIS database. Author's own graph.

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[89] IAEA PRIS database.

[90] "Nuclear power in the USA", *World Nuclear Association*, January 2021, https://www.world-nuclear.org/information-library/country-profiles/countries-t-z/usa-nuclear-power.aspx#

The graph above depicts an upward trend in construction times over the course of twenty-five years.

The analysis conducted was divided into five groups, each comprised of five-year periods.

1955-1960

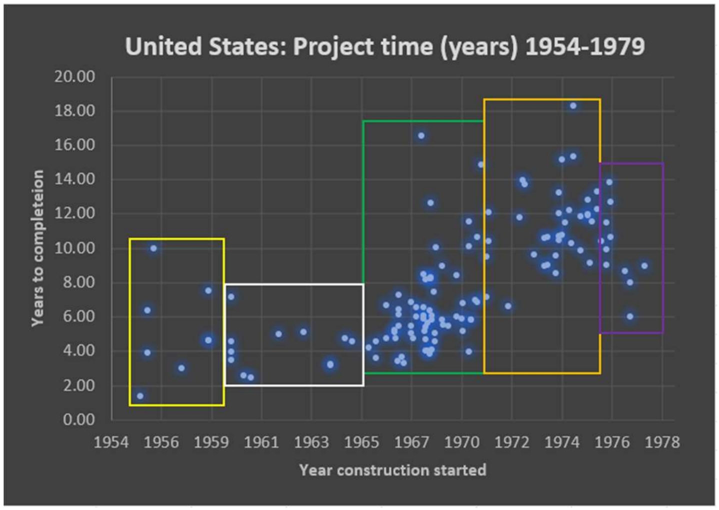

Figure 5-- Periods of civil nuclear power in America

The first period of civil nuclear power growth consisted of the first civil nuclear reactor—Shippingport—and the eight reactors that followed. (Yellow box—first from left in Figure 4.) Most reactors constructed during this period were small reactors ranging in output/size from twelve to seventy-five MWe. Three reactors that began construction at Dresden 1, Indian Point 1, and Yankee-Rowe were built on a larger scale at 197, 257, and 167 MWe, respectively. The average construction time for reactors from this period was 5.06 years.[91]

1960 to 1965

The fifteen plants that began construction during this period (white box--second from left) took an average of 4.15 years with an average design capacity of 545 MWe. General Electric's marketing of 'turnkey' reactors--exemplified by its sale of the Oyster Creek plant in 1964--sparked increased demand for nuclear plants.[92] Environmental concerns about air quality during the 1960s also played a part in energy utilities making the shift towards civil nuclear power.

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[91] Source: IAEA PRIS database; author's own calculations.

[92] "A Short History of Nuclear Regulation,1946-2009", U.S. NRC, accessed February 15, 2021, https://www.nrc.gov/docs/ML1029/ML102980443.pdf, 26-28

1965 to 1970

Civil nuclear power in the United States experienced rapid growth during this five-year period. This ‘Bandwagon Market’ saw fifty-three plants begin construction (green box--third from left). The average plant size was 865 MWe—an increase of fifty-eight percent from the preceding five-year period. The average time to complete construction was 6.17 years—two years higher than the preceding period. The timeline was also burdened on the front-end by an additional six months required to process construction permits. From 1965 to 1970 the construction permitting process extended from twelve months to eighteen months due to a 600 percent increase in licensing and inspection caseloads for AEC staff, while the staff only increased by fifty percent of their previous strength.[93]

Out of the fifty-three plants that began construction, only two plants completed their construction inside this period—R.E. Ginna and Nine Mile Point 1. The remaining fifty-one plants finished construction in the following period—a total of six plants finishing before December 2nd, 1970. The next section will demonstrate the importance of that date to U.S. nuclear power and its impact to nuclear power plant construction timelines.

1970 to 1975

The nuclear plant boom continued its momentum into this period. Fifty-six plants began construction from 1970 to 1975 (orange box--fourth from left). The designed capacity average among the plants increased to 1,070 MWe—an increase of twenty-three percent from the previous period.[94] Plant construction times nearly doubled during this period, taking an average of 11.32 years to finish construction.[95] Nuclear construction costs also rose from $330/kW in 1970 to $1,135/kW in 1975.[96] Several other factors led to these increased construction times.

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[93] “A Short History of Nuclear Regulation, 1946-2009”, US. NRC, accessed February 15, 2021, https://www.nrc.gov/docs/ML1029/ML102980443.pdf, 28.

[94] Source: IAEA PRIS database; author’s own calculations.

[95] Source: IAEA PRIS database; author’s own calculations.

[96] “Is Nuclear too costly?”, *New York Times*, Oct 5, 1975, https://www.nytimes.com/1975/10/05/archives/is-nuclear-too-costly-expenses-soar-as-demand-softens.html.

The year 1970 was a momentous year for environmental protection in the United States. On January 1st, 1970, the National Environmental Policy Act (NEPA) was enacted. It required that federal agencies conduct environmental assessments prior to any undertaking in order to determine the environmental impact that new policies or actions may have.[97] Later that same year, on December 2nd, the Environmental Protection Agency (EPA) was established. Stricter environmental regulations were put in place with the passage of the Clean Air Act of 1970. The 1970 act established the National Ambient Air Quality Standard (NAAQS) which measures carbon monoxide, nitrogen dioxide, sulfur dioxide, lead, ozone, and particle pollution in the atmosphere.[98] Even though a nuclear power plant does not directly emit any of the above gases and particulates during its operation, the construction activities of the plant contribute indirect emissions—carbon monoxide and particulate matter from heavy construction vehicles and workers personal vehicles--that need evaluation during the application phase.[99] The passage of both of these Acts (NEPA and Clean Air), as well as the establishment of the EPA, created more administrative work to be completed by both the nuclear plant builder as well as federal administrators. This increased the length of time to complete a nuclear power plant. The passage of the new environmental laws was not the only contributing factors caused delays for nuclear plants construction timelines.

In April of 1971, a lawsuit was filed in the U.S. Court of Appeals by Calvert Cliffs' Coordinating Committee Inc. *v.* United States Atomic Energy Commission. The citizens group based their lawsuit on the statutes of the newly passed NEPA law, stating that the federal

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[97] [97] "What is the National Environmental Policy Act", U.S. EPA, accessed April 7, 2021, https://www.epa.gov/criteria-air-pollutants/naaqs-table.

[98] Ibid.

[99] "NRC: Generic Environmental Impact Statement for License Renewal of Nuclear Plants (NUREG-1437 Vol. 1) - Part 3", U.S. NRC, accessed April 7, 2021, https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1437/v1/part03.html

government did not abide by the NEPA requirement to assess the environmental impacts of building the Calvert Cliffs nuclear power plant.[100] The NEPA text states:

> "The Congress authorizes and directs that, to the fullest extent possible:
> (1) the policies, regulations, and public laws of the United States shall be interpreted and administered in accordance with the policies set forth in this Act, and
> (2) all agencies of the Federal Government shall --
> …
> (C) include in every recommendation or report on proposals for legislation and other major Federal actions significantly affecting the quality of the human environment, a detailed statement by the responsible official on --
> (i) the environmental impact of the proposed action,
> (ii) any adverse environmental effects which cannot be avoided should the proposal be implemented,
> (iii) alternatives to the proposed action,
> (iv) the relationship between local short-term uses of man's environment and the maintenance and enhancement of long-term productivity, and
> (v) any irreversible and irretrievable commitments of resources which would be involved in the proposed action should it be implemented."[101]

The courts ruled on behalf of the plaintiffs, and the AEC revamped their licensing process to become compliant with NEPA. This resulted not only in delaying new plants from coming online and connecting to the grid, but also delayed construction breaking ground on new plants. Additionally, it delayed timelines of the plants that were already in the middle of construction by mandating new environmental assessments and new standards for the plants to comply with.

In addition to the public's concern over nuclear power following a large fire that took place at the Browns Ferry plant (discussed below), were reports from concerned scientists regarding the potential for nuclear meltdowns of the reactors. Noted nuclear physicists such as Ralph E. Lapp, who worked on the Manhattan Project, wrote a piece in the New York Times describing the dangers of a nuclear meltdown.[102] Lapp discussed a report from the head of an Oak Ridge National Laboratory nuclear safety task force, W.K. Ergen, regarding 'China Syndrome'.[103]

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[100] "Calvert Cliffs' Coordinating Comm., Inc. v. United States Atomic Energy Com. - 146 U.S. App. D.C. 33, 449 F.2d 1109 (1971)"; Lexis Nexis, accessed April 8, 2021, https://www.lexisnexis.com/community/casebrief/p/casebrief-calvert-cliffs-coordinating-comm-inc-v-united-states-atomic-energy-com

[101] "The National Environmental Policy Act of 1969, as amended", Department of Energy, accessed April 7, 2021, https://www.energy.gov/sites/default/files/nepapub/nepa_documents/RedDont/Req-NEPA.pdf

[102] Ralph E. Lapp, "Thoughts on Nuclear plumbing", New *York Times*, December 12, 1971; https://www.nytimes.com/1971/12/12/archives/thoughts-on-nuclear-plumbing.html.

[103] "Oak Ridge National Laboratory Review, Vol 9, No 4, 1976", Oak Ridge National Laboratory website, accessed April 8, 2021, 118, https://www.ornl.gov/sites/default/files/ORNL%20Review%20v9n4%201976.pdf.

China Syndrome was a term used to describe a reactor core meltdown whereby the melted core would burn through containment and burn down into the earth. (Figuratively, all the way to China. Hence the moniker.)[104]

In 1974, the U.S. Congress drafted the Energy Reorganization Act of 1974 in response to public concern over nuclear power plant safety. On January 19th, 1975, the U.S. NRC was established, thus separating nuclear promotion from nuclear regulation. In March of 1975, at the beginning of the NRC's reorganization efforts, disaster struck at a nuclear plant outside of Athens, Alabama at Browns Ferry nuclear plant. Unit 1 of the nuclear plant complex suffered from a fire that destroyed cables related to safety systems. This caused water levels inside the reactor vessel to drop significantly—but not drop low enough to cause a reactor meltdown. The incident caused anti-nuclear sentiments in the United States to rise and prompted the NRC to create stricter fire regulations for nuclear plants. In October of the same year, the ill-timed release of NRC's three-year study on reactor safety—the WASH-1400 report, or the Rasmussen report—submitted findings that nuclear power was safer than being struck by lightning.[105] This finding was not well-received by the general public due to a growing mistrust of the government. (The Vietnam was drawing down, and the government approval rates were low.) Following the accident, the NRC faced more scrutiny from the public and from Congress over reactor safety and emergency core cooling systems (ECCS). Twelve of sixteen plants that began construction in 1970 and 1971 were finished before 1979. The remaining forty-four plants saw their construction times increase by one-and-a-half times, double and triple time, and in the instance of Watts Bar 2, the project was indefinitely suspended and finally completed in 2016 on the project's forty-second year.

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[104] J. Samuel Walker and Thomas R. Wellock, "A Short History of Nuclear Regulation 1946-2009", 32., U.S. NRC, accessed April 8, 2021, https://www.nrc.gov/docs/ML1029/ML102980443.pdf.

[105] "Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants", U.S. NRC October 1975, accessed April 8, 2021, https://www.nrc.gov/docs/ML1533/ML15334A199.pdf; Table 6-3, 112.

1975-1979

Those familiar with civil nuclear power know the importance of the events that took place during this period. The events of the preceding period, along with the extended licensing and construction delays in the early-70s, reduced demand for new nuclear construction permits in the mid-to-late 70s. Half as many nuclear plants broke ground in this period—twenty-two—with an average completion time of 9.76 years and increased in average capacity to 1,182 MWe.[106]

In the early hours of March 28th, 1979, everything changed for the American nuclear industry. The nuclear plant at Three Mile Island suffered a partial meltdown. This was (and still is) the largest nuclear accident to occur in the United States, and at that time, in the world. This accident was caused by a cooling malfunction in the secondary coolant loop, which by design, shut down the reactor automatically. To release built-up pressure in the primary loop, a pressurizer relief valve was opened, but the valve failed open (was stuck in the open position). (See Appendix A or B for system diagram of Pressurized Water Reactors.) The chain of events that followed caused the reactor core to be uncovered (no coolant water covering the fuel rods) and the reactor overheated and caused a partial meltdown. The partial meltdown caused nuclear fuel rods to melt and collect at the bottom of the reactor core vessel as a substance called ‘corium’.[107] (See illustration of a meltdown in Appendix E.) The anti-nuclear sentiment in America had reached its height, and the public had spoken: “No Nukes”. On May 6th, a 65,000-person march on the nation’s capital took place. Massive protests took place in Pennsylvania on May 7th. The largest protest took place in New York City on September 23rd where a “No Nukes” concert festival was held. There were performances by Bruce Springsteen, Carly Simon, Chaka

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[106] Source: IAEA PRIS database; author’s own calculations.

[107] “Three Mile Island accident of 1979: Knowledge and Management Digest”, U.S. NRC, June 2016, 149, accessed February 20, 2021, https://www.nrc.gov/docs/ML1616/ML16166A358.pdf

Khan, Tom Petty, and many other famous musicians. Nearly 200,000 people attended the event.[108]

Following the accident at Three Mile Island, a de facto moratorium on new nuclear plant construction became the norm throughout the United States. Only one state, Minnesota, has instituted a state-wide de jure moratorium. Thirteen states instituted a conditional de jure nuclear moratorium in their state. California and Oregon are among six states that cite inadequate availability of nuclear waste disposal facilities as the reason for a moratorium on new nuclear plants. Hawai'i, Illinois, Massachusetts, Rhode Island, and Vermont require approval from state legislature, while Maine, Massachusetts, Montana, and Oregon require voter approval.[109]

1986

Chernobyl. The world's most significant nuclear accident to date. The impact of the events of April 26, 1986 cemented the anti-nuclear sentiment in the United States as well as other nations. It prevented any plans for new nuclear plants from being constructed in the United States. From 1979 until 2013, the United States did not begin construction on any nuclear power plants.[110] However, it did not deter the majority of plants whose construction was underway from going operational. A total of twenty-five nuclear power plants came online following the events of Chernobyl. All of those twenty-five plants had started construction prior to the events of Three Mile Island. Two plants of note are the Shoreham plant and the Watts Bar 2 plant. The Shoreham plant started construction in New York state in 1972 and finished in 1986

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[108] Robin Herman, "Nearly 200,000 Rally to Protest Nuclear Energy", *New York Times*, September 24, 1979, https://www.nytimes.com/1979/09/24/archives/nearly-200000-rally-to-protest-nuclear-energy-gathering-at-the.html

[109] "States Restrictions on New Nuclear Power Facility Construction ", National Conference of State Legislatures website, May 19, 2017, https://www.ncsl.org/research/environment-and-natural-resources/states-restrictions-on-new-nuclear-power-facility.aspx.

[110] Note: One exception exists—the Watts Bar 2 nuclear power plant that initially began construction in 1973, and in 1985 suspended construction. It resumed construction in 2007, completing the project in 2016. Source: IAEA PRIS

after nearly fourteen years. As soon as it was fully complete, it was shut down due to political protests.[111] Watts Bar 2 plant construction was halted in 1985, and not resumed until 2007. It was completed in 2013, almost forty-three years after it first broke ground. Excluding Watts Bar 2, the average construction time for the twenty-five plants was 13.07 years. Including Watts Bar 2, the average was 14.3 years.[112]

2005-present

In 2005, Congress introduced the Energy Policy Act of 2005 which offered strong incentives that piqued utility companies' interest in constructing new nuclear power plants. This act enabled the Department of Energy (DOE) to provide billions of dollars in federal loan guarantees to energy firms seeking to build nuclear power plants in the U.S. The text of the act also stipulates that the DOE will assist with costs related to project delays in the nuclear license application process or due to litigation preventing the plant from going operational once complete.[113] With the passage of this act, the U.S. entered a period of nuclear industry history referred to as the '*Nuclear Renaissance'*.

From 2007 to 2008, the U.S. NRC received seventeen applications to build new nuclear plants (twenty-seven reactors in total) across the country.[114] Five different nuclear plant designs were submitted to the U.S. NRC for approval during this period: six Westinghouse AP-1000, five GE-Hitachi ESBWR, four Areva EPR, one Mitsubishi APWR, and one GE-Toshiba ABWR. The process to license these first-of-their-kind reactors in the United States was longer than those in the past. The NRC shifted from a two-step license process (construction permit first, then license issuance after plant was completed) to a combined license application (where both are

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[111] John T. McQuiston, "15,000 Protest L.I. Atom Plant; 600 Seized", *New York Times*, June 4, 1979,

[112] IAEA PRIS database. Author's own calculations.

[113] "Section 638, Energy Act of 2005", DOE website, accessed February 26, 2021, pg. 1, 3,

[114] "Combined License Applications for New Reactors", U.S. NRC, accessed February 26, 2021, https://www.nrc.gov/reactors/new-reactors/col.html

done prior to breaking ground) after the passage of the Energy Policy Act of 1992.[115] The result of shifting to combined licenses equates to longer evaluations on the front end of the project, and further delays for any design revisions that are needed during plant construction. Of the seventeen applications submitted above, only seven combined license (COL) applications were approved and issued to applicants; eight applications were withdrawn, and two were suspended.

Endogenous and exogenous events played a very large role in the utility companies' decisions on whether to begin construction on these seven approved projects.

The Nuclear Renaissance was rather short lived. In 2006, advancements in fracking allowed the U.S. to tap into shale and oil deposits. Domestic natural gas production increased for a decade, making the United States the leading producer of natural gas.[116] In 2008, the U.S. oil boom began, and its oil production increased for the following seven years. Natural gas-fired plants became cheaper options than nuclear, and natural gas plants' share of U.S. energy market rose from twenty-two percent in 2006, to thirty-two percent in 2020.[117] In addition to the oil and natural gas booms, a third event occurred that diminished the Nuclear Renaissance—the 'Green tech boom' of 2009. The 'Green tech boom' of renewable technology followed the groundswell of support behind the climate change movement. Wide public support was sparked by Vice President Al Gore's "An Inconvenient Truth" in 2006. In 2009, President Obama called for a carbon tax to combat greenhouse-gas emissions, and $27B to the Department of Energy for: Energy Efficiency and Renewable Energy programs ($16.8B); and Electricity Delivery and

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[115] Note: "Title XXVIII: Nuclear Plant Licensing - Amends the Atomic Energy Act to prescribe conditions under which the NRC shall: (1) issue combined construction and operating licenses; and (2) hold post-construction hearings on such combined licenses." H.R. 776- Energy Policy Act of 1992, accessed February 27, 2021, https://www.congress.gov/bill/102nd-congress/house-bill/776

[116] Robert Rapier, "How the Shale boom turned the world upside down", *Forbes*, April 21, 2017, https://www.forbes.com/sites/rrapier/2017/04/21/how-the-shale-boom-turned-the-world-upside-down/?sh=18b12ef777d2

[117] "Table 1.3, 6.", U.S. Energy Information Administration, March 2021, https://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf

Energy Reliability ($4.5B); and $6B for an Innovative Technology Loan Guarantee Program to provide loan guarantees under the Energy Policy Act 2005.[118] Although the loan guarantees could be applied towards advanced nuclear projects, they were also applicable to solar and wind. This act incentivized energy market investors and utilities to build wind and solar power plants, which financially undercut options for civil nuclear power plants.

2011

The 'Nuclear Renaissance' came to an end on March 11, 2011. A 9.0-magnitude earthquake caused units 1, 2, and 3 at the Fukushima-Daiichi plant in Japan to automatically shut down. The reactor plant system relied on backup power from diesel generators in order to keep the primary coolant pumps operational. Immediately following the earthquake, a tsunami struck the coastline where the Fukushima-Daiichi nuclear plant was located. The seawater reached the diesel generators and caused them to fail. The three reactors did not have the necessary levels of primary coolant, which caused the cores to meltdown.[119]

The impact of this event affected not only Japan's civil nuclear programs, but the rest of the world. The NRC created task forces to evaluate safety measures for U.S. nuclear plants to prevent a Fukushima-level meltdown from happening. The NRC issued orders requiring nuclear plants to:

1. "Obtain and protect additional emergency equipment, such as pumps and generators, to support all reactors at a given site simultaneously following a natural disaster.
2. Install enhanced equipment for monitoring water levels in each plant's spent fuel pool.
3. Improve/install emergency venting systems that can relieve pressure in the event of a serious accident (only for reactors with designs similar to the Fukushima plant)."[120]

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[118] "American Recovery and Reinvestment Act of 2009", 111th U.S. Congress, PUBLIC LAW 111–5—FEB. 17, 2009, 138-140, accessed February 27, 2021, https://www.congress.gov/111/plaws/publ5/PLAW-111publ5.pdf

[119] "Backgrounder on NRC Response to Lessons Learned from Fukushima", U.S. NRC, https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/japan-events.html#accident

[120] Ibid.

At the time of the Fukushima event, there was one singular plant still under construction in the United States—Watts Bar 2. The Tennessee Valley Authority (TVA) stated that following the events of Fukushima, an additional $125M was needed to address regulatory requirements related to additional safety measures as well as cybersecurity concerns.[121] Newer nuclear plant designs—Gen III advanced reactors—have addressed these post-Fukushima concerns by incorporating passive safety systems designed to cool the reactor vessel in the event of power loss. Westinghouse's AP1000 was designed with passive safety measures such as these. The AP1000 design was one of the five aforementioned advanced reactor designs approved by the NRC. Of the seven approved COL licenses that were issued in 2007-2008, only two projects moved forward—Virgil C. Summer Nuclear Generating Station in South Carolina, and Vogtle Electric Generating Plant in Georgia. Both projects were owned by private energy firms, and both projects were adding reactors to sites with existing nuclear power plants. The license applications were applied for in 2008, and both plant design safety and environmental reviews were completed in late 2011. The combined licenses were issued in 2012—almost four years to the date of their initial applications.[122]

The AP1000 reactor design had many safety requirements that had to be approved by the NRC prior to licensing—including new requirements put in place following both 9/11 and Fukushima. The concrete shield building surrounding the reactor containment shell is rated to withstand being hit by an airplane.[123] Its passive safety design incorporates the use of natural circulation, battery powered valve actuation, and compressed gases that move coolant—all independent of the AC power from the grid/reactor. (See Appendix F.) The containment structure for the reactor also features an 800,000-gallon containment cooling tank above the

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[121] "Watts Bar 2 final completion cost approved", *World Nuclear News*, February 4, 2016, https://www.world-nuclear-news.org/NN-Watts-Bar-2-final-completion-cost-approved-0402167.html

[122] "Issued combined licenses or Virgil C. Summer Nuclear station, units 2 and 3", U.S. NRC, accessed January 18, 2021, https://www.nrc.gov/reactors/new-reactors/col/summer.html

[123] "Nuclear reactor gets OK on aircraft impact", *World Nuclear News*, January 24, 2011, https://www.world-nuclear-news.org/RS_Nuclear_reactor_gets_OK_on_aircraft_impact_2401111.html

containment shell capable of gravity draining water to cool the shell, natural air intake to bring in cool air, an option to flood the cavity beneath the reactor vessel, and ancillary tanks with water that can be diverted to the spent fuel pool.[124]

March of 2013 marked the end of the thirty-year break in new nuclear plant construction. Ground broke on the two AP1000 projects—Units 2 and 3 at the Virgil C. Summer nuclear plant in South Carolina and Units 3 and 4 at the Alvin W. Vogtle Electric Generating Plant in Georgia. At the time of writing, the Vogtle plant has completed its pre-commissioning tests and nears completion. The Department of Energy reports that Vogtle Unit 3 is expected to be complete by November of 2021, and Unit 4 is expected sometime in 2022.[125] Its owner, Southern Co., says that although Unit 3 nears completion there remains a possibility that further delays may push its operational date into a ninth year.[126] The Summer plant's timeline was also fraught with delays. Within a year of the Summer plant project breaking ground, it experienced manufacturing delays with its prefabricated modules (steel-reinforced concrete structures CA20 and CA01) being built off site. The delays and extra project costs added an estimated 1.2 billion dollars, raising the price tag to 9.8 billion. [127] More delays followed in 2015, 2016, and culminated with the bankruptcy of the reactor designer and manufacturer, Westinghouse, in 2017.

After a series of one-year delays the Summer project in South Carolina was ultimately abandoned. It joined the ranks of nearly forty other abandoned civil nuclear reactor construction projects from America's past.[128] Abandoned projects like Washington state's Satsop WNP 3 and

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[124] "Westinghouse AP1000 Nuclear Power Plant", Westinghouse corporate website, May 2011, accessed April 7, 2021, https://www.westinghousenuclear.com/Portals/5/Other%20PDFs/Spent%20Fuel%20Pool%20Cooling.pdf

[125] "5 Nuclear Energy Storylines to Watch in 2021", Office of Nuclear Energy, January 18, 2021, accessed April 7, 2021, https://www.energy.gov/ne/articles/5-nuclear-energy-storylines-watch-2021

[126] "Southern says startup delay possible for Georgia Vogtle 3 nuclear reactor", *Reuters,* March 22, 2021, https://www.reuters.com/article/us-usa-southern-co-vogtle-nuclear-idUSKBN2BE1MT

[127] "Nuclear New Build: Insights into financing and project management", NEA & OECD, 226, accessed February 26, 2021, https://www.oecd-nea.org/upload/docs/application/pdf/2019-12/7195-nn-build-2015.pdf, 224.

[128] Sonal Patel, "The Big Picture: Abandoned nuclear projects", *Power*, February 1, 2018, https://www.powermag.com/interactive-map-abandoned-nuclear-power-projects/

WNP 5—one of the largest municipal bond defaults in U.S. history[129]; Shoreham—the only nuclear plant to be fully operational but shut down before providing any power to the grid due to public protests; and Zimmer 1—a plant that was ninety-seven percent complete, but was uncertain it would meet federal regulations and was converted into a coal power plant instead. These are only a few examples of the failed civil nuclear power projects in the United States.[130] The forty abandoned nuclear construction projects; an even larger number of cancelled plans; and the bankruptcy of a former pilar of the nuclear industry, Westinghouse; have strongly reinforced the cautionary tale urging investors not to take a chance on large-scale civil nuclear power.

Future

With the completion of the Vogtle AP1000 project at hand, it may seem as though the U.S. is seeing the light at the end of a long, thirty-year tunnel; however, it is more likely that Vogtle represents the last attempt by U.S. utilities at building a large-scale nuclear power plant. Instead, American civil nuclear power will be envisioned on a much smaller scale. The civil nuclear power paradigm in the U.S. is shifting from large-scale power plants to small modular reactors (SMR). The SMRs are a scalable version of a nuclear power plant and constructed modularly. The NRC defines an SMR as a reactor designed to generate 300 MWe or less.[131] The reactor modules are small with an output capacity of only 77 MWe.[132] (See Appendix G.) The plant is scalable to suit the needs of the population, and the plant can house up to twelve reactor modules to produce a total output of 924 MWe (compared to the 1,117 MWe per unit capacity of the AP1000 reactors being built at the Vogtle plant.) Instead of one or two very large

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[129] Michael Blumstein, “The lessons of a bond failure”, *New York Times*, August 14, 1983, https://www.nytimes.com/1983/08/14/business/the-lessons-of-a-bond-failure.html

[130] “Nearly completed nuclear plant will be converted to burn coal”, *New York Times*, April 9, 2021, https://www.nytimes.com/1984/01/22/us/nearly-completed-nuclear-plant-will-be-converted-to-burn-coal.html

[131] “Small module Reactor (LWR designs)”, U.S. NRC, accessed April 9, 2021, https://www.nrc.gov/reactors/new-reactors/smr.html

[132] “A leader in small modular reactor innovation”, NuScale website, accessed April 9, 2021, https://www.nuscalepower.com/about-us#,

reactors that are typically custom built on site due to their size, SMRs are factory built using a standardized design—which significantly decreases the construction time. NuScale estimates thirty-six months to complete construction once the initial safety concrete is set.[133] The SMR manufacturers can take advantage of economies of scale and are able to offer the units for much less than the standard 4-loop PWR 1,147 MWe reactor plant. The NuScale 924 MWe plant has an estimated cost of $3.2B, which is fifty percent less than the $6.4B estimate for a 4-loop PWR 1,147 MWe (or sixty-two percent less than the $5.16B for a matching 924 MWe).[134] The Oregon-based company, NuScale, already has an SMR reactor design approved by the NRC. The plant layout would be similar to that in Figure 5 below.

NuScale Power Reactor Building

NuScale Power Reactors. ©NuScale Power, LLC. All Rights Reserved

Figure 6: NuScale SMR power plant, Image Source: https://www.neimagazine.com/features/featurethe-nuscale-smr-and-climate-change-7816602/featurethe-nuscale-smr-and-climate-change-7816602-504006.html

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[133] "A cost competitive nuclear power solution", NuScale website, accessed April 9, 2021, https://www.nuscalepower.com/benefits/cost-competitive#.

[134] Ibid.

The NuScale design has multiple passive safety designs. The reactor modules are submerged in a pool of water, and the reactor building is partially below ground. There is also no need for the traditional amount of acreage surrounding the facility, and coolant towers are not required--which may win the approval of some not-in-my-backyard (NIMBY) protesters.

The U.S. Department of Energy's Office of Nuclear Energy awarded $40M to NuScale in a cost-sharing project offered as part of the U.S. Industry Opportunities for Advanced Nuclear Technology Development program.[135] The goal of this DOE program is to promote innovation in nuclear power plant designs by offering funding for early research and development in advanced nuclear technology.

Findings

Standardized design

Since the United States does not have a nuclear state-owned enterprise, its nuclear engineering corporations, manufacturers, and suppliers were not, and are not, able to benefit from standardized design. The U.S. has built forty-five boiling water reactors, eighty-four pressurized water reactor (with two additional PWRs at Vogtle, and two abandoned at Summer), two high temperature gas-cooled reactors, one pressurized heavy water reactor, one fast breeder reactor, and four small experimental reactors. Those reactors were divided amongst ACF Nuclear, Babcock & Wilcox, Combustion Engineering, General Atomics, General Electric, and Westinghouse. While America is known for its strong spirit of independence, competitiveness, and innovation; frequency of design changes made to better compete with the competition has led to a disadvantageous nuclear industry.

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[135] "About us", NuScale website, April 9, 2021, https://www.nuscalepower.com/about-us/history
"Funding Opportunities", Office of Nuclear Energy, April 9, 2021, https://www.energy.gov/ne/funding-opportunities#

Economies of scale

If the reactor designs are split down the middle, or in America's case one-thirds- two-thirds, manufacturing efforts will match. This creates inefficiency in the marketplace. While market equilibrium will be achieved between buyers and sellers, the manufacturers must divide to specialize in one or the other technology, and thereby making the supply chain suboptimal. This inefficiency will manifest in supply chain delays, bottlenecks, and increased cost passed onto the nuclear construction contractor. The cost of nuclear components will rise, in turn increasing the project's financial risk. The increased financial risk will either turn away potential investors, or possibly lead to project failure.

Secure financing

Corporations like General Electric and Westinghouse do not have access to secure financing options from the government to cover the capital costs of constructing a plant. They are, however, able to apply for tax incentives and subsidies set forth in the Energy Policy Act of 2005.[136]

Project delays

The Energy Policy Act of 2005 also offers cost-overrun loans related to NRC licensing delays (e.g., the U.S. NRC license bottleneck of 1965-1970), and political risk/litigation setbacks preventing a completed reactor from coming online (e.g., Shoreham protests).

Inefficient nuclear supply chain also hindered U.S. nuclear efforts. The Virgil C. Summer nuclear plant experienced manufacturing delays with its prefabricated reinforced concrete structure modules built off-site. The supply chain for reactor vessels, steam generators, containment vessels, turbine generators, condensers, heat exchangers and accumulators could not be sourced domestically. The supply chain for those large reactor components had no market in

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[136] Rod Adams, "First New US Nuclear Plant Since 1996, Is Now Commercial", *Forbes,* October 19, 2016, https://www.forbes.com/sites/rodadams/2016/10/19/watts-bar-is-now-commercial/?sh=3d0d32503680

the United States for nearly 30 years. Reactor technology components were sourced from Japan and South Korea.

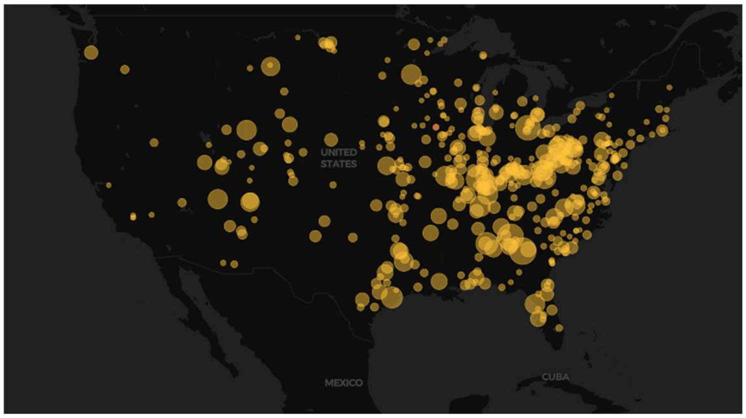

Figure 7-- Coal power plants in the United States in 2000. Source: Carbon Brief, https://www.carbonbrief.org/mapped-worlds-coal-power-plants

Environmental stewardship

Following the establishment of the EPA, the Clean Air Act was implemented to reduce greenhouse gases. One targeted gas was sulfur dioxide emissions from power plants—namely coal-fired. The National Environmental Policy Act (NEPA) requirements were also put in place in 1970. The time required to obtain a construction license, meet EPA/NEPA standards, and meet U.S. NRC requirements collectively increased by several months.

Return of experience

For the Virgil C. Summer and Vogtle projects, lack of ‘institutional skill’/experience in building advanced reactors factored into the projects. This reactor was a first-of-its-kind design, which meant that the domestic labor force was likely not experienced on this reactor design.

Closing

The U.S. civil nuclear power industry has been declining since the events of Three Mile Island. The United States maintains an aging fleet and has only successfully constructed one nuclear plant—Watts Bar 2—in the last twenty years. [137] That feat was only possible through the Tennessee Valley Authority (TVA), which is a Federal electric company—an SOE. The TVA does not receive federal funding, but it does have a reliable electricity customer base to generate revenue.[138]

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[137] “Watts Bar 2: First new US nuclear plant since 1996, is now commercial”, *Forbes*, October 19, 2016, https://www.forbes.com/sites/rodadams/2016/10/19/watts-bar-is-now-commercial/?sh=3d0d32503680

[138] “TVA Statement Regarding Proposal in President's 2019 Budget “, TVA website, February 12, 2018, https://www.tva.com/newsroom/press-releases/tva-statement-regarding-proposal-in-presidents-2019-budget

As mentioned in the *Future* section, small module reactors (SMRs) are the new direction for civil nuclear power in the United States. The scalable plant sizes and passive safety design features make this next generation reactor design the choice for investors and citizens alike. The economies of scale that can be achieved through standardized design, coupled with the significantly reduced construction time, make this an attractive option. Its (estimated) price tag of $3.2B still makes it a megaproject, but now financing is within reach for utility companies. This technology, paired with molten salt energy storage systems, would be highly efficient. Molten salt energy storage is currently only used in conjunction with solar towers but could be reconfigured to achieve the same result with nuclear reactors as the heat source. It would enable the heat (energy) to be created in off-peak hours, and then stored in molten salt tanks. Later during peak hours, that stored heat is connected to a boiler which creates the electricity.

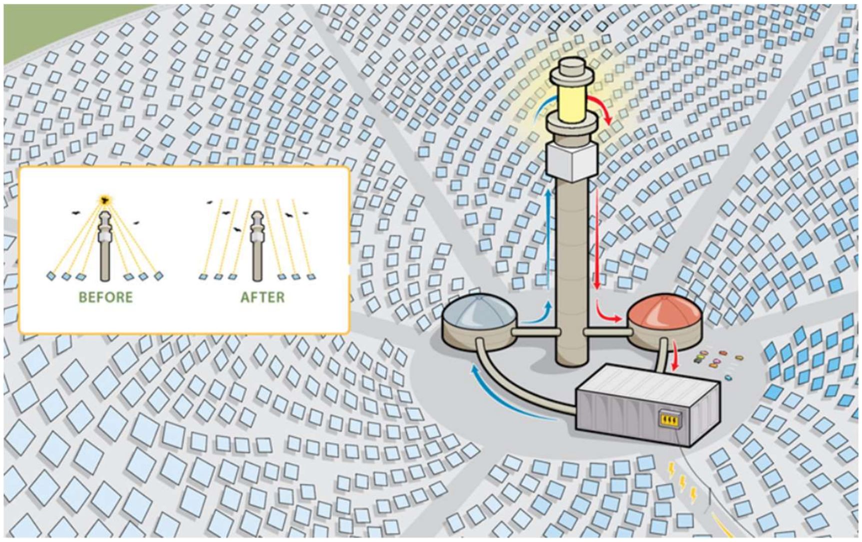

Figure 8-- Solar tower with molten salt tanks and boiler. Source: Eliza Strickland,"Nevada is the home of the world's first utility-scale molten salt facility", Sierra C. https://www.sierraclub.org/sierra/2018-4-september-october/sin-city-lights-dash-molten-salt

The United States could pursue distributed power generation and use SMRs with molten salt energy storage as the power source for microgrids---small isolated electrical grids, much like a college campus, or military base.[139] This approach would be less expensive than large scale 1,400 MWe nuclear power plants and is more efficient from an electricity transmission standpoint (transmission losses from hysteresis and eddy current losses.).

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[139] "Distributed Generation of Electricity and its Environmental Impacts ", EPA website, accessed April 14, 2021, https://www.epa.gov/energy/distributed-generation-electricity-and-its-environmental-impacts,

Case Study 2: Russian Federation

The Soviet Union was the second state to build a nuclear reactor as well as the second state to build and test a nuclear weapon. The F-1 nuclear reactor went critical on December 25th,1946. F-1 was a uranium graphite reactor that was used for plutonium production.[140] Three years later, on August 29, 1949, the Soviet Union tested their first nuclear weapon, RDS-1, at Semipalatinsk. The U.S.S.R. was the first state to connect a nuclear power plant to the electrical grid at Obninsk on June 27, 1954. Russia currently has a total of thirty-eight operational civil nuclear reactors, three new reactors under construction, and nine permanently shutdown reactors.[141] Nuclear energy accounts for 19.7 percent of Russia's energy.

Figure 9-- Construction times for reactors within Russia. Source: Data from IAEA PRIS database. Author's own graph.

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[140] "From the first reactor F1 to the X XI century nuclear power engineering through a gas bridge", IAEA, accessed April 12, 2021, https://inis.iaea.org/search/search.aspx?orig_q=RN:30003604.

[141] IAEA PRIS database.

The graph below depicts the number of years spent to construct a civil nuclear reactor project in Russia, referenced to the year each construction project started. When compared to the graph from the preceding United States case study, the number of power plants represented on the Russia graph may appear sparse by comparison. This graph is only depicting civil nuclear reactors built *inside* of Russia. Once all the nuclear reactors built inside Eastern Bloc states (Soviet republics and satellite states) are accounted for, the graph changes dramatically.

Figure 10-- Combined Russian and Eastern Bloc. Source: Data from IAEA PRIS database. Author's own graph.

1951 to 1992: Soviet-era builds: January 1st, 1951 to December 25th, 1991

During the forty-one years of civil nuclear power in the Soviet Union, a total of one-hundred and three civil nuclear reactor projects broke ground across the Eastern Bloc (Russia, fourteen Soviet Republics, and satellite states).[142] Of that one-hundred and three, only eighty-three civil nuclear reactors were completed during the Soviet Union's existence. The blue line on the graph marks the fall of the Soviet Union. A nearly twenty-year gap in (new) civil nuclear projects

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[142] Source: IAEA PRIS database.

began following the nuclear accident at Chernobyl in 1986 and ended when ground broke on the construction of Beloyarsk 4 nuclear plant project in 2006.Twenty reactor projects were suspended or abandoned due to the fall of the Soviet Union or the events of the Chernobyl disaster.

During this period, reactors were built by the Soviet Union's nuclear promoter--the Ministry of Medium Machine Building. The Soviets preferred the standardized VVER design and had developed fourteen different VVER designs from VVER V-179 to VVER V-1000.[143] During this period, the Soviet Union began construction on a total of seventy VVER design reactors, typically building multiple reactor units at each site—typically four. Out of the seventy projects, all but sixteen projects were completed prior to the fall of the Soviet Union. Of the sixteen uncompleted VVER projects, twelve were later completed by the Russian Federation or host state, and four are currently being constructed by their host state.[144]

The 1970s saw an additional design used to construct nineteen nuclear power plants across the Soviet Union--the RBMK. (РБМК, реактор большой мощности канальный). Of the nineteen, only seventeen finished--eleven of which were in built inside Russia and the others in Lithuania and Ukraine (This design will be discussed below.) The average time to complete an RBMK project was 6.11 years, compared to the 7.05 years for completion of Soviet-era VVER design projects.[145]

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[143] Note: VVER V-179/187/210/213/230/270/320/338/365/392M/440/491/510K/1000. Source: IAEA PRIS database.

[144] Note: The four projects that were not completed: Mochovce 3 and 4 in Slovakia; and Khmelnitski 3 and 4 in Ukraine. Source: "Mochovce 3 & 4 construction", Slovenské elektrárne, accessed April 17, 2021, https://www.seas.sk/mochovce-3-4-npp.
"Construction work resumes on Khmelnitsky units", *World Nuclear News*, November 30, 2020, accessed April 17, 2021, https://www.world-nuclear-news.org/Articles/Construction-work-resumes-on-Khmelnitsky-units.

[145] Source: IAEA PRIS database. Author's own calculations. 7.05 average without/ 7.09 with Bohunice 3 & 4. Note: Bohunice 3 and Bohunice 4 reactors were Soviet designed VVER V-213, but research indicated that they were constructed by Skoda. Skoda was nationalized due to communism making it an SOE from 1945 to 1989.

The average time to complete (all designs of) civil nuclear power plants during the Soviet era was 6.55 years.[146] That average was even lower for domestic builds inside the republic of Russia—5.78. The average time for constructing reactors in other Soviet republics and Eastern Bloc states was 6.63 years.[147]

Chernobyl-- April 26, 1986: Chernobyl, Ukraine

The events of this day were caused by a flaw in reactor design as well as operator error. The Soviet Union had chosen the RBMK design, a Gen II high-power channel type, graphite moderated, reactor. The main differences between the VVER design and the RBMK design is that the RBMK uses a (solid) graphite moderator as opposed to the water used to moderate (slow down neutrons) in the VVER design The RBMK reactors could run on Uranium 238, so no enrichment was necessary, and they were nearly double the MW generation of the VVER V-213 and VVER V-230s that the RBMK design competed against. (Until the VVER V-302 and V-320 designed reactors came online.) The major design difference of the RBMK design is that it does not have a concrete structure over the reactor vessel. It was argued that the RBMK design was so inherently safe, that no concrete structure was necessary. Due to its quicker construction times, ability to use unenriched fuel, and higher MW output, it was chosen for the Chernobyl nuclear plant site.[148]

The nuclear accident at Chernobyl occurred during a turbine test. The Unit 4 reactor was slated for a shutdown on that date, and the turbine test would be conducted concurrently with the shutdown. The reactor power levels were lowered, by procedure, from 1,600 MWt down to 760 MWt to conduct the turbine test. [149] A fault occurred during this process and the coolant

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[146] Author's own calculations based on data from IAEA PRIS database. Note: This figure excludes the reactors finished by the Russian Federation, and Soviet reactors completed by host state following breakup of Soviet Union.

[147] Source: IAEA PRIS database. Author's own calculations.

[148] Serhii Plokhy, *Chernobyl: A history of nuclear catastrophe*, (New York: Basic Books, 2018), 49.

[149] Ibid., 76-86. Note: MWt = Megawatt thermal. This is opposed to MWe, or megawatt electric. It is impossible for MWt to equal MWe due to Carnot Efficiency theory; however, the closer these two figures are determines the efficiency of the plant. (e.g., If a 3,000 MWt coal plant generates 1,000 MWe, it is only 33% efficient, as 2,000 MW of heat is wasted and lost to atmosphere.)

levels indicators notified the operators that they were low. Control rods were adjusted, operator error occurred, and the power level dropped to 30 MWt. This was much lower than the required 760 MWt required for the test (which requires the reactors heat to produce steam.) The operators were able to bring the reactor power back up to a stable 200 MWt, and the turbine test was carried out at this lower level. The problem with carrying the test out at the lower level, is that an isotope called Xenon-135 develops and if the reactor power isn't high enough, it won't burn it off. Xenon 135 isotope is a by-product of the fission of Uranium, and acts like a neutron vacuum cleaner—it absorbs neutrons better than the control rods do. The presence of Xe-135 in the reactor drastically lowers the reactivity—this is called 'Xenon poisoning'—and it may shutdown all reactivity of the reactor. The Chernobyl supervisor ordered the control rods to be removed to bring the power levels back up. The operators removed the majority of the control rods from the activity zone—this is not a normal action. A short amount of time passed during the turbine test, and the previously removed control rods were inserted to lower power levels. It was at that moment that the reactor got out of control. The RBMK model had graphite-tipped control rods (that do not absorb neutrons like the actual control rod), and when they were inserted back into the reactor, they displaced the necessary water (water slows down neutrons). The result allowed more neutrons to start more fissions, which caused a huge spike in reactor activity. The cladding on the control rod cladding melted, which resulted in the control rods not being able to insert and shutdown (SCRAM) the reactor.[150] The superheating of the reactor's coolant water cracked open the reactor vessel and created a steam explosion, the latter sending an immense 200-tonne concrete plate flying through the roof. The end result was a release of nuclear radiation into the atmosphere, the death of two plant workers and twenty-eight first responders (firemen).[151]

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[150] Plokhy, *Chernobyl*, 76-86.

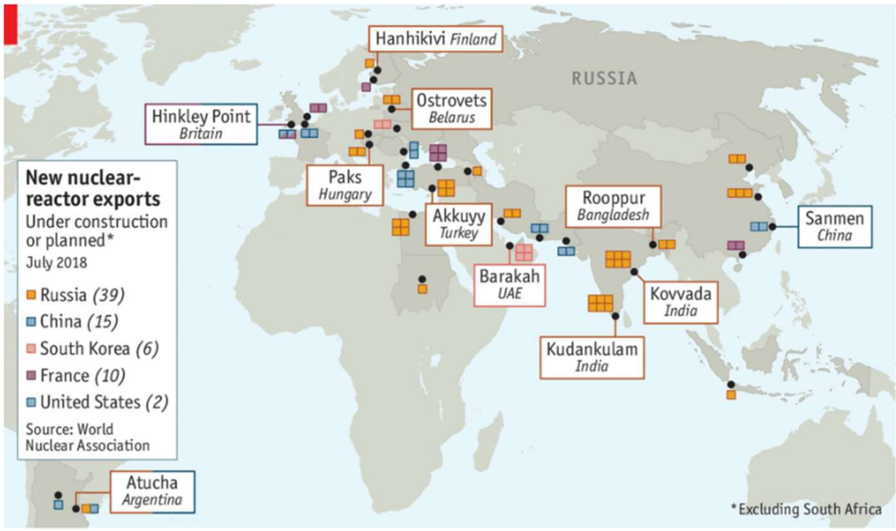
[151] Montgomery and Graham, *Seeing the* Light, 156-157.

Note: Additionally, fifteen children, who were within the radiation affected area, died of thyroid cancer years later.

Another effect of the Chernobyl nuclear accident was felt twenty years later. European states seeking accession (membership) into the European Union (EU) had to permanently shut down any Chernobyl-era RBMK reactors and one particular VVER design—V-230---that was not trusted due to the design not employing a containment structure. [152]

1992-present—Russian Federation

After the fall of the Soviet Union, the Russian Federation was formed and continued its predecessor's mission of nuclear promotion efforts. The Ministry of Medium Machine Building was replaced with the Ministry for Atomic Energy of the Russian Federation (MinAtom) on January 29, 1992.[153] Russia resumed construction efforts on, and completed, five of the suspended reactor projects that had begun construction prior to the fall of the Soviet.[154] Twelve new reactors had also begun construction since 1992. Nine of the twelve reactors have since been completed with an average completion time of 9.5 years. The cause for the higher construction average for this period was due to the Russian Federation taking on builds from its predecessor. Additionally, for the twelve new reactors, their start time predated the Fukushima nuclear accident and design changes to plants had to be made, thus increased construction times.



The Economist

Figure 11-- Nuclear exports. Source: The Economist. See footnotes.

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[152] "Early Soviet Reactors and EU Accession", *World Nuclear Association*, June 2019, accessed April 12, 2021, https://www.world-nuclear.org/information-library/safety-and-security/safety-of-plants/appendices/early-soviet-reactors-and-eu-accession.aspx.

[153] Note: The Ministry of Medium Machine Building combined with the Ministry of Nuclear Power to form the Ministry of Atomic Energy and Industry of the U.S.S.R. in September of 1989. It later became MinAtom on January 21, 1992. Source: C.M. Johnson, *The Russian Federation's Ministry of Atomic Energy: Programs and Developments*, PNNL, February 2000, https://inis.iaea.org/collection/NCLCollectionStore/_Public/31/051/31051595.pdf.

[154] Note: Rostov 1 and 2, Balakovo 4, Kalinin 3 and 4. Source: IAEA PRIS database.

The Russian Federation has built reactors beyond its borders as well. The Russian Federation is the number one exporter of civil nuclear power in the world.[155] As the map in Figure 11 depicts, Russia has been busy in China, India, Turkey, and several other states. The next section will discuss Russia’s state-owned enterprises in the nuclear industry, and Russia’s nuclear export industry.

Russian State-owned enterprises, nuclear regulation, and nuclear export

Russia has four different categories of state-owned enterprises: unitary enterprises, joint-stock companies with government majority ownership, natural monopolies, and state corporations.[156] The State Atomic Energy Corporation Rosatom, or Rosatom, was created by President Putin on December 1, 2007 by federal law and named a state corporation.[157] Article 2 of this federal law granted Rosatom with the following responsibilities and authority:

> “1) …the State Atomic Energy Corporation "Rosatom" given authority on behalf of the Russian Federation to exercise public administration of use of atomic energy, public administration when implementing the activities connected with development, production, utilization of nuclear weapon and military nuclear power plants and also normative **legal regulation in the field of use of atomic energy**; [emphasis author’s]
>
> 2) the state inventory of special raw materials and the sharing materials - set of the material values which are in federal property intended for ensuring steady functioning and development atomic power industrial and nuclear weapon complexes of the Russian Federation, defensive needs and for use in emergency situations, and also as the instrument of state regulation of the prices of special products;
> …
> 6) special reserve funds of Corporation - the financial resources centralized by Corporation created due to assignments of the companies and the organizations operating especially radiation dangerous [sic]…”[158]

Initially, Rosatom was responsible for both promoting and regulating civil nuclear power. In 2004, Russia’s nuclear regulation and nuclear promotion were separated during restructuring

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[155] “Russia leads the world at nuclear-reactor exports”, *The Economist*, August 7, 2018, https://www.economist.com/graphic-detail/2018/08/07/russia-leads-the-world-at-nuclear-reactor-exports.
[156] “Russia Country Commercial Guide: Investment Climate Statement”, U.S. International Trade Administration, accessed April 10, 2021, https://www.trade.gov/knowledge-product/russia-investment-climate-statement.
[157] “Federal Law of the Russian Federation of December 1, 2007, No. 317-F3”, CIS Legislation, accessed on April 13, 2021, https://cis-legislation.com/document.fwx?rgn=20174.
“Presidential Decree of the Russian Federation of March 20, 2008, No. 369”, CIS Legislation, accessed on April 13, 2021, https://cis-legislation.com/document.fwx?rgn=21817.
[158] “Federal Law of Russian Federation”

and Rostekhnadzor, a nuclear regulatory body was created. It was initially housed under the Ministry of Natural Resources and Environmental Protection, but was later moved due to proximity to nuclear promotion.[159] In 2010, Rostekhnadzor transferred to the Federal Service for Environmental, Technological, and Nuclear Supervision in the where it became a federal service, where it achieved independence from nuclear promotion.[160]

Atomstroyexport was established as a subsidiary of Rosatom and is responsible for constructing nuclear power plants overseas.[161] Rosatom is currently the number one nuclear exporter in the world. From 2007 until present they have begun construction on fifteen civil nuclear power projects (in addition to the eleven civil nuclear reactors being constructed domestically).[162] They have completed seven nuclear power plants and completed an eighth nuclear power plant project in Iran (previously abandoned by Germany in 1979—Iranian Revolution).[163] Russia is successful at overseas reactor construction for several reasons.

First, Russia's export arm uses a build-own-operate (BOO) project delivery mechanism for its overseas efforts. Taking a step back to explain project delivery mechanisms is warranted. A project delivery mechanism answers the following questions: who pays for the project, how do they pay for the project, who does the design, who does the building, who is responsible for maintenance, who collects applicable rents, and who owns it after it is completed. There are many different types of project delivery mechanisms: BOO, BOT, BOOT, PFI, PPP, EPC, LSTK, and various other combinations. The few that would be helpful to know for the case studies are:

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[159] "NTI Federal Service for Environmental, Technological, and Nuclear Supervision (Rostekhnadzor)", NTI, accessed February 9, 2021, https://web.archive.org/web/20110510173316/http://www.nti.org/e_research/profiles/Russia/Nuclear/government/rostekhnadzor.html

[160] "Federal Service for Environmental, Technological, and Nuclear Supervision", The Russian Government, accessed April 11, 2021, http://government.ru/en/department/212/events/.

[161] Note: The Atomstroyexport name will typically only be seen in official documents or plant designs. 'Rosatom' is widely used in its place in media coverage and academic works. 'Rosatom' will be used in the same manner in this paper.

[162] IAEA PRIS database.

[163] "Iran takes control of Bushehr nuclear plant", *France 24*, September 9, 2013, https://www.france24.com/en/20130923-iran-gains-control-bushehr-nuclear-reactor

BOO—build, own, operate; BOT—build, operate, transfer; BOOT—build, own, operate, transfer; and LSTK—lumpsum turnkey. (See Appendix N for a list and definitions). For now, the focus is on Russia's build, own, operate (BOO).

A build, own, operate (BOO) project delivery mechanism is a very interesting incentive for nuclear infrastructure. Russia is offering reactors to states without the capability to build it, without the experience of how to operate it, and offering loans to states that cannot afford it. For example, Russia offers to build a reactor for Turkey for $5B (2020 USD). Russia will build it, and once it is complete, Russia will *own* it. Russia will staff it with experienced personnel, and they would likely begin training local personnel in the plant to work alongside Russian personnel. Russia will sell the electricity generated to the host state, at a contracted rate stipulated in the BOO contract. That is the end of the contract stipulations. While a contract that entails a foreign nation building a nuclear plant on another state's soil and keeping it may not appeal to many states, it does to those who cannot afford a nuclear reactor. Interested states may view it from a strictly economic viewpoint, an electricity scarcity viewpoint, or perhaps global warming/carbon emission/air quality is a priority for their citizens.

The other important models for this paper are BOT, BOOT, and LSTK. Build, operate, own transfer (BOOT) is very similar to the BOO that Russia is offering. The key difference is that after a specified period of time of Russia operating the plant and collecting rent (revenue from electricity sales), it would transfer back ownership to the host state. The period where Russia would be able to charge rents, the concession, is negotiable, but typically it would be as long a mortgage—30 years. This enables Russia to recoup the money they lost in future value (FV), (future value is the how much your money would be worth in a year given an interest rate.) BOT is a shorter version of BOOT and stipulates a shorter concession period before transferring the plant back to the host state. And LSTK, or lumpsum turnkey, is similar to buying a car with cash. A state purchases the nuclear plant and is immediately turned over the keys and is expected to staff it and maintenance it themselves.

Atomstroyexport’s 2030 goal was for its export arm to increase its foreign sales to account for half of Rosatom’s revenue stream. They hit that mark four years ago and have since retargeted for sixty-six percent by 2030.[164]

Future

Russia’s goals for the future are geared toward mobile nuclear power, distributed power, and increasing foreign reactor sales. Russia has constructed two ships that each have two 35 MWe reactors on board—Akademik Lomonosov 1 and 2. (These were counted among the nine reactors completed from 1992 to present.) The purpose of these floating nuclear power plants is dock and provide power to far eastern Russian cities in the Arctic. Another maritime goal is centered on trade through the Northeast and Northwest Passages market. Global warming has melted a significant amount of ice in the Barents Sea, thus making it easier for ice-breaker ships to make the journey through the ice. Rosatom has been given the mandate to manage the Northern Sea route.[165] Russia developed ships for just the occasion—nuclear powered icebreakers (like the one in red to right.)

Figure 13-- Akademik Lomonosov. Source: Lev Fedoseyev, "Russia's floating nuclear power plant arrives at far east base", RadioFreeEurope Radio Liberty, September 14, 2019, https://www.rferl.org/a/russia-s-floating-nuclear-power-plant-arrives-at-far-east-base/3016

Figure 12--Yamal: a nuclear-powered icebreaker, Cool Antarctica, https://www.coolantarctica.com/Antarctica%20fact%20file/ships/Yamal_ice_breaker.php

The third objective is developing small modular reactors (SMRs) in remote towns in Far Eastern Russia. There is already a chosen location at Ust-Kuyga, Yakutia. The 40-50 MWe SMR design

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[164] “Russia looks to 2030”, *Nuclear Engineering International*, May 26, 2020, https://www.neimagazine.com/features/featurerussia-looks-to-2030-7940206/#.

[165] “Rosatom will manage Russia’s Northern Sea Route”, *Artic Today*, January 2, 2019, https://www.arctictoday.com/rosatom-will-manage-russias-northern-sea-route.

reactor will replace coal and diesel plants in Yakutia.[166] If successful, Russia will construct more distributed land based SMRs in Far East Russia.

Findings

State-owned enterprises

The future of Russia's nuclear program is very bright. Russia's methodical, strategic approach is paying dividends—and not just in the long run. Russia's ability to use its SOEs, not only Rosatom, but the hundreds of other SOEs in various industries to achieve its long-term strategic goals is a great example of Lenin's 'Commanding Heights' concept. Vladimir Lenin's speech for his New Economic Policy included a discussion on Commanding Heights as they applied what would now be termed SOEs.[167] The Commanding Heights principle is that the government could stand up on top of a hill and look down at all the organizations in its control and move them in concert to achieve the governmental and societal goals. This is referred to as 'state control'. In 2007, Russia was able to advance its civilian nuclear power goals by having one of its joint-stock companies (an SOE), Eximbank, offer Belarus a $2B credit line towards obtaining two VVER V-491 reactors technology. [168] Russia is also able to control other state corporations that can assist Rosatom in their builds—banks, construction firms, logistics, raw materials, etc.

Strategic plans would be much harder to accomplish if Russia's governmental system had Presidential Term limits like the U.S. Russia's sitting president cannot have more than two consecutive term limits. The result is that President Putin and Vice President Medvedev have been swapping back and forth as president and vice-president that were able to establish a period of consistent leadership—a dynasty, so to speak. A power vertical dynasty with access to

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[166]"Rosatom to begin work on land-based SMR", *NEI*, January 4, 2021, https://www.neimagazine.com/news/newsrosatom-to-being-work-on-land-based-smr-8436408#.

[167] Lin, et al., "State-owned enterprise in China: A review of 40 years of research and practice", *China Journal of Accounting Research*, February 15, 2020, https://reader.elsevier.com/reader/sd/pii/S1755309119300437.

[168] "Belarus nuclear plant gets Russian credit", *World Nuclear News*, Jun 12, 2007, https://www.world-nuclear-news.org/Articles/Belarus-nuclear-plant-gets-Russian-credit

Russia’s commanding heights is a powerful combination, one that should see Russia accomplishing even more of its strategic energy goals ahead of time.

Standardized design

Russia was able to take advantage of standardized VVER designs. With exception of the floating reactors, all the designs were from the VVER-V392/V491/V320, as Chernobyl had eliminated any thought of constructing new RBMK design reactors. In using only one baseline design with variations to account for slightly higher or lower MWe, Russia was able to benefit from return of experience on constructing two of each of the designs above over the course of thirteen years.

Project delays

By simply looking at the Soviet-era construction time average (6.63 years) to the current construction completion time averages (9.5 years), it is a little alarming—but only because of Russia’s long, consistent track record of completing plants in six year and seven-year mark. The

Environmental Stewardship

Russia is doing well in this department from a greenhouse-gas emission point of view. Russia does not operate many coal power plants, has natural gas plants, and a steady amount of nuclear power. Russia is currently using floating nuclear plants to power towns in Far East Russia, and developing sites for SMRs in Far East to reduce reliance on coal factories.

Long-term strategic plan

Russia’s “Development of Russia’s Atomic Power Complex from 2007-2010, and 2015” have stated, strategic goals for the direction of the Russian nuclear industry.[169] Russia stated that goals were to develop the capacities of the reactors, renovate fuel cycle capabilities, develop better management of spent fuels, and develop innovative technologies. The scope and intent of this plan is very similar to China’s ‘Five Year Plan’.

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[169] Alexander Bychov, “The Strategy of Nuclear Energy Developments in Russia”, *Internationalization of the Nuclear Fuel Cycle,* (Washington: National Academies Press, 2009), 135.

Closing

Russia could benefit from using one design more prolifically (the new VVER V1200)—as they did with the VVER V-320 design in the early 1980s. This would increase the speed of construction, and free up labor force and capital to pursue their stated goal of capturing a larger share of foreign nuclear reactor builds. They have some competition at their heels—China and now Korea. Russia is trying to spread out Rosatom too thin, by assigning them to develop rare earth magnets turbine. With Rosatom being assigned the mandate of managing the Northern Sea, managing domestic and foreign builds, as well as manage the floating nuclear plants and the SMR plans for the Far East of Russia, the ball will get dropped somewhere. Rosatom should focus on domestic builds and export builds (Atomstroyexport). The Northern Sea project should be turned over to another department, as should the rare earth batteries. Just because the ice breakers are nuclear powered, does that mean that they cannot be the wards of the Coast Guard or another ministry.

Russia is using the advantages of SOEs to a high level and seeing the results of it. Russia needs to focus on what they are best at, and that is building large-design capacity VVER plants safely and on schedule. Then wait for opportunities like the setbacks at Olkiluoto, Flamanville, and Virgil C. Summer, and then make public comparisons to demonstrate how safe the how fast the VVER V1200 design can be completed in. That may not win any clients on first pass, but when word spreads in the industry/media as to how quickly and efficiently the new design is compared to the VVER V-392, V-430, or V-491 cards, the clients may opt for the second/third reactor units to be built by Rosatom. Small modular reactor technology as well as floating technology should still be developed as necessary for exports purposes.

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Case Study 3: Canada

Canada was the third state to build a nuclear reactor. In 1943, Canada and the United Kingdom collaborated with the United States in the Manhattan Project during World War II. The three parties freely exchanged scientific knowledge of nuclear technology with one another. In 1944, scientists from Canada and the United Kingdom, with the assistance of France, worked on the design for the Zero Energy Experimental Pile (ZEEP) reactor. Within sixteen months, Canada's first nuclear reactor went critical on September 5, 1945.[170] The NPD nuclear reactor began construction in 1958 in Rolphton, Ontario. Its design was a Pressurized Heavy Water Reactor (PHWR) had a design capacity of only 17 MWe, and it was operational in the summer of 1962. Canada has built twenty-four additional civil nuclear power reactors since the NPD reactor. At present, nineteen nuclear reactors are operational, and six are permanently shutdown. Nuclear power plants produce 14.9 percent of Canada's electricity.

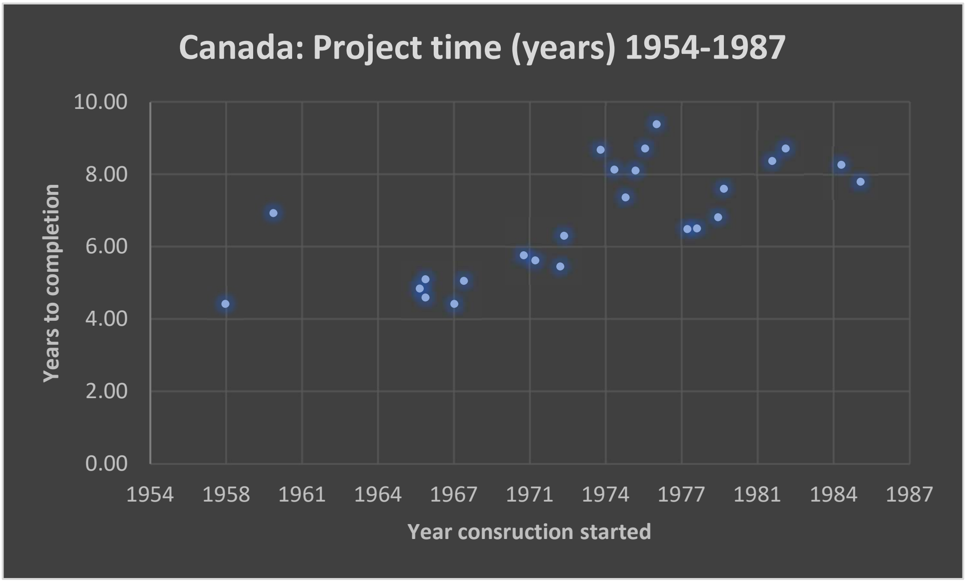

Figure 14-- Canada nuclear reactor construction time. Source: Data from IAEA PRIS database. Author's own graph.

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[170] "Canada's historical role in developing nuclear weapons", Canadian Nuclear Safety Commission, May 28, 2012, accessed April 21, 2021, https://nuclearsafety.gc.ca/eng/resources/fact-sheets/Canadas-contribution-to-nuclear-weapons-development.cfm#.

Canada’s average construction time is 6.78 years. That is one year shorter than the United States’ average, and on par with Russia’s Soviet-era average. The reason that Canada was able to achieve such short construction times was due to the creation of the Atomic Energy of Canada Limited (AECL) in 1952. The AECL is a ‘Crown corporation’, or a state-owned enterprise (SOE).[171] Canada’s reactor fleet is very homogenous—both in design, and location. Canada’s presents the best case study of standardized design. Like something out of the pages of Adam Smith’s *Wealth of* Nations, Canada specialized in making one design--CANDU. Twenty-four of the twenty-five reactors built were CANDU PHWR designs, and the singular outlier, Gentilly 1, was an experimental heavy water light water reactor (HW BLWR) design, which ultimately was not preferred over the PHWR design.

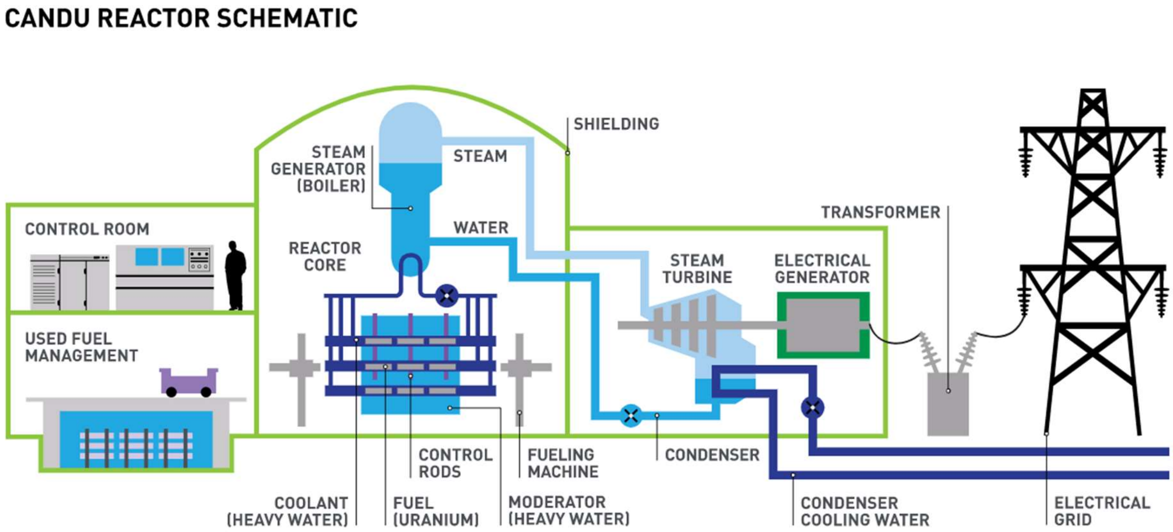

Figure 15-- CANDU design, Canadian Nuclear Association, https://cna.ca/reactors-and-smrs/how-a-nuclear-reactorworks/

The CANDU design is similar to that of a PWR except that reactor vessel has pressure tubes running horizontally through it (See Figure 15 or Appendix M), and the *moderator* is full of *heavy water*, also called deuterium, D_2O. (Eighty percent of reactors are light water reactors—which use ordinary water, H_2O.) The importance of heavy water is due to the moderator. A moderator

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[171] “1944-2019 AECL Historical Timeline”, AECL, accessed April 08, 2021, https://www.aecl.ca/aecl-historical-timeline/

is a water or solid (e.g., graphite) that is used to slow down the *fast neutrons* produced from the splitting of Uranium atoms in the reactor. The neutrons have an atomic weight of 1 atomic mass unit (amu). Water has Hydrogen atoms—two of them, and a Hydrogen atom also has the atomic mass of 1 amu. The fast neutron, which is going too fast to stop and interact with Uranium atoms to produce additional fissions (macroscopic cross section rate), has a very good chance of hitting a Hydrogen atom in the water molecules abundant in the moderator (water in the reactor vessel). The collision between the Hydrogen atom and the neutron is elastic---meaning that the moving neutron hits the Hydrogen atom like a cue ball hits an 8 ball at rest, transferring momentum to the 8 ball. When this occurs, the neutron becomes a *slow neutron*, and now it is able to interact with the Uranium and cause a fission—which in turn cause more neutrons to split and the process starts over exponentially. (This is a chain reaction.) The reason why *heavy water* is used as opposed to *light water* is that light water has the ability to capture neutrons, whereas heavy water does not.

The other benefit of the heavy water reactor, as mentioned earlier in this paper, is that it can used 'natural' or un-enriched Uranium. Canada's AECL preferred this for cost reason as well as the fact that Canada has Uranium native to their soil.[172] (See Figure 16)

Figure 16-- Uranium mining and reactor locations, World Nuclear Association (see footnotes below.)

The Uranium mining takes place in Saskatchewan province. Canada was the world's number one Uranium

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[172] "Uranium in Canada", *World Nuclear Association*, updated January 2021, accessed April 12, 2021, https://www.world-nuclear.org/information-library/country-profiles/countries-a-f/canada-uranium.aspx

producer in the world before Kazakhstan surpassed them in 2009.[173]As mentioned earlier, the reactors were almost entirely geographically based out of Ontario province. Gentilly 1 and 2, are based in Quebec province; and Point Lepreau is based in New Brunswick province.

Nuclear regulation

The Atomic Energy Control Act was passed on October 12, 1946, creating the Atomic Energy Control Board (AECB).[174] Canada's government declared that "production, use and application of nuclear energy" was subject to its legislative control.[175] The AECB regulated nuclear activities until 2000.

In 2000, Canada established a new, independent, regulatory body following the passage of the Nuclear Safety and Control Act of 1997—the Canadian Nuclear Safety Commission (CNSC). [176] The CNSC states that this piece of legislation focuses on: "health, safety, national security and environmental protection—updated legislation was required for more explicit and effective nuclear regulation."[177]

Nuclear exports

Canada has exported ten CANDU heavy water nuclear reactors, as well as the earlier mentioned CIRUS research reactor to India.[178] The average construction time for completing the CANDU reactors overseas is 7.93 years. This average was affected by two outliers, both of which were projects based in Romania. Romania's economy was impacted by its transition to a

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[173] "Uranium in Canada", *World Nuclear Association*

[174] "Canada's nuclear history", Canadian Nuclear Safety Commission, accessed April 15, 2021, http://nuclearsafety.gc.ca/eng/resources/canadas-nuclear-history/index.cfm.

[175] Canadian Nuclear Safety Commission, *Canadian National Report for the Convention on Nuclear* Safety, Sixth Report, (Ottawa: Government of Canada, 2013), 25, https://www.iaea.org/sites/default/files/canada_6thnatlreport.pdf

[176] "The Commission", Canadian Nuclear Safety Commission, accessed February 5, 2021, http://nuclearsafety.gc.ca/eng/the-commission/index.cfm/.

[177] Canadian Nuclear Safety Commission, *Canadian National Report for the Convention on Nuclear* Safety, 25.

[178] IAEA PRIS database. Note: Canada has also exported its CANDU reactor to India, but it was not used for civil power.

free-market economy and resulted in long delays.[179] Without the largest outlier (24.1 years for Cernavodă 2 to be completed), that average is lowered down to 6.14 years.[180]

Privatization and Refurbishment

Canada's nuclear fleet is aging, and units are coming offline with no new nuclear units planned to replace them at present. There are, however, plans in place for a select group of reactors with good performance records to undergo refurbishment to extend their life and update their safety features.[181] To date, five reactors have been refurbished: Pickering Unit 1 and 4, Bruce A Unit 1 and 2, and Point Lepreau.[182]

In October of 2011, Canada sold its CANDU reactor and designer, AECL, to the engineering firm SNC Lavalin for $15M.[183] The firm had worked with AECL on a joint construction project plans and was looking to expand into the nuclear reactor market.[184] Canada was looking to divest itself of this Crown corporation due to AECL's corporate losses of $493M (2011 CAD) accrued over the preceding two years, as well as cost overruns on several projects. The cost overruns were experienced on reactor plant refurbishments conducted at Point Lepreau ($1B CAD on a $1.4B CAD) and Bruce A ($2B CAD); the overseas project at Wolsong in South Korea also went over time and over budget.[185] (It should be noted that Canada did not

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[179] Daniela L. Constantin, et al., "The Romanian Economy from Transition to Crisis. Retrospects and Prospects", *World Journal of Social Sciences* 1, no. 3. (July 2011): 155-171. https://www.researchgate.net/publication/251573467_The_Romanian_Economy_from_Transition_to_Crisis_Retrospects_and_Prospects

[180] IAEA PRIS database. Author's own calculation.

[181] "Refurbishment and life extension", Canadian Nuclear Safety Commission, accessed April 15, 2021, https://nuclearsafety.gc.ca/eng/reactors/power-plants/refurbishment-and-life-extension/index.cfm.

[182] Ibid.

[183] "AECL sold for $15M to SNC-Lavalin", *CBC News*, June 29, 2011, https://www.cbc.ca/news/business/aecl-sold-for-15m-to-snc-lavalin-1.985786#.

[184] Zach Dubinsky, "AECL woes could spell end of Canada's reactor business", *CBC* news, March 30, 2011, https://www.cbc.ca/news/canada/aecl-woes-could-spell-end-of-canada-s-reactor-business-1.989545.

[185] Point Lepreau: "Point Lepreau costs could hit $3.3B, PMO memo says", *CBC news*, July 11, 2011, https://www.cbc.ca/news/canada/new-brunswick/point-lepreau-costs-could-hit-3-3b-pmo-memo-says-1.1344861.
South Korea: "Korean Candu restarts after refurbishment", *World Nuclear News*, July 29, 2011, https://www.world-nuclear-news.org/C_Korean_Candu_restarts_after_refurbishment_2907114.html.

have to pay for the entire refurbishment project—just portions of the overruns that exceeded the contracted amounts.) There are many nuclear plants within Canada's aging fleet of CANDU reactors that will need refurbishment in the future, but it will be an uphill battle to convince the public that refurbishment projects are economically worth it.[186]

Environmental

As far as energy generation goes, Canada is very environmentally friendly. Due to their geography, their energy generation mix is sixty percent hydro. Coupled with their fifteen percent share nuclear power, the remaining twenty-five percent share is divided up between coal (7 percent), gas and oil (11 percent), and non-hydro renewable (7 percent).[187]

There is an active resistance to civilian nuclear power in western Canada—in British Columbia. The environmental group Greenpeace is headquartered in Vancouver and has actively worked towards turning public opinion against nuclear energy in that province. The British Columbia government has legally prohibited both the operation of nuclear power plants and uranium mining.[188]

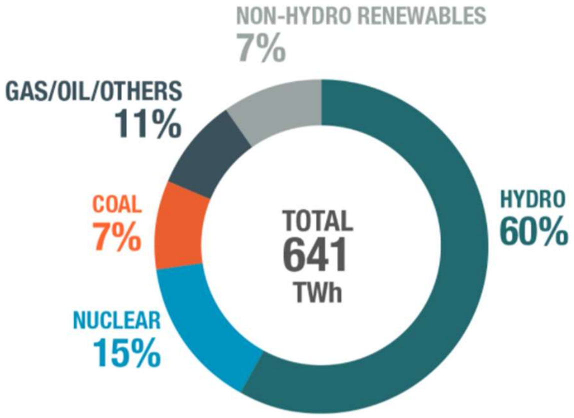

Figure 17-- Canada's energy generation by source (2018). Source: "Electricity Facts", Government of Canada. See footnotes.

The resistance against nuclear energy is also a financial one. The overrun costs mentioned above are warranted, but full consideration of the costs and benefits should be

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Bruce A: John Spears and Robert Benzie, "Brue nuclear refit $2 billion over budget", *Toronto Star*, November 3, 2010, https://www.thestar.com/business/2010/11/04/bruce_nuclear_refit_2_billion_over_budget.html.

[186] MV Ramana, and Xiao Wei, "Why Ontario must rethink its nuclear refurbishment plans", *The Conversation*, January 6, 2020, https://theconversation.com/why-ontario-must-rethink-its-nuclear-refurbishment-plans-127667.

[187] "Electricity Facts", Government of Canada, updated October 6, 2020, https://www.nrcan.gc.ca/science-data/data-analysis/energy-data-analysis/energy-facts/electricity-facts/20068

[188] "Nuclear Power", Energy BC, updated February 2017, http://www.energybc.ca/nuclear.html#
"Nuclear Energy", Greenpeace, accessed April 15, 2021, https://www.greenpeace.org/usa/ending-the-climate-crisis/issues/nuclear/

weighed carefully. The focus on cost should rightfully be of concern to nuclear power plant financial managers, project managers, and utility's consumers; and the government is equally right to be concerned as their budgets are not structured with $1B of added flexibility. However, with all the media coverage on cost overruns, there is not much press on the benefits of nuclear power—especially where climate change or public health are concerned.[189] Two of the benefits of maintaining or building civil nuclear reactors is that they do not contribute to air pollution (once construction is complete, and they do not emit greenhouse gases. The first benefit is received by the public—the taxpayers and electricity consumers in Ontario and New Brunswick areas. The second benefit of lessoning greenhouse gases is received by a third party—the world. This benefit is viewed as a positive externality. Positive externalities of reducing greenhouse gases have costs that corporations are either not willing to bear, or not able to bear alone. Corporations are accountable to their investors, and as such must concern themselves with the short term. Governments, on the other hand, are able to act in the best interests of their citizens in the long run by choosing to pay extra costs that are associated with positive eternities such as joining alongside other states to combat the global effects of climate change.

Future

Small modular reactors (SMR)

Like its neighbor to the south, Canada is looking into SMR designs. Ontario Power Generation corporation—a provincial utility owned by government of Ontario—is selecting an SMR design to have constructed and completed at the Darlington site by 2028.[190] In future, it is expected that Canada will pay the costs to refurbish other reactor units, but no expectations should be made for new, large-scale plants to be constructed. SNC Lavalin, AECL's successor,

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[189] For further reading on the benefits of nuclear power, the author recommends Montgomery and Graham's *Seeing the Light: The case for nuclear power in the 21st century*.

[190] "Canada's nuclear future brightens", *Physics Today*, January 1, 2021, https://physicstoday.scitation.org/doi/10.1063/PT.3.4653

plans to bring three SMRs online per year from 2035 to 2030 in order to combat climate change.[191]

Environment future

The Canadian Net-Zero Emissions Accountability Act was introduced in legislature in late 2020 This follows Canada's signing of the Paris Agreement in 2015.[192] Both the act and the agreement aim to reduce emissions of 'the big four' greenhouse gases--carbon dioxide, methane, nitrous dioxide, and fluorinated gases. Reducing these gases works to limit global temperature increases to 1.5 to 2 degrees Celsius above pre-industrial period (1850-1900 timeframe.)[193] The 'net-zero' goal is to balance the amount of greenhouse gases a state is producing, with the amount a state is removing from the atmosphere. Once the balance is met, it is considered 'carbon neutral'. Carbon neutrality for a state can be accomplished one of two ways: by stopping emissions of greenhouse gases; or limiting greenhouse gas emissions and offsetting it by planting trees or using Carbon capture and sequestering technology (CCS).

To meet the Net Zero 2050 challenge, Canadian private nuclear firm SNC Lavalin produced a report of recommendations on how to achieve net zero. The report estimated that Canada's electrical need would increase from the current 500 TWh to a range of 1,250-2000 TWh by 2050. In order to meet that electrical need, SNC Lavalin recommended building more hydroelectric (500 TWh), wind (300 TWh), solar (60 TWh), and nuclear (275-440 TWh). Natural gas with carbon capture and sequestration (CCS) technology (8 percent of proposed energy mix), and biomass plants (1 percent of proposed energy mix) were also recommended. SNC

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[191] "Engineering Net Zero: Canadian Executive Summary", SNC Lavalin, March 2021, accessed April 18, 2021, https://www.snclavalin.com/~/media/Files/S/SNC-Lavalin/download-centre/en/report/canada_enz-executive-summary_en.pdf.

[192] "Government of Canada charts course for clean growth by introducing bill to legislate net-zero emissions by 2050", Government of Canada, November 19, 2020, https://www.canada.ca/en/environment-climate-change/news/2020/11/government-of-canada-charts-course-for-clean-growth-by-introducing-bill-to-legislate-net-zero-emissions-by-2050.html.

[193] "Key aspects of the Paris Agreement", United Nations Climate Change, accessed April 18, 2021, https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement/key-aspects-of-the-paris-agreement.

Lavalin strongly urged to begin building the nuclear infrastructure now and stated that one 1,000 MWe CANDU reactor should be completed every year from 2030 to 2050.[194] That is in addition to the three SMRs per year to be completed starting in 2035. Given Canada's construction project completion times ranged from 4.42 to 9.39 years, if the project broke ground at the time of writing, it would be possible for former nuclear state-owned enterprise, AECL, to meet this benchmark by 2030. Whether or not it will be possible for current private corporation SNC Lavalin to meet this benchmark, that remains to be seen.

Findings

State-owned enterprises

Canada's SOE, AECL, was critical to Canada's nuclear program success. All twenty-five reactor projects were completed---no abandoned or suspended projects. All projects were completed in under nine years, with an average completion time of 6.78 years.[195]

Secure financing

The ability of the Canadian government to absorb the large cost overruns described earlier is one of the largest advantages to states owning nuclear SOEs. The sum of the overruns mentioned earlier is $4B CAD of charges to the government over the course of several years, spanning several projects. This amount may seem large; but when put into context relative to the $9B project overruns at Virgil C. Summer plant on just one project (and having no completed power plant to show for it.

The case of Ontario Power Generation Corporation (OPG), an SOE on the provincial level, is also worthy of note. ONG is one hundred percent owned by the government of Ontario. As noted in the future section, ONG is planning to build a SMR in Ontario by 2028. Due to

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[194] "Engineering Net Zero: Canadian Executive Summary", SNC Lavalin, March 2021, accessed April 18, 2021, https://www.snclavalin.com/~/media/Files/S/SNC-Lavalin/download-centre/en/report/canada_enz-executive-summary_en.pdf.

[195] IAEA PRIS, author's own calculations.

scaling of projects, SMRs are more easily afforded by a provincial governments and private energy corporations. Now that that Canada's nuclear reactor industry is privatized, it is reasonable to presume that larger-scale civil nuclear power plants—aside from the much more economical refurbishing of existing plants—will not be favored over smaller module designs.

Standardized design

AECL's ability to use the same CANDU design base to construct its twenty-five reactors, and the resulting low average time to complete said projects, demonstrates that standardized design is advantageous to a nuclear infrastructure marketplace with competing designs. Given that the AECL alone was given a nuclear mandate to promote nuclear power, they did not have to compete with other firms and other designs. Additionally, the nuclear supply chain was free from having to divide its resources to produce separate, competing components.

The privatization that occurred in 2011 opened the door to competition and innovation in the Canadian nuclear industry. With the introduction of the SMR concept and design, many would be nuclear reactor design challengers emerged onto the field. In addition to SNC Lavalin, Canadian designers such as Global First Power, Terrestrial Energy and Starcore Nuclear have thrown their hats into the ring. Global First Power has teamed up with Ontario Power Generation to submit a SMR design application to the Chalk River project.[196] These entrants also have to compete with Westinghouse NuScale, and several other firms to win the build contract. This competition now means multiple designs, across multiple firms and manufacturers. Unless one design is chosen, and then preferred for projects going forward, nuclear firms will not be able to take advantage of standardized design or economies of scale.

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[196] "Canada SMR groups pass early development tests in first reactor push.", *Reuters Events*, March 13, 2019, https://www.reutersevents.com/nuclear/canada-smr-groups-pass-early-development-tests-first-reactor-push.

Economies of scale

While AECL was an SOE, it was able to manufacture parts and large components in greater quantity, owing to their knowledge that they would be selected to build more than one unit across different sites. While the economies of scale are greater for a corporation such as NuScale, that can build the same size reactor and then sell multiple reactors to scale up, they cannot be overlooked for large-scale nuclear reactor suppliers with monopoly rights.

Return of experience

The breadth of knowledge and experience that was acquired from designing, licensing, manufacturing, constructing, operating, refitting, and decommissioning CANDU reactors is of tremendous value. Every one of the above seven touchpoints that existed between the AECL and the customer (utility/government/taxpayer) was an opportunity to gain feedback on design, operation, and best practices. This information could not only be applied to concurrent operations, but that data could be applied to make improvements to design or make changes to procedures which make operations more efficient.

Project delays

As mentioned earlier, the project delays that were experienced at the Wolsong refit project overseas was able to be weathered by the SOE only through government assistance. This assistance not only saved the project but protected future business with the overseas owner—the owner now knows that even when push comes to shove, the government will cover costs and the project will be completed as promised. The same cannot be said for private firms. Following the bankruptcy of Westinghouse during the Virgil C. Summer project build, domestic and foreign utility providers will be wary of the possibility their new construction could be ‘the next Virgil C. Summer’. Likewise, private firms will be less likely to bite off more than they can chew with large-scale nuclear plants, as they are aware they could become ‘the next Westinghouse’.

Environmental Stewardship

The natural resources available to Canada have enabled the state to have an environmentally friendly energy production mix. The abundant water enabled the majority of power to be hydro, and the abundance of natural Uranium helped make a fifteen percent mix of civil nuclear power possible.

Civilian nuclear power's prominence in Canada, and abroad (seventh in world for electricity produced by nuclear energy), cannot be overlooked. Canada's reliance on both hydro and nuclear power plants to supply a combined 74% percent of energy—the production of which emits no greenhouse gases—has made Canada's air and environment healthier than states like the United States (69 percent fossil fuels), Russia (75 percent fossil fuels), or the United Kingdom (76 percent fossil fuels.)[197]

Long-term strategic plan

The long-term strategy of Canada for their nuclear industry is not clearly defined at present. The short term is to build a first-of-its kind SMR reactor, and once proven successful, Canada will likely have more SMRs built on alternate sites. The SMR reactor designs from competing vendors are still in the design review and application phase at the Canadian Nuclear Safety Commission (CNSC). Even with shorter construction periods, an SMR is not likely to come online before 2028-2029.

Closing

Canada's privatization occurring at a time when its aging fleet of nuclear reactors needs to be refurbished or replaced is not advantageous for the nuclear power industry. Firms may opt to decommission the nuclear plant over paying to refurbish it.

The Net Zero policy may favor new nuclear builds, but the events of Fukushima, the Westinghouse bankruptcy, Flamanville 3, Olkiluoto 3, and Hinkley Point C, do not tip the scales

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[197] "Canada: Overview", U.S. EIA, last updated October 7, 2019, https://www.eia.gov/international/analysis/country/CAN.

in favor of large nuclear plants. Canada will best be served by starting by building SMRs. Once specialized skill and experience return, once supply chains become efficient, and once construction times become shorter, then larger-scale projects may be resumed. That is, unless the SMR design and construction process has not made large-scale designs economically obsolete.

*   *   *

Preface to case studies 4, 5 and 6

The following three case studies on the United Kingdom, France, and Germany, are critical to the argument that the post-Fukushima nuclear industry has many barriers in place for civil nuclear construction projects in Europe. The deregulation of energy markets that occurred throughout Europe in the 1990s, as well as the privatization of former state-owned enterprises, has made it difficult for states and utilities to advance their civil nuclear power programs. The following case studies will illustrate the point that even states that operate nuclear state-owned enterprises meet with difficulty when undertaking a civil nuclear power project, and states that do not operate nuclear SOEs are at a significant disadvantage.

*   *   *

Case Study 4: United Kingdom

In March of 1940, Britain began conducting research on the theoretical possibilities of using nuclear fission for military use, as well as for an energy source, following the release of Frisch-Peierls memorandum.[198] A year later the MAUD Committee report concluded it was theoretically possible to develop an atomic bomb, and the Tube Alloys project was created and later relocated to Montreal, Canada. In a meeting August of 1943, the Prime Ministers of Canada and the United Kingdom, and U.S. President Franklin D. Roosevelt, met at the Quebec Conference. The result was the Quebec Agreement of 1943—a cooperative agreement between the United Kingdom and the United States to pool their scientific resources in the pursuit of the atomic bomb.[199] The United Kingdom, Canada and France had worked together to bring the ZEEP reactor online at Chalk River, Montreal in 1945. Then in 1946, the U.S. Congress passed the McMahon Act, which ended the United States' cooperation with the United Kingdom and Canada.[200]

Two years after Canada's ZEEP reactor went critical, the United Kingdom had constructed their own nuclear reactor. The Graphite Low Energy Experimental Pile (GLEEP) reactor went critical on August 15, 1947. Six years later, Britain's first civil nuclear power plant began construction at Calder Hall in the summer of 1953 and was completed in 1956.

At present, the United Kingdom operates fifteen civil nuclear reactors, and has thirty reactors in permanent shutdown. Two EPR reactors are under construction at Hinkley Point C with an

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[198] "British Nuclear Program", Atomic Heritage Foundation, March 16, 2017, https://www.atomicheritage.org/history/british-nuclear-program

[199] "The Manhattan Project", OSTI Office of History and Heritage Resources, accessed January 19, 2021, https://www.osti.gov/opennet/manhattan-project-history/Events/1945-present/international_control_1.htm.

[200] Warren Young, "Atomic Energy: From 'Public' to 'Private' Power - the US, UK and Japan in Comparative Perspective", in *Annales historiques de l'électricité* 2003, Vol. 1, no.1, 133-153, accessed January 19, 2021, https://www.cairn.info/revue-annales-historiques-de-l-electricite-2003-1-page-133.htm.

expected completion date of June 2026.[201] The United Kingdom's nuclear electricity production share is 15.6 percent.

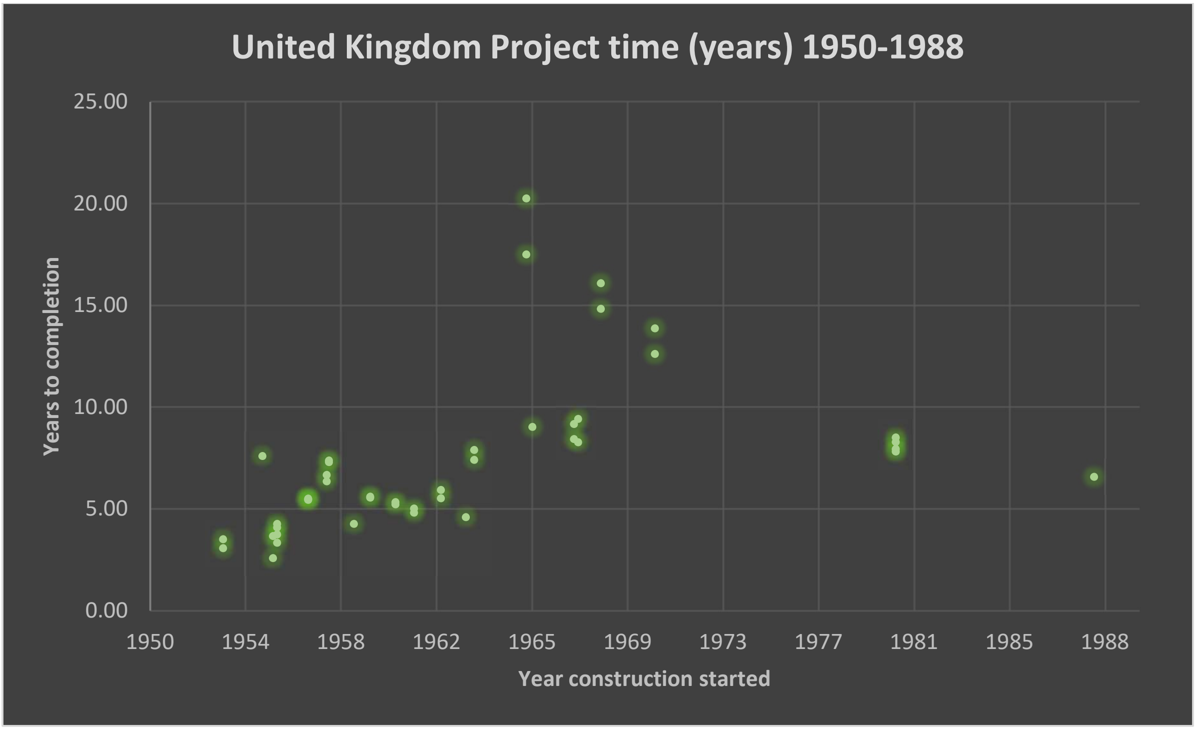

Figure 18-- United Kingdom nuclear reactor construction completion times. Source: data from IAEA PRIS database. Author's own graph.

As the graph above indicates, the bulk of the civil nuclear reactors were built within a twenty-year span from 1950 to 1970. There were only seven nuclear plants built outside of this span, not including the two reactors currently under construction. The average time for the United Kingdom to complete a reactor project is 7.36 years. The United Kingdom used two major reactor design types—the Magnesium Non-Oxidising (Magnox) reactor, and the Advanced Gas-cooled Reactor (AGR). Four additional designs were used: two Fast Breeder Reactors units at Dounreay; one modified Westinghouse's 4-loop PWR, the Standardized Nuclear Power Plant System (SNUPPS), unit at Sizewell B; one steam generator heavy water reactor (SGHWR) design at Winfrith; and two EPR units at Hinkley Point C mentioned earlier in this paper.

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[201] "Hinkley Point C nuclear plant to open later at greater cost", *BBC News*, January 27, 2021, accessed April 11, 2021, https://www.bbc.com/news/uk-england-somerset-55823575#,

Design

The Magnox design, or Magnesium Non-Oxidising reactor, is different than the previously discussed PWR, BWR, and CANDU reactor designs in that it is gas cooled (CO_2), graphite moderated, and does not require enriched Uranium fuel. The choices in design were economical—enriched Uranium was not readily available, and the reactor design had to be able to use natural Uranium. Natural Uranium has less fissile isotopes (0.7 percent occurrence) of U-235 than enriched Uranium. This means that there is less of a chance for a neutron to strike a Uranium isotope capable of producing a fission event. This situation creates the need to increase the number of available neutrons present in the reactor, and since light water moderators capture more thermal neutrons, a graphite moderator was chosen. The solid graphite moderator oxidizes (rusts) when exposed to oxygen, making carbon dioxide gas an option for the reactor coolant. The advantage of the magnesium alloy cladding of the Magnox is that the alloy metal captures less neutrons than other materials, but its disadvantage is that the alloy is not able to withstand high temperatures. (It would melt the metal cladding that encases the nuclear fuel rods.) Its temperature limitations make the Magnox reactor a low efficiency engine.[202]

The AGR design was an improvement to the less efficient Magnox design. The AGR fuel rods are clad in stainless steel and thus the reactor is capable of operating at hotter temperatures. This increases the thermodynamic efficiency of the heat engine (Carnot's theory) and converts a higher percentage of heat into electrical energy.

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[202] "Description of the MAGNOX type of gas cooled reactor", IAEA, accessed April 12, 2021, https://inis.iaea.org/collection/NCLCollectionStore/_Public/30/052/30052480.pdf

Analysis

1953-1964

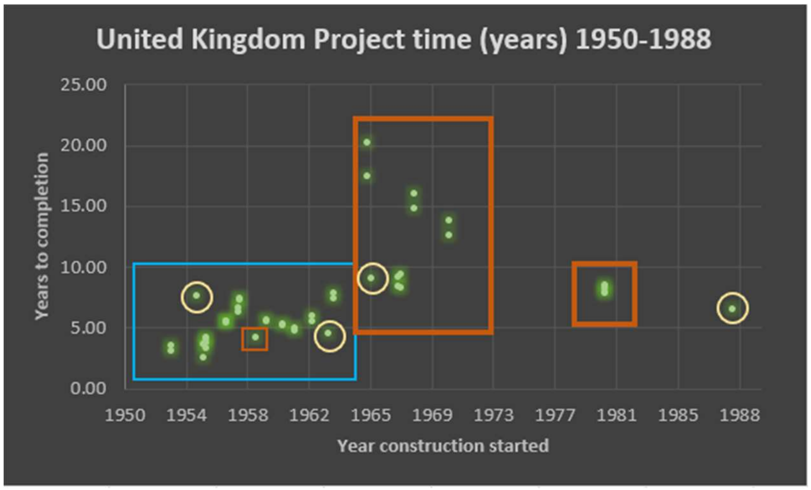

Figure 19-- UK design types. Source: IAEA PRIS database. Author's own graph.

During this period, twenty-six Magnox reactor designs began construction. The blue box (first box from left) depicts all the project starts from this period. The first Magnox reactor began construction in August of 1953, and the last unit was completed at Hinkley Point in 1976. These twenty-six reactors were completed quickly with an average construction time of 5.24 years.[203] The early Magnox reactors that started construction from 1953 to 1955 had a standard 35 MWe design capacity and an average build time of 3.53 years.

The 150 MWe power units all began construction in 1957 and were completed in 1962-1964 with an average completion time of 5.82. The tripling of design capacity contributed to longer completion times in this period. In addition to the six units built at home, two 150/200 MWe Magnox reactors were exported to Japan/Italy, respectively. They both took four and a half years each to construct.

The third grouping of Magnox reactor builds had a 250-300 MWe design capacity with an average completion time of 5.76 years.

The fourth group consisted of two reactors built with a 550 MWe design capacity. The two 550 MWe units constructed at Wylfa took over seven years to construct—again the design capacity changed (doubled) and the completion times increased. No further 550 MWe design Magnox units were constructed afterwards. However, the expectation would have been to see

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[203] IAEA PRIS database. Author's own calculations.

lower completion times for additional units due to increased efficiency in supply chain and return of experience gained from the first 550 MWe projects. All the Magnox reactors have been decommissioned.

There were also three other designs that were built during this period. In Figure 19 above, the brown box around the 1958-year line graphs the first small-scale AGR design that was built. The two yellow circles inside the blue box corresponds to the fast breeder (FBR) and prototype fast breeder (PFR) reactors built at Dounreay, and the (SGHWR) built at Winfrith.

1958, 1964-1970

Fifteen AGR units were constructed from 1958 (first AGR to break ground) to 1989 (last AGR to complete.) The reddish-brown boxes in Figure 19 depicts all the AGR projects by their start year.[204] All of the AGR projects, save for the initial unit at Windscale (small reddish-brown box at 1959), were constructed from 1965-1989. The design capacity for these units was relatively uniform, 600 MWe +/- 55, owing to standardized design. The average time of 11.64 years to construct the AGR design plants was twice that of its predecessor, the Magnox.[205]

A few notable outliers exist in this data set. The Dungeness B1 and B2 reactors took 17.5 and 20.24 years to build, respectively, due to the project being a first-of-its-kind full-scale Advanced Gas-cooled Reactor (AGR). Subsequent AGR builds throughout the 1960s and 1970s took 10.97 years on average to complete.[206]

1970-1980

The large ten-year gap on between construction projects breaking ground displayed in Figures 18 and 19 above was during the recession. The recession was caused by the 1973 Oil Crisis, raising unemployment, and diminishing GDP.[207]

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[204] Note: In addition to the large box in the center, there is also a medium-sized box (1980), and a small box (1959).

[205] Ibid.

[206] Note: With Dungeness B1 and B2 included, the AGR average is 12.10 years. Authors own calculations.

[207] Alan A. Tait, “Political Economy: The British Budget 1971”, *FinanzArchiv/ Public Finance Analysis*, Bd. 30, H. 3, (Mohr Siebeck GmbH &Co., 1972), 489-509, https://www.jstor.org/stable/40910907

State-owned enterprises

Churchill created the Department of Atomic Energy in 1954, and afterwards the U.K. Atomic Energy Authority (UKAEA). The UKAEA was a state-owned enterprise responsible for Britain's nuclear program, and it oversaw nuclear plant construction and reactor manufacturing. In 1957, the Electricity Act created the Central Electricity Generating Board (CEGB), a state-owned enterprise which later operated all the nuclear plants.[208] In 1971, the Atomic Energy Authority Act 1971 broke the UKAEA into three separate groups, the nuclear energy aspect being housed in British Nuclear Fuels Ltd. (BNFL). The BNFL was responsible for research and designing nuclear power plants, and the nuclear fuel cycle, but no longer for construction of nuclear plants.

Privatization

The Electricity Act of 1989 was passed which allowed for the privatization of Britain's energy sector. *In 1990,* the United Kingdom deregulated (privatized) its national electric company (CEGB). CEGB was broken into three companies: PowerGen, National Power, and Nuclear Electric—the latter remaining under government ownership.[209] In 1995, Nuclear Electric merged with Scottish Nuclear to form British Energy. In 1996, British Energy, was privatized, but the state retained a 35 percent ownership in the company.[210] Nuclear decommissioning activities at Magnox sites were still carried out by the state. In 2008, French state-owned energy firm, EDF (formerly Framatome/Areva), purchased the United Kingdom's majority of shares (35 percent) of British Energy for $16.5B (2008 USD).[211]

2008- present

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[208] John E. Kwoka Jr., "Transforming Power: Lessons from British Electricity Restructuring", CATO, accessed April 26, 2021, https://www.cato.org/sites/cato.org/files/serials/files/regulation/1997/7/reg20n3e.html

[209] Warren Young, "Atomic Energy: From 'Public' to 'Private' Power - the US, UK and Japan in Comparative Perspective", in *Annales historiques de l'électricité* 2003

[210] "CHRONOLOGY-British Energy in bid talks", *Reuters*, March 17, 2008, https://www.reuters.com/article/uk-britishenergy-chronology/chronology-british-energy-in-bid-talks-idUKL1759378020080317.

[211] Terry Macalister and Graeme Wearden, "EDF to buy British Energy for £12.4bn", *The Guardian*, September 24, 2008, https://www.theguardian.com/business/2008/sep/24/britishenergy.edf.nuclear.

In the same year that EDF acquired British Energy, the French SOE applied for a license to build two European Pressurized Reactors (EPR) reactors at Hinkley Point C.[212] In 2013, British gas firm Centrica withdrew from its partnership with France's EDF on the Hinkley Point C project. This caused delays on the project as EDF sought out new financial partners. EDF partnered with the Chinese nuclear SOE, China General Nuclear Power (CGN).[213] In 2015, the European Commission delayed the project breaking ground due to an investigation conducted into whether or not the state aid being given to the Hinkley Point C project would negatively impact other European states.[214] (State aid given to projects has to be investigated to determine if it gives an unfair advantage to a firm in the EU, or if the aid is necessary for economic development.[215]) The Commission ruled in favor of Hinkley Point C. In 2016, there were delays caused by EDF's board of shareholders, who ultimately, and narrowly, voted in favor of proceeding with the project and accepting the financial risks.[216] In December of 2018 and 2019, ground was broken on two (EPR) reactors at Hinkley Point C. (See Appendix L for project timeline.)

The project has been further delayed due to site precautions taken during the COVID pandemic (limiting personnel on site, etc.). The current estimate for Unit 1 completion is June of 2026.[217]

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[212] Nina Chestney, "Timeline: Britain's Hinkley Point C nuclear project", *Reuters*, August 3, 2016, https://www.reuters.com/article/us-edf-britain-nuclear-hinkley-timeline/timeline-britains-hinkley-point-c-nuclear-project-idUKKCN10E1JS.

[213] Damian Carrington, "Centrica withdraws from new UK nuclear projects" *The* Guardian, February 4, 2013, https://www.theguardian.com/environment/2013/feb/04/centrica-withdraw-new-nuclear-projects

[214] Phedon Nicolaides, "The Common European Interest and the Environmental Impact of State Aid: The Case of Nuclear Power", *Lexxion*, October 27, 2020, https://www.lexxion.eu/en/stateaidpost/the-common-european-interest-and-the-environmental-impact-of-state-aid-the-case-of-nuclear-power/.

[215] "State aid control", European Commission, updated on February 4, 2019, accessed April 24, 2021, https://ec.europa.eu/competition/state_aid/overview/index_en.html.

[216] Chestney, "Timeline: Britain's Hinkley Point C nuclear project", *Reuters*.

[217] "Hinkley Point C delayed until at least 2026", *World Nuclear News*, January 27, 2021, https://world-nuclear-news.org/Articles/Hinkley-Point-C-delayed-until-at-least-2026.

Future

The current delays experienced with the Hinkley Point C project will likely lower chances that a private corporation will build a large-scale nuclear plant in the near future. The British government has financially committed $50M (2020 USD) to research and develop SMRs and Advanced Modular Reactors (AMR) technology.[218] Additionally, the United Kingdom has been researching fusion reactors. Their goal is to have a fusion reactor online by 2040.[219] Fusion is difficult, not only by technical standards, but by cost standards. Currently the UK achieved its 'first plasma' result in November of 2020, which is a good indicator of success.[220] This technology is still years away from being effectively used as a power source. The likely energy future for the United Kingdom will be dependent on the outcome of the Hinkley Point C project. If there is no profit made by EDF, it will signal to other SOEs or private firms that now is not the time for large-scale reactors. If the Hinkley Point C project can turn it around and generate profit, then it is possible that more builds will be attempted with the promise of quicker construction times.

It is likely that the SMRs will be pursued in future. The abandoned large-scale project of Wylfa Newdd (discussed previously in Chapter 2, and below in *Secure Financing*) is being considered as new site for a hybrid SMR/wind farm project by Shearwater Energy. Shearwater proposes to use 12 SMRs supplied from NuScale and 1,000 MWe wind power generation on site. The firm estimates the project will cost less than £8B.[221]

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[218] "UK government support for modular reactor deployment", *World Nuclear News*, July 13, 2020, https://world-nuclear-news.org/Articles/UK-government-support-for-modular-reactor-deployme.

[219] Peter Ray Allison, "The UK's quest for affordable fusion by 2040", BBC News, December 15, 2020, https://www.bbc.com/future/article/20201214-the-uks-quest-for-affordable-fusion-by-2040#.

[220] Peter Dockrill, "A huge fusion experiment in the UK just achieved the much anticipated 'First Plasma'", *ScienceAlert*, November 3, 2020, https://www.sciencealert.com/huge-fusion-experiment-achieves-first-plasma-in-landmark-step-towards-clean-energy.

[221] George Herd, "Wylfa: New hybrid nuclear power plan for Anglesey", *BBC* News, January 16, 2021, https://www.bbc.com/news/uk-wales-55682005.

Findings

State-owned enterprises

The United Kingdom's ownership of UKAEA, CEGB and later British Energy, was pivotal in the construction of nuclear power. The centralization of nuclear promotion enabled all forty-five nuclear power plants to be successfully completed. With exception of the four experimental reactors built, the state-owned corporation used only one standardized design for serial construction periods—Magnox, then later replaced by the AGR design. These enabled economies of scale to be taken advantage of, as well as increased return of experience. Critical of the role state-owned enterprises played in the selection of designs, British economist David Henderson states:

> "A continuing feature was the uncritical acceptance, by governments, media and public opinion alike, of official scientific advice. Policies took the form of risky investments of a kind, and on a scale, which private businesses could not have undertaken: these were huge gambles that only the public sector could have ventured on." [222]

Secure Financing

The construction of nuclear plants in the United Kingdom were advantaged by the presence of SOEs. The British government was able provide funding and underwrite loans for its nuclear SOEs.[223] This provided greater financial security for the construction projects which greatly contributed to the project success rate. Additionally, government funding of nuclear research (BNFL) has a significant impact on the nuclear industry and is an investment in the success of future projects.[224]

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[222] David Henderson, "The more things change", *NEI*, June 21, 2013, accessed April 22, 2021, https://www.neimagazine.com/opinion/opinionthe-more-things-change/.

[223] John Moore, "British Privatization—Taking Capitalism to the People", Harvard Business Review, February 1992, accessed April 23, 2021, https://hbr.org/1992/01/british-privatization-taking-capitalism-to-the-people.

[224] "The Nuclear Energy Option in the UK", Parliamentary Office of Science and Technology, No. 208, December 2003, accessed April 23, 2021, https://web.archive.org/web/20060103235611/http://www.parliament.uk/documents/upload/postpn208.pdf.

A year after the British government’s sale of its nuclear SOE, British Energy in 2009, the British Parliament was supportive of the idea of new nuclear projects, provided no public funds were spent on them.[225] The Wylfa Newdd project, that was slated to begin in 2015 but delayed due to financing, changed that policy.[226] The U.K. government offered to stake the Wylfa Newdd project with £5B.[227] Ultimately, Hitachi thought the project was too expensive to complete without additional funding from the U.K. government, and the two parties were not able to come to an agreement as to the amount or structure of funding

Standardized design

The United Kingdom built twenty-six reactors of Magnox design in series, followed by fifteen reactors of AGR design. The standardized design process was able to yield results in efficiency, and this is demonstrated in the graph in Figure 19. With the exception of the experimental reactors built, the United Kingdom built reactors in pairs. The AGR construction times, once graphically depicted, demonstrate that standardized design, economies of scale, and return of experience were able to decrease the time required to build these reactors—even while increasing the design capacity. The trend depicted in the graph shows an average decrease in completion time of 3.42 years from the first grouping of the Dungeness 1965 projects to the second grouping of Hartlepool-A 1968 projects; and it also shows an average decrease of 2.2 years from the Hartlepool-A 1968 projects to the Heysham-A 1970 projects.[228] The two reactor projects that began construction in 1980 at Heysham-B (B-1 and B-2) and

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[225] “Huhne outlines coalition deal over nuclear power plants”, *BBC news*, May 13, 2010, http://news.bbc.co.uk/2/hi/uk_news/politics/8679827.stm.
[226] “Wylfa Newydd planning decision delayed again”, NEI, April 6, 2020, https://www.neimagazine.com/news/newswylfa-newydd-planning-decision-delayed-again-7859280
[227] Adam Vaughan,”UK takes £5bn stake in Welsh nuclear power station in policy U-turn”, *The Guardian*, June 4, 2018, https://www.theguardian.com/environment/2018/jun/04/uk-takes-5bn-stake-in-welsh-nuclear-power-station-in-policy-u-turn.
[228] IAEA PRIS database. Author’s own calculations.

Torness (1 and 2) were completed 5.1 years quicker than those constructed at Heysham-A 1970.

Constructing reactor projects based off of one design, even when increasing design capacity, allows the project to take advantage of shorter completion times, and increases the success rate of the project.

Economies of scale

As mentioned above, the United Kingdom built two reactors at a time. This practice enabled the projects to save money and time by using the same geographical site, the same license application process window, and obtain volume discounts for goods and services. Additional economies of scale are achieved on the supply side. The manufacture of the multiple reactors and reactor-specific components provide further savings to the state-owned enterprise.

Return of experience

As mentioned above in the standardized design section, the return of experience gained from working on successive projects of the same, standardized design benefited the workforce and supply chain. The workforce, both the skilled labor and the project managers, were able to increase project efficiency with each successive build. The nuclear industry was continuously engaged in constructing twenty-six Magnox reactors from 1955 until 1971. There was a new Magnox reactor breaking ground almost every other year from 1955-1963, and each new project had detailed experience acquire from the previous project.

Project delays

Construction delays can be seen on the first AGRs constructed at Dungeness, and this can be attributed to first-of-its-kind problems and component design failures. The Hinkley Point C EPR project is currently experiencing project delays. The largest delays occurred on the front end when a joint venture partner backed out of the deal. The EPR plant is also a first-of-its kind design being constructed in the United Kingdom.

Environmental Stewardship

In 2019, the United Kingdom committed to a net-zero carbon emission policy by 2050. This commitment was written into law with the amendment made to the Climate Change Act.[229] The United Kingdom will host the Copenhagen 26 (Cop26) Conference in November of 2021 where the state will be expected to present its net zero plan. Prime Minister Boris Johnson previously addressed the possibility of new nuclear plants to aide in reaching the net zero goal.[230]

Closing

The United Kingdom did an excellent job of constructing nuclear reactors while they were using standardized design. After privatization, the one instance of a nuclear build is at Hinkley Point C. The analysis on this plant and the factors for its success or failure cannot be completed at present, but it seems the plant has been disadvantaged throughout its construction process with the only clear advantage being a financial one—given its construction firm is an SOE.

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[229] Peter Walker, et al., "Theresa May commits to net zero UK carbon emissions by 2050", *The Guardian*, June 11, 2019, https://www.theguardian.com/environment/2019/jun/11/theresa-may-commits-to-net-zero-uk-carbon-emissions-by-2050.

[230] Fiona Harvey, "Boris Johnson failing on UK plan to reach net zero, says MPs", *The Guardian*, March 5, 2021, https://www.theguardian.com/environment/2021/mar/05/boris-johnson-failing-on-uk-plan-to-reach-net-zero-say-mps.

Case Study 5: France

France was the fifth state to build a nuclear reactor. On December 15th, 1948, the Zoé EL-1 reactor went critical. Much like the Soviet Union, the United States, and the Commonwealth before it, France pursued civil nuclear power. France surpassed its predecessors with its percentage share of nuclear-produced electricity in the world—70.6 percent. The next closest state is a two-way tie between Ukraine and Slovakia, both at 53.9 percent share.[231] France has seventy-two civil nuclear reactors, of which fifty-six are operational, fourteen are permanently shut down, and one is currently under construction. The average reactor project completion time is 6.25 years—surpassing both Canada and the Russian Federation (during its Soviet era).[232] France is also second in the world for civil nuclear power production (335 TWh).[233]

1955-1970

In the early days of France's civil nuclear power program, it began construction on eleven civil nuclear power reactors. Eight of the eleven were gas-cooled reactors (like those in Britain), with the remaining three designs being: heavy water gas-

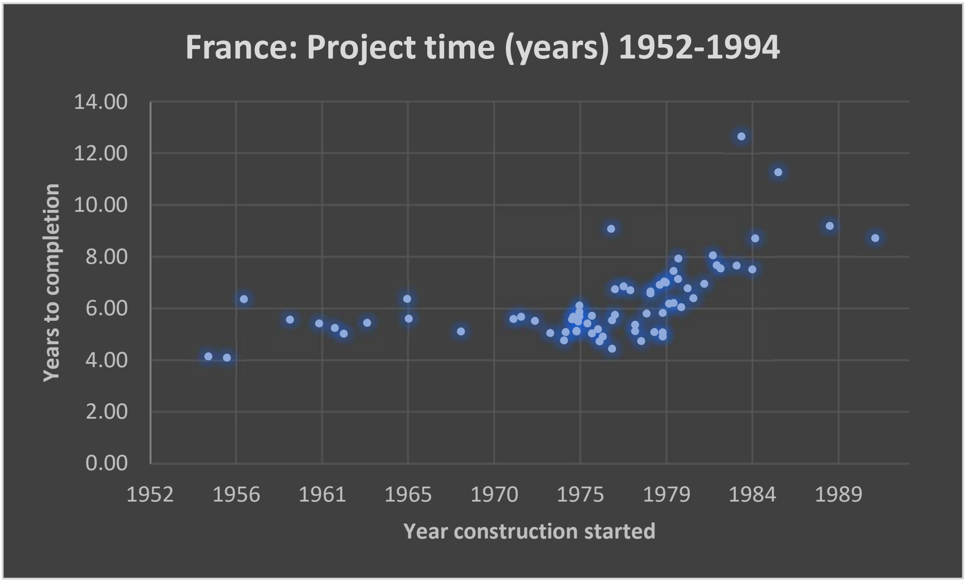

Figure 20-- France reactor construction times. Source: data from IAEA PRIS. Author's own graph.

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[231] IAEA PRIS Country Statistics. https://pris.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=FR

[232] IAEA PRIS database. Author's own calculations.

[233] Andreas Franke, "EDF keeps 2021 French nuclear target at 330-360 TWh; 33 TWh coronavirus impact 2020", *S&P Global*, February 18, 2021, https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/021821-edf-keeps-2021-french-nuclear-target-at-330-360-twh-33-twh-coronavirus-impact-2020.

cooled (HWGCR), pressurized water (PWR), and fast breeder reactor (FBR). The average construction time for these reactors was 5.31 years with an average design capacity of 266 MWe.[234]

1970-1980

This period saw the most nuclear reactor builds begin across France. During this decade, thirty-nine civil nuclear reactors began construction with an average completion time of 5.68 years.[235]

France moved away from the gas-cooled reactor design and shifted to the pressurized water reactor (PWR) design. All reactors constructed during this period were PWRs save for the fast breeder reactor named 'Super Phenix'. The average design capacity was 973 MWe.

It was also during this period that France began exporting civil nuclear power. They built two PWR reactors each at Tihange in Belgium, and at Koeberg in South Africa. Belgium's 870 MWe reactor at Tihange 1 and 900 MWe reactor Tihange 2 took 4.76 and 6.53 years to build, respectively. South Africa's 921 MWe reactors at Koeberg 1 and Koeberg 2 took 7.76 and 9.07 years to build, respectively.

The extra time spent France spent constructing the Koeberg reactor was, in part, due to a first-of-its-kind earthquake protection design feature for the foundation.[236] The construction was largely delayed due terrorism. In 1982, a former employee and African National Congress (ANC) sympathizer-turned member, Rodney Wilkinson, bombed the Koeberg plant while it was

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[234] IAEA PRIS. Author's own calculations.

[235] IAEA PRIS. Author's own calculations.

[236] Wilson, J.H. (1985), "Earthquake precautions at Koeberg nuclear power station", *Nuclear Engineering*, 26(2), 40-44.

under construction.[237] The attack was conducted prior to the loading of nuclear fuel, and set back the nuclear reactor construction by 18 months.[238]

1980-2000

This was France's second largest period of growth in their nuclear industry. Construction on nineteen reactors began in France from 1980 to 1991. Similar to later periods in the evolution of other states' nuclear industry, the power plants were designed with much larger capacities. The design capacity increased 33.6% from the previous period to reach 1,300 MWe.[239] The reactor type chosen for all nineteen plants was a standardized PWR design. The average time for constructing a reactor in this period was 7.9 years. The average would have been slightly lower (7.2 years) but for the four reactors constructed to meet a 1,455 MWe design capacity.[240]

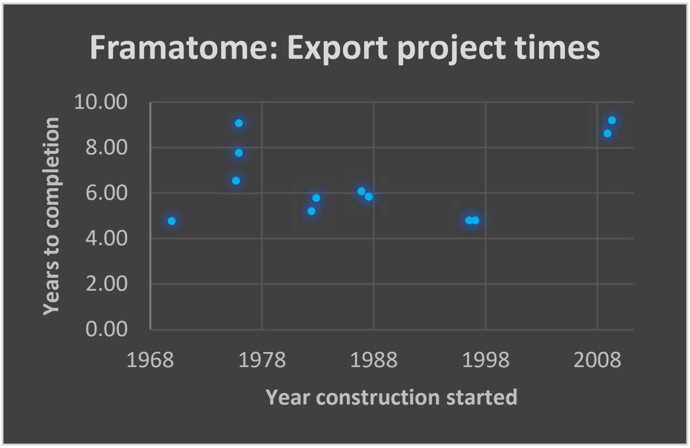

Figure 21-- Framatome reactor construction times. Source: data from IAEA PRIS. Author's own graph.

France's Framatome, a state-owned enterprise, made a play for the Asian market during this period. From 1983 to 1987, Framatome began construction on six reactors in South Korea and China. These included two reactors at Hanul, South Korea; two at Daya Bay, China; and two at Ling Ao, China. The reactor design chosen for Hanul 1 and 2 was the CP1 design—a standardized PWR design that France perfected in the mid-1970s with an established track record of finished construction in an average of 5.5 years. (They completed

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[237] Douglas Birch, "South African who attacked a nuclear plant is a hero to his government and fellow citizens", The Center for Public Integrity, accessed 12 April 2021, https://publicintegrity.org/national-security/south-african-who-attacked-a-nuclear-plant-is-a-hero-to-his-government-and-fellow-citizens/.

[238] Jo-Ansie van Wyk, "Nuclear terrorism in Africa: The ANC's Operation Mac and the attack on the Koeberg Nuclear Power Station in South Africa", Vol. 60, n. 2, *Historia*, (November 2015), pg 51-67, accessed April 12, 2021, http://www.scielo.org.za/scielo.php?script=sci_arttext&pid=S0018-229X2015000200003#back_fn65

[239] IAEA PRIS. Author's own calculations.

[240] Ibid.

both Hanul reactors in 5.49 years.) The Daya Bay project was a little different. The design used was based off the French CP1 reactor design used at the Gravelines 5 and 6 plant but used Westinghouse turbines. It was also different in that this was not a turnkey project--China contracted to participate in the construction process in order to cultivate domestic scientific and engineering experience. The first reactor at Daya Bay took 6.07 years to build, and the second 5.84 years.[241] The project at Ling Ao, which is a ten-minute drive from Daya Bay, was a similar venture. Framatome/Areva supplied the reactor and oversaw construction with Chinese engineering firms assisting.[242] Ling Ao 1 and 2 were both constructed in 4.79 years. (These plants will be discussed in greater depth in the China case study.)

2000- present

France departed from their tried-and-true 1,300 MWe and more recent 1,450 MWe PWR designs and developed a new, Gen III (third generation), European Pressurized Reactor (EPR) design. The new design addressed safety concerns following the event of Fukushima. The Gen III design has safety features that reduce the possibility of a core meltdown by incorporating passive cooling systems. Redundant systems were also designed—multiple emergency diesel generators for backup. (See Appendix H.)[243]

Framatome/Areva started construction on this new EPR design in Finland at the Olkiluoto plant. The project began in 2005 and has experienced many setbacks beyond those typically seen in first-of-its-kind design builds. At the time of writing, the project is still incomplete. The Olkiluoto 3 project recently passed the fifteen-year mark and is projected to be complete in October of 2021.[244]

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[241] IAEA PRIS. Author's own calculations.

[242] "Ling Ao Nuclear Power Plant", *NTI*, July 25, 2012., https://www.nti.org/learn/facilities/780/

[243] Brian Wheeler, "Gen III reactor design", *Power Engineering*, April 6, 2011, https://www.power-eng.com/nuclear/gen-iii-reactor-design/#gref.

[244] "Further delay in commissioning of Finnish EPR", *World Nuclear News*, August 28, 2020, accessed April 12, 2021, https://world-nuclear-news.org/Articles/Further-delay-in-commissioning-of-Finnish-EPR.

This EPR design was used at home in France. The Flamanville 3 project was started in late 2007 and is still under construction. As mentioned earlier in the paper, there have been many lengthy delays to this project. As Flyvbjerg's Iron Law of Megaprojects warned of projects of this size, the project became "over budget, over time, under benefits, over and over again." [245] The delays were not a one-time occurrence, and neither were the massive increases in cost. In 2011, following the events of Fukushima, the EDF put additional safety reviews in place. The same year also saw two fatal industrial accidents where workers fell. The resulting additional safety reviews and fatal accident investigations pushed the Flamanville 3 project to the right of the timeline by two years.[246] In 2014, the project experienced further delays obtaining necessary plant components due to supply chain problems.[247]

In 2015, weak spots were discovered in the steel of the reactor vessel.[248] In 2019, eight defective welds were discovered in the secondary coolant system, which delayed the project an additional year and added $346M (2019 USD) to the project.[249] The project that broke ground in late 2007, is estimated to be ten years behind schedule (late 2023) and $10 billion USD over budget.[250]

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[245] Bent Flyvbjerg, "Introduction: The Iron Law of Megaproject Management," in *The Oxford Handbook of Megaproject Management*, ed. Bent Flyvbjerg, (Oxford: Oxford University Press, 2017), 1-18; accessed January 20, 2021, http://bit.ly/2bctWZt.

[246] "France delays new generation nuclear plant", *France 24*, July 20, 2011, https://www.france24.com/en/20110720-france-delays-new-generation-nuclear-plant-safety-concerns-edf-flamanville.

[247] "FACTBOX-French EPR reactor years behind schedule, billions over budget", *Reuters*, September 3, 2015, https://www.reuters.com/article/edf-nuclear-flamanville/factbox-french-epr-reactor-years-behind-schedule-billions-over-budget-idUKL5N1182LY20150903

[248] Geert De Clercq, "UPDATE 2-Weak spots found in steel of Areva's French EPR reactor", *Reuters*, April 7, 2015, https://www.reuters.com/article/areva-nuclear-anomalies/update-2-weak-spots-found-in-steel-of-arevas-french-epr-reactor-idUSL6N0X41S920150407.

[249] "Flamanville 3 delayed until 2022", *NEI*, July 30, 2019, https://www.neimagazine.com/news/newsflamanville-3-delayed-until-2022-7341187.
"Weld repairs to delay Flamanville EPR start-up", *World Nuclear News*, June 20, 2019, https://www.world-nuclear-news.org/Articles/Weld-repairs-to-delay-Flamanville-EPR-start-up.

[250] Francois De Beaupuy, "EDF Cost Overrun at French Plant Piles Pressure on Nuclear Giant Bloomberg", *Bloomberg*, October 9, 2019, https://www.bloomberg.com/news/articles/2019-10-09/edf-lifts-cost-of-french-nuclear-reactor-by-14-to-13-6-billion?sref=RuowHo8w.

While the EPR projects were ongoing at Olkiluoto and Flamanville, a new EPR project was simultaneously being constructed in China in 2009. Twelve years after Framatome broke ground on Ling Ao 1 and 2, EDF began construction on Taishan 1 and 2. In November of 2007, China agreed to purchase Framatome/Areva's new advanced reactor design, the EPR-1750, for $10.4B (2012 USD).[251] The agreement with Framatome/Areva for Taishan was similar to Framatome's Ling Ao project in that Chinese engineers and scientists were integrated into the construction and operations of the project. Unlike the Olkiluoto project in Finland, the Taishan 1 and 2 reactors experienced relatively minor delays (11 months) and finished in 8.61 and 9.19 years, respectively.[252]

The most recent usage of the EPR design was in the United Kingdom. The Hinkley Point C project began in 2007 and broke ground in December of 2018 and 2019. This £22-23M (2021) project is still ongoing. The numerous delays for this project (detailed in the previous case study) resulted in the scheduled completion being pushed out to 2025-2026. [253] (See Appendix L for Hinkley Point C timeline.) EDF is working with another financial partner on the Hinkley project—China's China General Nuclear Power Group (CGN). [254] The two SOEs successfully worked together on the EPR reactor project in Taishan.

State-owned enterprise

The French nuclear reactor manufacturer, Framatome/Areva, was not always part of the France's state-owned enterprise Électricité de France S.A. (EDF). Framatome and EDF have been working together since 1958, one a nuclear reactor supplier and the other the customer.

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[251] "Reactor vessel installed at Taishan", *World Nuclear News*, June 6, 2012, https://www.world-nuclear-news.org/Articles/Reactor-vessel-installed-at-Taishan#.

[252] "China delays nuclear reactor start again", *AFP news*, February 21, 2017, https://au.news.yahoo.com/china-delays-nuclear-reactor-start-again-34464586.html.

[253] Sudip Kar-Gupta, and Susanna Twidale. "EDF warns UK nuclear plant could cost extra $3.6 billion, see more delays", *Reuters*, September 25, 2019, https://www.reuters.com/article/us-britain-nuclear-hinkley-edf/edf-warns-uk-nuclear-plant-could-cost-extra-3-6-billion-see-more-delays-idUSKBN1WA0T0.

[254]Rob Davies, "China-UK investment: key questions following Hinkley Point C delay", *The Guardian*, August 9, 2016, https://www.theguardian.com/business/2016/aug/09/china-uk-investment-key-questions-following-hinkley-point-c-delay.

The path of Framatome from private corporation to partially owned state enterprise, to majority owned state enterprise was a fifty-seven-year journey punctuated with many corporate mergers and acquisitions.

It started in 1958 with the creation of Franco-Américaine de Constructions Atomiques, or Framatome for short.[255] This group was a French American engineering partnership between Schneider, Merlin Gerin, (both French) and Westinghouse (American) firms. These firms were created to build pressurized water reactors (PWRs) in France. In 1974, Prime Minister Pierre Messmer shifted France's energy policy away from oil to nuclear power. This was following the Oil Crisis of 1973 and resulted in plans to increase the number of nuclear plants in France and do so quickly using standardized design.[256] In December of 1975, the French government made a deal with Westinghouse to purchase a 30 percent share of Framatome. The 30 percent share went to Commissariat à l'énergie atomique (CEA), a state-owned enterprise of France responsible for energy, and Westinghouse's remaining 15 percent was transferred to the majority shareholder of Framatome, Creusot-Loire Co. This increased Creusot-Loire's share to 66 percent.[257] In 1984, when Cresusot-Loire went bankrupt, CEA acquired an additional 5 percent for a total of 35 percent share of Framatome; the French engineering firm, CGE, acquired 40 percent, and EDF acquired 10 percent.[258] The combined 45 percent majority share held by CEA and EDF, both being owned by the state, made Framatome a state-owned enterprise.[259] In 2001, Framatome merged with CEA Industrie and Cogema (later Orano) to

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[255] "From an engineering department to an international company", Framatome, 2019, accessed November 15, 2020, https://www.framatome.com/EN/businessnews-492/framatome-our-history-from-an-engineering-department-to-an-international-company.html

[256] Montgomery and Graham, *Seeing the Light*, 114.

[257] "French deal set by Westinghouse", *New York Times*, December 31, 1975, https://www.nytimes.com/1975/12/31/archives/french-deal-set-by-westinghouse-twothirds-of-45-interest-in.html

[258] Stephen D. Thomas, "Corporate Policies of the Nuclear Vendors", in Haas R., et al. (eds), *The Technological and Economic Future of Nuclear Power*, April 27, 2019, https://link.springer.com/content/pdf/10.1007%2F978-3-658-25987-7_10.pdf

[259] Note: CGE made a power play and acquired additional shares bringing their share up to 52 percent—controlling interest. This move was countered by French government intervention, thus reducing CGE shares down to 44

form Areva. In 2015, Areva sold its majority shares to EDF and by 2017, EDF held controlling interest in Framatome/Areva.[260]

In addition to the domestic corporate moves, Framatome acquired Babcox & Wilcox Nuclear Technology (BWNT) in stages from 1989 to 1993.[261] Also in 1989, Framatome created a joint-venture company with Siemens, Nuclear Power International (NPI) to begin development of the EPR design. In 2001, Framatome merges with Siemens nuclear division, forming Framatome ANP. Framatome holds a 66 percent share, and Siemens holds 34 percent. In 2007, EDF created a joint venture with China Guangdong Nuclear Power Holding Corp [now China General Nuclear Power Group (CGN)] called the Taishan Nuclear Power Company (TNPJVC). The CGN holds 70 percent share and France's EDF holds 30 percent share.[262] The joint venture was created for the construction of the Taishan reactors.

Future

In 2016, France announced a plan to start constructing new reactors with EPR designs to replace their older civil nuclear power plants.[263] France has not yet decided as to whether they will begin to replace older reactors within France until after the completion of Flamanville 3 plant.[264] The SMR research trend of other states is also present in France. In 2019, the CEA

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percent. Source: "Adapting to a Bearish Nuclear Market. The transition of Framatome in the 1980s", in *Electric Worlds*, ed. Alain Beltran et al., (Brussels: Peter Lang SA, 2016), https://www.peterlang.com/view/title/51121.

[260] Framatome, 2019.

[261] C.W. Forsberg, et al., "The Changing structure of the international commercial nuclear power reactor industry", Oak Ridge National Laboratory, December 1992, https://www.osti.gov/servlets/purl/6822127

[262] "From an engineering department to an international company", Framatome, accessed April 21, 2021, https://www.framatome.com/EN/businessnews-492/framatome-our-history-from-an-engineering-department-to-an-international-company.html

[263] Benjamin Mallet and Geert De Clercq, "EDF plans two new nuclear reactors in France by 2030-document", *Reuters*, January 21, 2016, https://www.reuters.com/article/edf-nuclear-epr/edf-plans-two-new-nuclear-reactors-in-france-by-2030-document-idUSL8N1554S4

[264] "EDF plans to announce new EPR nuclear reactor by mid-2021", *Reuters*, October 15, 2020, https://www.reuters.com/article/us-edf-nuclear/edf-plans-to-announce-new-epr-nuclear-reactor-by-mid-2021-idUSKBN2701B8

discussed plans to complete the Nuward SMR design, and expect the plant to be finalized and certified by 2030, with construction to follow.[265]

Findings

State-owned enterprises

There are two sides of the SOE coin at play in France's nuclear industry. The nuclear reactor manufacturer and construction company Framatome/Areva, and EDF. It is correct to say that those two firms have since merged and are now one and in the same. In the early years of nuclear reactor construction in France, from 1955 to 1975, twenty reactors began construction under Framatome, then a non-SOE. During this period, the consumer, EDF, disagreed with the state research agency CEA, and requested Framatome only build PWR reactors. (The CEA preferred a Uranium Natural Graphite Gas design.)[266] In 1975, the Messmer plan took effect and France sought out Westinghouse to gain more control over the construction of civil nuclear power. During this period, the CEA owned 30 percent and EDF owned 10 percent of Framatome; the EDF worked with Framatome to construct fifty civil nuclear plants, all standardized design.

Although the reactor supplier and plant construction firm were not state-owned for the entire duration of the builds, the customer was an SOE, and it was the customer that drove the design selection and the quantity of reactors. It was also the customer that drove down costs and construction times by requesting a standard design, with standard design capacity, opposed to utilities in other case-studies that opted for innovation and newer designs.

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[265] "French-developed SMR design unveiled", *World Nuclear News*, September 17, 2019, https://www.world-nuclear-news.org/Articles/French-developed-SMR-design-unveiled.

[266] Claire Mays, Henri Boye, and Marc Pumadere, "Nuclear Procurement in the French Context", Korea Development Institute, in Ilchong Nam and Geoffrey Rothwell (eds) *New nuclear power industry procurement markets*, December 2014, https://www.files.ethz.ch/isn/187508/13874_2.pdf

Secure financing

Since the customer was a state-owned enterprise, the funding for domestic projects came from the state. In the case of exports for the EPR design, when Framatome/Areva needed additional capital to continue the project, EDF was able to offer additional shares (diluting shares) on the stock market. This provided EDF with £3B to continue the project at Hinkley Point C.[267]

Standardized design

As mentioned earlier, France was the pioneer of civil nuclear plant design standardization. This was because the French government approved the PWR design, resulting in 59 PWR plants being built. Compare the construction starts in 1970-1990 in France to those in the United States over the same period. The United States began construction on 62 reactor projects, with four nuclear firms designing and building the plants (Westinghouse, General Electric, Combustion Engineering, and Babcox & Wilcox). Their average completion time during this period--10.77 years. During the same time period, France began construction on 58 reactor projects, with only one firm designing and building the plants (Framatome/Areva.) The average completion time for this period was 6.38 years.[268] Among other potential factors, it is likely that standardization of design largely enabled France to complete reactor projects four years quicker than the United States.

Economies of scale

France was able to take advantage of economies of scale by building the same reactor design base across 59 builds. The supply chain was not divided by multiple designs for multiple components. One manufacturer was able to produce components for one reactor design.

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[267] Paul Homewood, "EDF shares tumble on plan to raise cash to help fund Hinkley Point", *The Telegraph*, April 25, 2016, https://www.telegraph.co.uk/business/2016/04/25/edf-shares-tumble-on-plan-to-raise-cash-to-help-fund-hinkley-poi/.
Nils Zimmermann and Jo Harper, "French nuclear company EDF to get cash infusion", Deutsche Welle (DW), July 7, 2016, https://www.dw.com/en/french-nuclear-company-edf-to-get-cash-infusion/a-19428058.

[268] IAEA PRIS database. Author's own calculations.

Return of experience

Over the course of 59 builds, France was able to maintain a consistent skilled workforce. The supply chain was also consistently meeting its market demands. This meant that a considerable amount of experience was gathered by the workforce and supply chain during these builds. Since the designs were standardized, the experience on one project directly related to the following, and efficiency of the construction process increased as a result. Figure 20 above shows that France was able to maintain an average completion times of six years, and saw increases only correlating to large jumps in design capacity.

Project delays

The EPR projects at Flamanville, Olkiluoto, Taishan, and Hinkley depict the breadth of first-of-its-kind project delays. The Olkiluoto and Hinkley projects both experienced delays on the front end due to long administrative delays caused by nuclear regulators/licensing, delays during construction related to a lack of institutional skill and experience, and delays caused by supply chains having to be reestablished after a nearly three-decades-long intermission between builds. Flamanville and Taishan experienced shorter licensing times due to the fact that the project's nuclear promoters and builders were both SOEs. Flamanville, however, did experience serious delays due to design and engineering flaws. The Taishan project illustrates how SOEs can leverage the return of experience as well as current supply chains to make their projects run more smoothly. The Taishan project was able to avoid project pitfalls and engineering issues that the Olkiluoto and Flamanville projects experienced.

Closing

From 1970 until 2000, France excelled at building civil nuclear power plants because of its use of standardized design; its ability to tap into economies of scale with reactor vessel and reactor component production/supply; fresh and consistent supply chains; the return of experience gained from constructing reactor projects with the same design; and maintaining a continuously engaged skilled labor force.

Once the EPR projects at Olkiluoto, Flamanville, and Hinkley are completed, France can take one of two routes. If its government, investors, and citizens are wary of future EPR builds, France could invest its time and money into SMR or smaller-scale reactor builds—900 MWe. Then, once the supply chain and institutional skills have returned to efficient and reliable levels, resume building EPR design models. If there is support at home to build more EPRs, France could capitalize on the return of experience from the completed EPR projects, a revived civil nuclear supply chain, and from a labor force that continues to build in skill level. If France choses to stay the course and continues to build EPRs at home and abroad, it could very well achieve the same level of success as it did before.

* * *

Case Study 6: Germany

Although German scientists were the first to discover nuclear fission, the aftermath of World War II and the exodus of German, Jewish, and other prominent scientists from across Axis-power and Nazi-occupied states left the Third Reich bereft of its greatest scientific minds. Notable physicists such as Albert Einstein (Germany), Niels Bohr (Denmark), Enrico Fermi (Italy), Leo Szilard (Hungary), George Placzek (Czechoslovakia), Rudolf Peierls (Germany), Otto Frisch (Austrian), and notable chemist Lise Meitner (Austria) moved out of Nazi Germany's reach.[269] This emigration of human capital, often referred to as 'brain drain', delayed Germany's entry into the ranks of civil nuclear power states well after the destruction of the Third Reich and formation of the Federal Republic of Germany.

Fifteen years after the United States' Chicago Pile 1, and six years after France's Zoé reactor, Germany's Atomic Egg reactor went critical on October 31st,1957. Less than a year later, Germany had begun construction of the VAK Kahl civil nuclear power plant. The Kahl reactor was a boiling water reactor (BWR) with a net capacity of 15 MWe.[270] Within ten years Germany had begun construction on another ten reactors. By 1980 Germany had completed builds on twenty-three civil nuclear reactors. Germany began construction on a total of forty-one nuclear reactors, but only completed thirty-six. Currently, Germany has only six operating nuclear reactors, and thirty reactors that have permanently shutdown. Germany plans to phase out (i.e., permanently shutdown) the remaining six reactors as early as 2022 or as late as 2030.[271] Nuclear energy accounted for 12.4% of electricity generated in Germany.[272]

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[269] Craig Morris and Arne Jungjohann, *Energie Democracy*, (London: Palgrave Macmillan, 2016), 300.
[270] IAEA PRIS database.
[271] Morris and Jungjohann, *Energie Democracy*, ch 1.
[272] "Country Nuclear Power Profiles: Germany", IAEA, updated 2020, accessed November 16, 2021, https://cnpp.iaea.org/countryprofiles/Germany/Germany.htm.

Before proceeding, it should be noted that for the entirety of Germany's civil nuclear construction period, 'Germany' did not exist. Germany was divided into East and West, the Federal Republic of Germany (West) and the German Democratic Republic/DDR (East). (See figure 22.) As a result of this divide, the Soviet Union was responsible for promoting, funding, and building civil nuclear power plants in the DDR, and the West German government was responsible for the West.

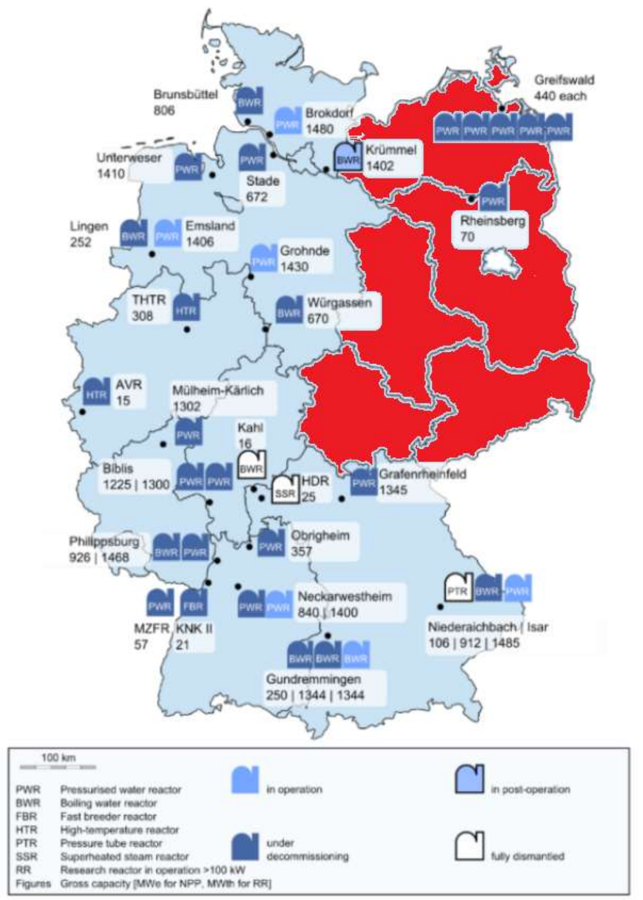

Figure 22—Map of West Germany and East Germany. Source: https://cnpp.iaea.org/countryprofiles/Germany/Germany.htm, [Image altered by author. Red color added to differentiate West from East.]

1958-1970

During this period, Western Germany began construction on ten civil nuclear plants. (see Figures 23 and 24) Several different reactor designs were used—BWR, PWR, pressurized heavy water (PHWR), high temperature gas-cooled (HTGR), and heavy water gas-cooled (HWGCR).[273] The West's average design capacity across these varied reactor types was 223 MWe, with an average construction time of 4.4 years. In 1960, East Germany began construction on only one reactor—a 62 MWe VVER-70 (V-2) reactor at Rheinsberg. This was the first civil nuclear reactor built within the Eastern Bloc outside of the Soviet Union, and East Germany built this reactor with very close collaboration with the Soviet Union.[274] The Rheinsberg reactor took 6.74 years to complete.

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[273] IAEA PRIS database.

[274] W. Fiss and H. Quasniczka, "Rheinsberg nuclear power station - a review of 23 years of operation", *Atomtechnik in der* Atomwirtschaft ATW, 36(4), 174-179, (2019), accessed February 27, 2021, https://inis.iaea.org/search/search.aspx?orig_q=RN:22052041.

1970-1980

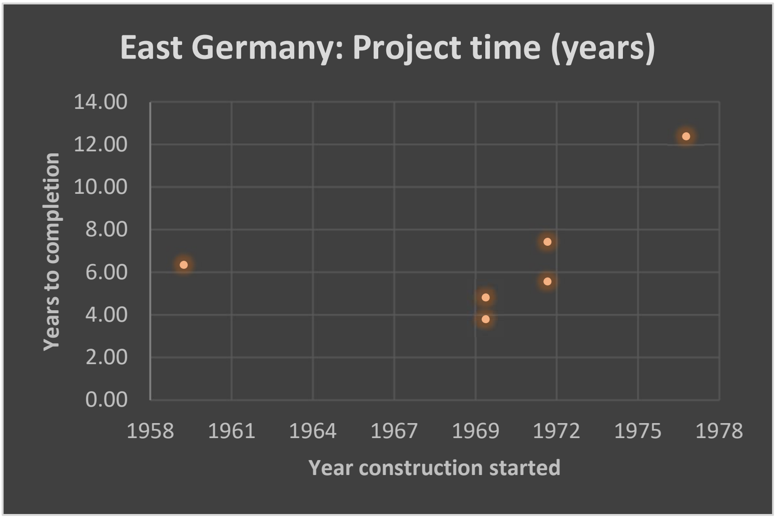

Figure 22--East Germany reactor construction times. Source: data from IAEA PRIS. Author's own graph.

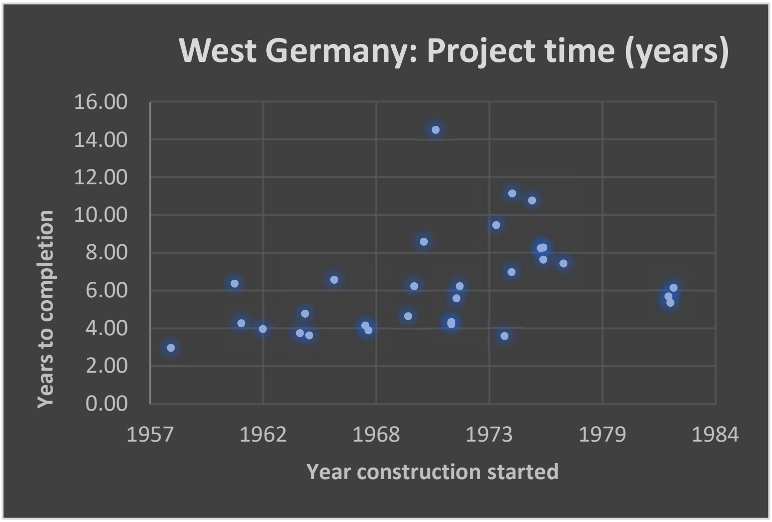

Figure 23-- West Germany reactor construction times. Source: data from IAEA PRIS. Author's own graph.

Both East and West Germany hit their nuclear stride during this decade. The DDR (East) began construction on an ambitious nuclear plant at Greifswald. Construction began on five VVER-440 reactors (the 440 designator is the MWe design capacity). The average construction time for these reactors was 6.8 years.[275] More reactors at this plant site would soon follow.

West Germany began construction on eighteen civil nuclear plants during this period. West Germany constructed mostly PWRs and BWRs with an average design capacity of 1,089 MWe. The West's average construction time for its civil nuclear plants during this period was 7.54 years.

1980-1990

In 1982, West Germany began construction on three reactors at three separate sites—Emsland at Lingen, a second Isar unit at Essenbach, and a second unit at Neckwestheim. The three reactors averaged 1,250 MWe with an average construction time of 5.73 years.[276] All the nuclear plants that began construction in this period, as well as nine plants that began construction in the previous decade, were completed by April of 1989.

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[275] IAEA PRIS database. Author's own calculations.

[276] Ibid., author's own calculations.

In 1981, East Germany continued expanding the capacity of the Greifswald nuclear plant site and began construction on units 6, 7, and 8. In 1982, construction began on an even more ambitious project at Stendal. East Germany planned to build less units than they had at Greifswald, but with a much higher design capacity per unit---1,000 MWe.[277] However, events took place that stopped these plants from seeing completion.

On November 9,1989, the Berlin Wall came down. Less than a year later, Germany was reunified after a forty-five-year separation. No nuclear plants have been built in Germany since the reunification. The average construction time for the six plants built in East Germany from 1958-1989: 6.72 years. The average construction time for the thirty plants built in West Germany from 1958-1989: 6.32 years.[278]

2011—Fukushima and Energiewende

The German response to the Fukushima nuclear disaster was swift and decisive. Germany's Chancellor, Angela Merkel, temporarily shut down seven out of seventeen operating civil nuclear power plants after the Fukushima disaster.[279] This was a dramatic reversal on nuclear energy policy from Merkel's political party, the Christian Democratic Union (CDU), that had worked to extend the life of civil nuclear plants beyond the phase out dates set by the 2008 law.[280] Merkel, a physicist, was in favor of civil nuclear power as a means to combat global warming as well as means of energy independence (from Russia).[281] Months after Fukushima, Germany ordered the permanent shutdown of eight nuclear plants: Biblis A, Biblis B, Brunsbuettel, Phillipsburg 1, Neckarwestheim 1, Isar 1, Unterweser, and Kruemmel. The eight

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[277] IAEA PRIS database.

[278] Ibid., author's own calculations.

[279] "Merkel shuts down seven nuclear reactors", *Deutsche Welle*, March 15, 2011, https://www.dw.com/en/merkel-shuts-down-seven-nuclear-reactors/a-14912184.

[280] "Merkel's Conservatives Advocate Return to Nuclear Energy", *Deutsche Welle*, September 6, 2008, https://www.dw.com/en/merkels-conservatives-advocate-return-to-nuclear-energy/a-3399861.
"UPDATE 2-German poll gives mandate to delay nuclear phaseout", *Reuters*, September 28, 2009, https://www.reuters.com/article/germany-election-nuclear/update-2-german-poll-gives-mandate-to-delay-nuclear-phaseout-idUSLS30439120090928.

[281] Ibid.

plants all shut down on August 6th, 2011.[282] Germany stated the remaining nine reactors would be phased out no later than 2022. Three additional reactors have permanently shut down since then: Graffenrheinfeld, Gundremmingen B, and Phillipsburg 2. There are six remaining operational reactors left in Germany, and they will be shut down in two groups of three. Brokdorf, Grohnde, and Gundremmingen C, will permanently shut down on December 31, 2021; Emsland, Isar 2, and Neckarwestheim 2 will permanently shut down on December 31, 2022.[283]

This drastic shift in Germany's nuclear energy policy has been associated with the buzzword '*Energiewende*', or energy transition. The energy transition is focused on movement away from oil and nuclear towards renewable power. The term became well known outside of Germany following the state's phase out of civil nuclear power, but the phrase had been in use since 1980.[284] The German government took concrete steps in 2000 with a call for a nuclear phase out of all civil nuclear power plants by 2022.[285] Germany's nuclear phase out was preceded by decades of anti-nuclear protests.

Environmental Movement

The 2011 Fukushima disaster was not the first time German citizens were active in voicing their political concerns. In 1975, massive protests—30,000 protesters occupying the construction site—prevented the construction of the Wyhl civil nuclear power plant being built

Figure 22--Wyhl protests in Germany, Source: Deutsche Welle, https://www.dw.com/en/germanys-anti-nuclear-movement-still-going-strong-after-four-decades-of-activism/a-39494549

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[282] IAEA PRIS database.

[283] "Operating times and electricity volumes of German nuclear power plants", Federal Office for the Safety of Nuclear Waste Management, accessed April 26, 2021, https://www.base.bund.de/EN/ns/ni-germany/npp/operating-times/operating-times.html#.

[284] Craig Morris and Arne Jungjohann, *Energy Democracy: Germany's Energiewende to Renewables*. Ch 1

[285] Ibid. Ch. 1

along the Rhein.[286] On May 4, 1981, an estimated 100,000 anti-nuclear protesters assembled at Hamm-Uentrop in protest against the THTR 300 Thorium High Temperature Reactor. The THTR prototype pebble-bed modular reactor had an accident where a pebble was stuck in the feeder tube and its extraction resulted in a release of radiation to the atmosphere.[287] (See Appendix I and J for reactor design description and illustration.)

Figure 23-- Brokdorf protestSource: Deutsche Welle, https://www.dw.com/en/germanys-anti-nuclear-movement-still-going-strong-after-four-decades-of-activism/a-39494549

The combination of the accident at Hamm-Uentrop, followed by the events of the Chernobyl nuclear accident one month later, increased the anti-nuclear sentiments of German citizens. A massive protest was staged at the construction site of a nuclear plant being built west of Hamburg at Brokdorf. The construction site was host to 40,000 demonstrators who violently clashed with 7,000 police.[288] The demonstration turned into a riot, and Molotov cocktails and rocks were thrown at the police force.[289] The protests, while delaying civil nuclear power construction projects, were not stopping the plants from going operational. In 1988, after years of citizens protesting against the Mülheim-Kärlich civil nuclear power plant, the government ended the plant’s operations just 13 months after it was completed.[290] In 2009, protesters built a brick wall blocking the entrance of

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[286] Ibid., Ch 2.

[287] “Protesters Battle Police at Brokdorf, Wackersdorf”, *Associated Press*, June 7, 1986, https://apnews.com/article/485992cc8752979b1c2f1f2367b4a7f5

[288] Richard Bernstein, “Protesters battle police at West German A-plant”, *New York Times*, June 8, 1986, https://www.nytimes.com/1986/06/08/world/protesters-battle-police-at-west-german-a-plant.html.

[289] “Protesters Battle Police at Brokdorf, Wackersdorf”, *Associated Press*

[290] “Germany demolishes cooling tower of former nuclear power plant”, *Deutsche Welle*, September 8, 2019, https://www.dw.com/en/germany-demolishes-cooling-tower-of-former-nuclear-power-plant/a-49967279.

the Neckarwestheim plant keeping preventing plant workers from entering.[291] And in 2011, following the events of Fukushima, citizens staged a protest where a human chain stretched for miles between Stuttgart and the Neckarwestheim nuclear plant. While the political risks posed by the likelihood of protests were assumed by all German private nuclear corporations, one private nuclear corporation absorbed most of the risks in building—Siemens AG.

State-owned Enterprises:

Germany does not currently have state-owned enterprises in the nuclear industry. Similar to Westinghouse in the United States, Germany has a leading private nuclear manufacturer—Siemens AG. Siemens is responsible for designing and building all the western German civil nuclear power plants save for Gundremmingen, Mülheim-Kärlich, HDR Großwelzheim, and Germany's first reactor, VAK Kahl—which were built by U.S. firms (AEG and GE).

Siemens did have joint ventures with other state's SOEs. In 1989 Siemens/KWU and Framatome signed a joint declaration to market PWR reactor abroad.[292] Two years later, Siemens and Framatome formed the joint venture—Framatome ANP, a nuclear export arm of Framatome.[293] Siemens owned 34 percent of the joint venture, and Framatome 66 percent.[294] In 2003, the joint venture contracted with Finland to build the world's first EPR reactor. In 2007, Framatome NP (now renamed Areva NP) contracted with EDF to build the EPR design at Flamanville, and another EPR project in China at Taishan. In 2009, Siemens sold its 34 percent stake in Areva NP citing its "lack of exercising entrepreneurial influence with the joint venture"

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[291] "Thousands protest against Germany's nuclear plants", *BBC News*, Mar 12, 2011, https://www.bbc.com/news/world-europe-12724981

[292] "Framatome memorandum to U.S. NRC", U.S. NRC, April 19, 1989, accessed April 27, 2021, https://www.nrc.gov/docs/ML2009/ML20092K821.pdf.

[293] "From an engineering department to an international company", Framatome corporate website, accessed April 21, 2021, https://www.framatome.com/EN/businessnews-492/framatome-our-history-from-an-engineering-department-to-an-international-company.html

[294] "Siemens to divest its stake in Areva NP joint venture", Siemens, January 26, 2009, accessed April 27, 2021, https://press.siemens.com/global/en/pressrelease/siemens-divest-its-stake-areva-np-joint-venture-loscher-nuclear-power-essential-part

as the reason for the sale.[295] Following Siemens' departure from Areva NP, Siemens started a joint venture with Rosatom. Siemens held one share less than a 50 percent and Rosatom held 50 percent plus one share majority. The focus of the joint venture was to advance the VVER design technology.[296]

Following the events of Fukushima, and Germany's plan to phase out civil nuclear plants in 2022, Siemens announced that it would no longer be involved in the nuclear industry. Siemens stated the move was due to "the clear positioning of German society and politics for a pullout from nuclear energy".[297]

During the East/West divide, the Soviet's state-owned enterprise, Atomenergoexport, was responsible for the six civil nuclear reactors built in East Germany.[298]

Future

Germany plans on retiring the remaining six reactors by the end of 2022. The *Energiewende* plan to replace nuclear and oil with renewables still continues. The year 2019, marked the first time that renewables accounted for more electrical production than coal and nuclear combined.[299] With the phase out of the remaining six nuclear reactors in 2022 there are concerns that Germany may have to rely on importing French electricity—which is

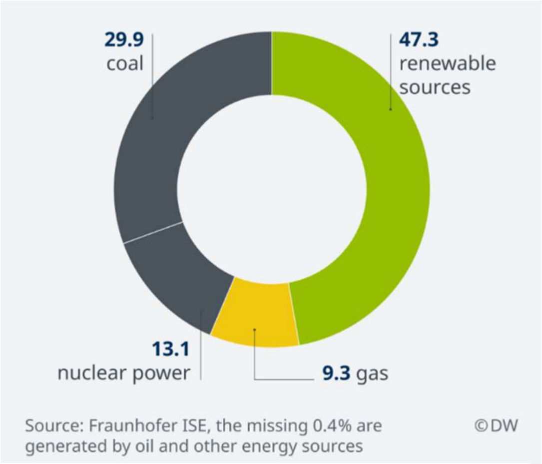

Figure 24-- Germany's energy mix 2019, Deutsche Welle, https://www.dw.com/en/german-renewables-deliver-more-electricity-than-coal-and-nuclear-power-for-the-first-time/a-49606644

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[295] Ibid.

[296] "Rosatom and Siemens sign Memorandum of Understanding on the creation of a nuclear joint venture", Siemens, March 3, 2009, accessed April 27, 2021, https://press.siemens.com/global/en/pressrelease/rosatom-and-siemens-sign-memorandum-understanding-creation-nuclear-joint-venture.

[297] "Siemens to quit nuclear industry", *BBC* News, September 18,2011, https://www.bbc.com/news/business-14963575#.

[298] Gloria Duffy, "Soviet Nuclear Exports", *International Security*, Vol. 3, no.1, 1978, 88, https://www.jstor.org/stable/2626645

[299] "German renewables deliver more electricity than coal and nuclear power for the first time", *Deutsche Welle*, July 16, 2019, https://www.dw.com/en/german-renewables-deliver-more-electricity-than-coal-and-nuclear-power-for-the-first-time/a-49606644

mostly generated by nuclear. Craig Morris, one of the authors of *Energy Democracy*, addressed this concern in an article online.[300] He stated that Germany does import some nuclear-derived power from France when the latter needs to offload excess electricity but does so at very low prices.

Germany continues to construct more renewable energy sources but does not have as strong as an aversion towards coal as it does nuclear. To bridge the gap from a nuclear era to a renewable era, Germany has built a new coal plant--the 1,100 MWe Datteln 4 plant which opened in 2020. The German government has set a phase-out date for coal plants—2038. Climate activists in Germany protested the opening of the plant and voiced concerns of the plants impact on climate change.[301]

Findings

Secure Financing, Standardized Design, and Return of Experience

Siemens AG, as a private corporation, was not able to take advantage of secured government financing. While the preferred supplier of nuclear technology to Germany, it still faced outside competition from U.S. firms. Siemens varied its designs from PWRs and BWRs as well as some experimental reactor designs.[302] Due to design innovation, Siemens did not take advantage of standardized design, or economies of scale. Siemens return of experience was limited due to the variation in plant design.

Atomenergoexport was able to take advantage of secured government financing, standardized design, economies of scale, and return of experience. The dissolution of the Soviet Union as well as the reunification of East and West Germany were extraordinary events that significantly impacted the completion rate of East Germany's civil nuclear power plants—especially

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[300] Craig Morris, "Is Germany reliant on foreign nuclear power?", *Energy Transition*, June 30, 2015, https://energytransition.org/2015/06/germany-reliant-on-foreign-nuclear-power/#.

[301] "Climate activists protest Germany's new Datteln 4 coal power plant", *Deutsche Welle*, May 30, 2020, https://www.dw.com/en/climate-activists-protest-germanys-new-datteln-4-coal-power-plant/a-53632887.

[302] IAEA PRIS database.

the project planned for Stendal and the completion of Greifswald 6, 7, and 8. East Germany had thirteen units planned across three sites: the first plant at Rheinsberg, eight planned for Greifswald, and four planned for Stendal. East Germany, through the Soviet SOE Atomenergoexport, only had one standard VVER PWR design and was able to benefit from standardized design. East Germany's average construction time was 6.72 years. East Germany was also able to take advantage of economies of scale as they constructed five units at one site, Greifswald, and planned for an additional three plants at that site. The planned project at Stendal would also have benefited from economies of scale had the four planned units been constructed there. East Germany was in a unique position to benefit from the return of experience not only from the previous VVER plants that were constructed within East Germany, but those that came before that were constructed in the Soviet Union and other Bloc states.

Project delays

There were significant delays in six projects that well exceeded the average construction times for both East and West Germany. The Mülheim-Kärlich project experienced significant delays due to the aforementioned protests. The project took 11.16 years to complete when the average construction time in the West was 6.32 years. Brokdorf took 10.78 years to complete, and Kruemmel and Phillipsburg 2 took nine years (9.48 and 8.59 years, respectively).[303] East Germany also saw large delays in construction at the Greifswald 5 project. Greifswald 5 was delayed three years due to post-Chernobyl safety changes.[304] The project was completed in 1989, 12.39 years after it began. German reunification occurred a year later, and the plant was taken offline. The longest civil nuclear project that took place in Germany was the THTR 300 Thorium pebble-bed reactor. The design was based on the AVR experimental pebble bed

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[303] Ibid.

[304] "Last Soviet Reactor in Eastern Germany shut", *New York* Times, December 16, 1990, https://www.nytimes.com/1990/12/16/world/last-soviet-reactor-in-eastern-germany-shut.html.

reactor built in 1960. The long delays are typical for constructing a prototype reactor and took 14.54 years to complete.

Closing

Germany's construction of thirty-seven reactors over the course of its divided, and reunited, history was marked by low average construction times (6.39 years--combined East and West), five abandoned projects (all East Germany), and the government-driven early closures of two civil nuclear plants (Mülheim-Kärlich and Greifswald 5 in West Germany).[305] The data for this case study showed that East Germany's construction times were slightly higher than its western counterpart (5 months longer.) This data is slightly skewed as Germany had five civil nuclear power plants that were small (less than or equal to 50 MWe), and additionally four small plants with 100-300 MWe design rating. Once these small plants from the West, and the small 62 MWe plant from the East are factored out, the East and West are close to even at 6.80 (East) and 6.81 (West) years to complete on average.[306]

Within one year from the time of writing, Germany will have shutdown all its nuclear reactors. Germany will rely on coal for approximately a third of its electricity needs and rely on renewable for more than half.[307] Germany will have to expand its renewable energy production further as it plans to phase out coal by 2038.

The decline of German civil nuclear power did not come as a result of failed or abandoned nuclear projects, but due to nuclear fear prompted by nuclear accidents at home and abroad. Should Germany revisit the idea of using nuclear energy to provide electricity, the exit of Siemens AG from the nuclear industry may necessitate importing nuclear technology and expertise from outside Germany. Although Siemens AG could re-enter the nuclear industry

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[305] IAEA PRIS dataset. Author's own calculations.

[306] Ibid. Author's own calculations.

[307] Author's own calculation based on percentages cited in Germany's energy mix chart above.

years down the road, the supply chains and skilled labor forces would likely need to be reestablished.

* * *

Preface to case studies 7, 8, 9, and 10

The following four case studies on China, Japan, South Korea, and India illustrate the advantages of state-owned enterprises operating in Asia, and South Asia. Most of the barriers to constructing a civil nuclear plant that exist in Europe are not present in Asia and South Asia. The post-Fukushima nuclear industry in Asia and South Asia is home to SOEs, utility companies operating monopolies, and governments directing energy market activities. The deregulation of energy markets that occurred throughout Europe in the 1990s has either not transpired in the states discussed in the following case studies, or it occurred long after the state built up its civil nuclear power infrastructure.

These case studies also illustrate how imported civil nuclear power plant projects have the potential to accelerate a host state's civil nuclear power programs, and how the host state quickly develops indigenous design, manufacturing, and construction efforts.

The ability of the state-owned enterprises to take advantage of standardized design, economies of scale, and return of experience is crucial to the paper's argument. Attention should also be paid to the relationship between governments and their nuclear regulatory agencies.

* * *

Case Study 7: China

Although China developed civil nuclear power decades after the first nuclear states, it was able to not only close the gap with other civil nuclear power states, but pass them.[308] In 1985, construction began on China's first civil nuclear reactor, Qinshan 1, along Hangzhou Bay—two hours southwest of Shanghai. The reactor was the first indigenously designed and constructed civil nuclear reactor in China. Its PWR design capacity was 300 MWe, and took 6.74 years to complete.[309] Qinshan 1 connected to the grid on December 15, 1991. After Qinshan, China contracted with nuclear exporters from France, Canada and the Russian Federation to build more advanced nuclear reactors. This afforded China's indigenous scientists and engineers opportunities to learn from nuclear experts from more advanced nuclear states.

China currently has fifty nuclear reactors in operation, zero shutdown reactors, and fifteen reactors under construction. [310] China's average time to complete construction of a civil nuclear reactor project is 5.92 years. That figure broken down into indigenous builds and foreign corporation-led builds: China's average completion time for indigenous builds is 5.4 years, and the average time for foreign nuclear corporations to build in China is 6.94 years.[311] China is the world's third largest producer of civil nuclear power (330 Terawatt hours supplied), but nuclear power only accounts for 4.9

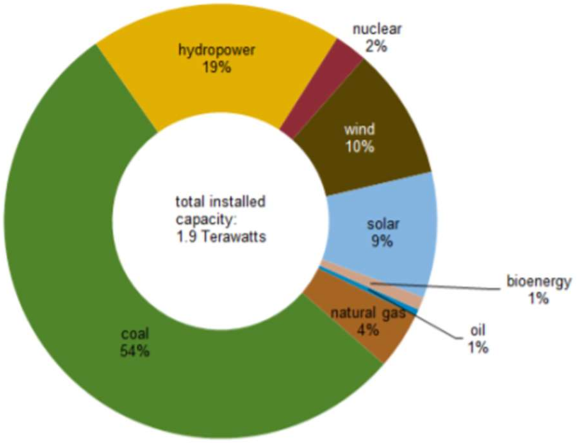

Figure 25-- China's energy production 2018. Source: International Energy Agency, World Energy Outlook report 2019.

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[308] Note: In the 1960s, China constructed nuclear facilities to produce fissile material to build their nuclear bomb. "China's Bomb", *New York Times*, October 18, 1964, https://www.nytimes.com/1964/10/18/archives/chinas-bomb.html

[309] "China updates its oldest reactor", *World Nuclear News*, April 17, 2019, https://www.world-nuclear-news.org/Articles/China-uprates-its-oldest-reactor

[310] Note: IAEA PRIS data from 'Taiwan, China' is excluded from the China data set. The eight (total) reactors at Chinshan, Kuosheng, Lungmen and Maanshan are not included on the IAEA PRIS database at time of writing.

[311] IAEA PRIS database. Author's own calculations.

percent of the electricity generated in China in 2020.[312] The 2019 International Energy Agency reported that coal is relied on for 54 percent of China's electricity production.[313] (Coal production accounts for 58 percent in 2021.)[314] China is increasing its share of nuclear in an effort to meet rising electricity demand. Civil nuclear power can aide in reducing their carbon emissions to meet their Paris Agreement and carbon neutrality pledge timelines of 2030 and 2060, respectively.[315]

The analysis periods for China's civil nuclear power production are grouped as before, by significant periods of construction and demarcated by civil nuclear power milestones (e.g., first-of-its-kind build, switching design types, significant design capacity increases, etc.) This case study will differ from the previous case studies in that strategic planning periods—*Five-year plans*—are added to the analysis period headers.[316] The Five-year plan for each analysis period will be addressed when applicable to nuclear energy.

Five-year plan proposals are issued every five years by the Central Committee of the Chinese Communist Party (CCP). The proposal sets the direction for social and economic development in China.[317] A more detailed discussion of Five-year plans will follow under the *Long-term strategic plan* section.

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[312] "Top ten nuclear energy-producing countries", *Power Technology*, February 12, 2021, https://www.power-technology.com/features/top-ten-nuclear-energy-producing-countries/#.
IAEA PRIS database.

[313] Note: The International Energy Agency's *World Energy Outlook* report is what the U.S. EIA uses in their country analysis reports. (below) The current IEA reports are based on 2018 data. https://www.iea.org/regions/asia-pacific "Country Analysis Executive Summary: China", U.S. Energy Information Administration, updated September 30, 2020, https://www.eia.gov/international/content/analysis/countries_long/China/china.pdf.

[314] "What is China's five-year plan?", *The Economist,* March 4, 2021, https://www-economist-com/the-economist-explains/2021/03/04/what-is-chinas-five-year-plan

[315] Steven Lee Myers, "China's Pledge to Be Carbon Neutral by 2060: What It Means", *New York* Times, September 23, 2020, https://www.nytimes.com/2020/09/23/world/asia/china-climate-change.html.

[316] Note: These Five-year plans may slightly overlap analysis periods, but by no more than one year.

[317] "What is China's five-year plan?", *The* Economist.

1985-2001 (7th, 8th, and 9th Five Year Plans)

In the early stages of China's nuclear industry development, China sought civil nuclear power exporters to build reactors in China: Canada's AECL, France's Framatome/Areva/EDF, and Russia's Atomstroyexport (subsidiary of Rosatom). This first stage of nuclear development provided Chinese scientists and engineers exposure to the construction processes of Canadian CANDU, French M310, and Russian VVER reactor designs. As previously discussed in the case study on France, Chinese personnel also assisted with the civil nuclear power plant construction and operation, under the supervision of the nuclear exporter. This enabled China to develop experience with a variety of different reactor technologies and reactor construction methods.

During this sixteen-year period, twelve civil nuclear plants began construction. One 289 MWe, and two 610 MWe reactors were indigenously designed and constructed at Qinshan with an average construction time of 6.45 years.[318] Nine imported reactor designs were constructed in the period: Framatome built two M310 reactors each at Daya Bay and Ling Ao in 5.95 and 4.79 years, respectively; AECL built two CANDU reactors at Qinshan in 4.58 years; Atomstroyexport built two reactors at Tianwan in 6.6 years; and OKBM Afrikantov Experimental Design Bureau for Mechanical Engineering, alongside the China National Nuclear Corporation (CNNC), built China's experimental fast reactor (CEFR) outside of Beijing. This experimental project took time to complete—11.2 years.

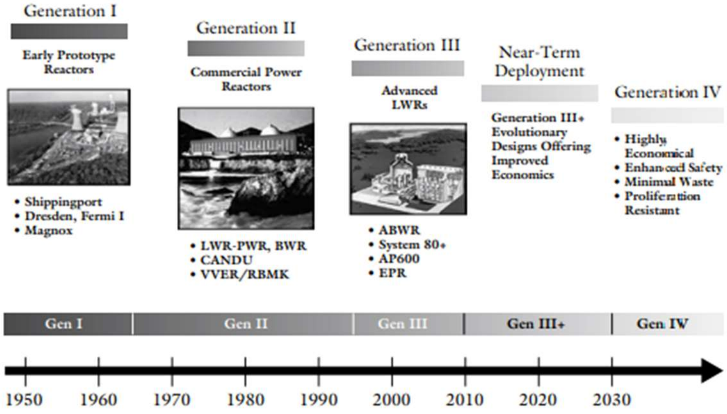

Figure 26—Generations of civil nuclear power designs.

2001-2009 (10th and 11th Five-year plans)

China's 11th Five-year plan included $309B (USD 2011) of government support for clean energy technology—which included

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[318] IAEA PRIS database. Author's own calculations.

nuclear.[319] This period of nuclear construction was the beginning of China's 'Generation II+' reactor designs. (See Figure 26 above.[320])

Although China's nuclear development lagged twenty years behind its nuclear peers, it caught up quickly. From 2005 to 2009, China began construction on a total of twelve nuclear plants. These CNP-600s and 1000s, and CPR-1000s were designed indigenously and built fast.[321] They were modeled after the Framatome M310, which featured post-Three Mile Island safety measures built into the design.[322] These plants were constructed in an average of 5.2 years—which is faster than the averages of France, Russia, and the United States.[323]

The graph in Figure 27 shows not only the consistency with which China built the CNP and CPR reactors, but also the speed. During the gap between 1985 and 1996, when no new indigenous civil nuclear projects broke ground, two imported nuclear projects broke ground. The same is true for the gap between 1997 and 2005 with six imported plants.

Figure 27--China's indigenous project times for CNP and CPR 600-1000 reactors. Source: data IAEA PRIS, author's own graph.

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[319] Joseph Casey and Katherine Koleski, "Backgrounder: China's 12th Five-Year Plan", U.S.- China Economic and Security Review Commission, June 24, 2011, https://www.uscc.gov/sites/default/files/Research/12th-FiveYearPlan_062811.pdf.

[320] Stephen M. Goldberg, and Robert Rosner, "Nuclear Reactors: Generation to Generation", American Academy of Arts and Sciences, 2011, Image "reprinted from U.S. Department of Energy, Office of Nuclear Energy, "Generation IV Nu clear Energy Systems: Program Overview", http://www.amacad.org/sites/default/files/academy/pdfs/nuclearReactors.pdf

[321] Note: CPR reactors are from China's SOE China Guangdong/General Nuclear Power Group (CGN); and CNP reactors are from China's second SOE, China National Nuclear Corporation (CNNC).

[322] Sonal Patel, "Evolutionary Triumph: China's First ACPR1000", *POWER*, November 1, 2019, https://www.powermag.com/evolutionary-triumph-chinas-first-acpr1000/.

[323] IAEA PRIS database, author's own calculations.

Starting in 2009, imported Gen III reactor designs were built concurrently with domestic projects. (See Figure 27.)

2009-2019 (12th and 13th Five Year Plans)

After China gained proficiency building their Gen II+ CPR/CNP 1000 reactors, they contracted with Westinghouse to acquire the new Gen III+ AP1000 reactor, and with Framatome to acquire the new Gen III+ EPR-1750 reactor. Unlike builds from the first period, China had built up sufficient experience and took on more of the projects. While the reactor designs and reactor vessels were supplied by the nuclear exporters, the steam generators, nuclear fuel, and other systems were designed and produced domestically. China also had a larger role in the construction process. The contracts were written such that the nuclear exporters agreed to transfer nuclear technology to China—this transfer is not only for the physical equipment, but the designs, and all other knowledge required to replicate the effort on their own. This technology transfer was a contentious point for both exporters.[324] Technology transfers would be analogous to a baker selling their secret recipe to a competitor—there would be nothing stopping the competitor from later building a reactor of that design for themselves.

The first Gen III+ reactor to begin construction was the Westinghouse AP1000 reactor in Sanmen. Concurrently, the Framatome EPR-1750 began construction at Taishan.[325] Even though it started five months later, the EPR project overtook Sanmen-1's progress and finished a day before it. In June of 2018, China had not only caught up to its nuclear peers but surpassed them by building not one but two Gen III+ reactors. At the time of writing, no other

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[324] Leslie Hook, "U.S. group gives China details of nuclear technology", *Financial* Times, November 23, 2010, https://www.ft.com/content/fcac14a8-f734-11df-9b06-00144feab49a
David Winning, "Westinghouse Seals China Deal", *Wall Street* Journal, July 25, 2007, https://www.wsj.com/articles/SB118530110836876396

[325] "China loads fuel at world's first AP1000 nuclear reactor", *Reuters*, April 27, 2018, https://www.reuters.com/article/china-nuclear-ap1000/china-loads-fuel-at-worlds-first-ap1000-nuclear-reactor-idUSL3N1S503S.

state has an operational Gen III reactor (AP1000 and EPR design types are examples of Gen III+.) France has not yet completed its own EPR reactor at Flamanville, and the United States has yet to complete its AP1000s at Vogtle. The U.S. had also recently abandoned the AP1000 project at Virgil C. Summer the year previous.[326] In addition to those 'firsts' for China, progress continued and an additional three AP1000s were constructed—one more at Sanmen, and two reactors at Haiyang. An additional EPR was constructed and completed at Taishan, a year after the first. Russia's Atomstroyexport built two Gen III VVER V-428M design reactors at Tianwan.[327]

The EPR units 1 and 2 at Taishan were built in 9.2 and 8.69 years, respectively. This is a remarkable feat considering the comparison to the Flamanville and Olkiluoto projects passing their thirteen and fifteenth year of the project, respectively. The success of the AP1000 projects at Sanmen and Haiyang are also remarkable. Sanmen units took an average of 8.94 years, and Haiyang's average was 8.61 years.[328]

China's 12th Five-year plan (covering 2011-2015) included a goal to develop civil nuclear power more efficiently and called for a 40 million kW increase in nuclear capacity.[329] During the 12th Five-year plan, China began construction on the first Advanced Chinese Pressurized Reactor (ACPR1000) in 2013. Its design was based off the M310/CPR1000 design with 28 modifications and safety improvements to the old design that address safety issues from the Fukushima event. The ACPR1000 has various passive systems put in place (passive meaning they work during a power outage) such as long-term and passive heat removal systems, as well as a reactor pit flooding system.[330]

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[326] Brad Plumer, "U.S. Nuclear Comeback Stalls as Two Reactors Are Abandoned", *New York Times*, July 31, 2017, https://www.nytimes.com/2017/07/31/climate/nuclear-power-project-canceled-in-south-carolina.html
[327] Kamen Kraev, "China / Tianwan-4 VVER Handed Over To Operator By Russia's Atomstroyexport", *NUCNET news*, December 28, 2020, https://www.nucnet.org/news/tianwan-4-vver-handed-over-to-operator-by-russia-s-atomstroyexport-12-1-2020
[328] IAEA PRIS database. Author's own calculations.
[329] Joseph Casey and Katherine Koleski, "Backgrounder: China's 12th Five-Year Plan"
[330] Sonal Patel, "Evolutionary Triumph: China's First ACPR1000", *POWER*.

The graph in Figure 28 shows the varying rates of the nuclear imports being constructed in China. The red triangles show the construction times of the VVER-428, the white circle shows the Gen III+ AP1000 and EPR, and the gold boxes show the M310 and CANDU reactors. The outlier near the top of the graph is the experimental CEFR reactor.[331]

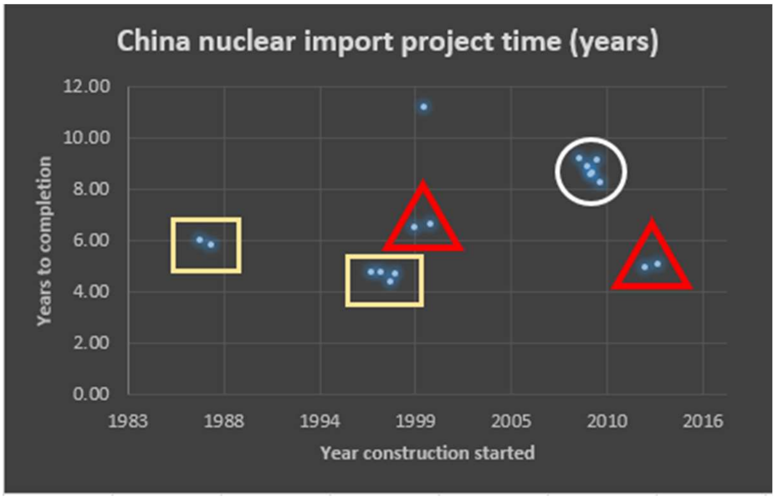

Figure 288-- China's reactor construction times for imported reactor builds. Source: data from IAEA PRIS. Author's own graph.

2019—present (14th Five-year plan)

In 2019, China used the experience gained from the second round of nuclear reactor imports to design and build a next-generation reactor. The Hualong One (HPR1000) is China's first indigenous Gen III design, with a domestically built reactor vessel.[332] In 2019 and 2020, China began construction on two Hualong One (HPR1000) reactors at Zhangzhou, two at Taipingling, and one at Zheijiang San'ao.[333] At the time of writing, the Hualong One reactors are all still under construction.

China also reached an agreement with Russia and contracted with them to build two Gen III+ VVER-1200 reactors at Tianwan, and two more at a new site—Xudabao.[334] China has also partnered financially with France's EDF on the Hinkley Point C project in the United Kingdom.

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[331] IAEA PRIS database.

[332] "Reactor vessel installed at Chinese Hualong One Unit", *World Nuclear News*, January 29, 2018, https://www.world-nuclear-news.org/NN-Reactor-vessel-installed-at-Chinese-Hualong-One-unit-2901184.html

[333] IAEA PRIS database

[334] "China and Russia sign general contract for two Xudabao units", *World Nuclear News*, June 6, 2019, https://world-nuclear-news.org/Articles/China-and-Russian-sign-general-contract-for-two-Xu.

State owned enterprises

China has an incredible number of SOEs—over 150,000.[335] Seventy-five SOEs are in the Fortune Global 500.[336] China has not one, but two major nuclear promotion SOEs: China General Nuclear Power Group (CGN) and the China National Nuclear Corporation (CNNC). China has many more SOEs that work in conjunction with the nuclear promotion SOEs. Engineering SOEs like the China Nuclear Engineering & Construction Corp (CNEC) and banking SOEs like the China Development Bank, and China Power Investment Corporation (CPI) are able to work in concert with the nuclear promotion SOEs to advance China' nuclear goals. Much like the case study of Russia, China's usage of their SOEs is an excellent example of Lenin's 'Commanding Heights' principle. China can coordinate SOEs' actions to achieve their governmental and societal goals.

The China National Nuclear Corporation (CNNC) was established in 1988 as a state-owned enterprise by the State Council. The CNNC is responsible for nuclear promotion, front-end fuel cycle production (Uranium mining and fuel-fabrication), research and development of nuclear technology, reactor design, and back-end fuel cycle (reprocessing fuel cells and waste disposal.)[337] The CNNC designed the CNP-300, CNP-600, CNP-1000, ACPR-1000, and HTR-PM reactors. The CNNC also jointly designed the first indigenous Gen III reactor--Hualong One (HPR-1000) --with the CGN. These designs are built by the China Nuclear Engineer &

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[335] Karen Jingrong Lin, et al., "State-owned enterprises in China: A review of 40 years of research and practice", *China Journal of Accounting Research*, Vol. 13, no. 1, (March 2020), 31-55. https://doi.org/10.1016/j.cjar.2019.12.001.
"China's state enterprises are not retreating but advancing", *The Economist*, July 20, 2017, https://www.economist.com/leaders/2017/07/20/chinas-state-enterprises-are-not-retreating-but-advancing.

[336] Note: *Fortune Global 500* is the global version of the Fortune 500. The Fortune 500 only accounts for U.S. companies.

[337] "Nuclear Organisations [sic] in China", *World Nuclear Association*, updated September 2020, https://world-nuclear.org/information-library/country-profiles/countries-a-f/appendices/nuclear-power-in-china-appendix-1-government-struc.aspx

Construction Corp (CNEC) and with the support of other SOEs. In 2018, China merged the CNEC into the CNNC to increase the efficiency of civil nuclear power plant construction.[338] The CNNC has designed and built 21 reactors, and jointly designed and built the 5 Hualong One (HPR-1000) reactors at Taipingling (2), Zhangzhou (2), and Zheijiang San'ao (1) with CGN.

The China General Nuclear Power Group (CGN)—formerly the China Guangdong Nuclear Group—was established in 1994 as a state-owned enterprise. Initially, the CNNC owned a 45 percent share of the CGN, the provincial government owned 45 percent, and the remaining 10 percent was owned by China Power Investment Corporation (CPI).[339] The CGN is historically responsible for constructing and operating civil nuclear power plants in Guangdong province (the coastal province opposite Hong Kong). Initially, the China Guangdong Nuclear Group only built nuclear plants within its province, likely owing to the fact that the Guangdong provincial government was a principal shareholder. In 2012, the China Guangdong Nuclear Group was reconstituted, and majority ownership (82 percent) was placed in the hands of the State-owned Assets Supervision and Administration Commission (SASAC).[340] (The SASAC was established in 2003 to consolidate select government ministries centered on industry.[341]) The state province's share was reduced from 45 percent down to 10 percent, and CNNC's share was reduced from 45 percent down to 8 percent.[342] When the CGN was reconstituted, it was rebranded from China Guangdong Nuclear Group to the China General Nuclear Power Group due to its expanding mission to build and operate nuclear power plants outside of Guangdong

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[338] Huang Kaixi, et al., "China combines two state-owned nuclear firms into powerhouse", *Caixin*, February 1, 2018, https://www.caixinglobal.com/2018-02-01/china-combines-two-state-owned-nuclear-firms-into-powerhouse-101205786.html

[339] "Nuclear Organisations in China", *World Nuclear Association*, September 2020, https://world-nuclear.org/information-library/country-profiles/countries-a-f/appendices/nuclear-power-in-china-appendix-1-government-struc.aspx

[340] Ibid.

[341] John Bryan Starr, *Understanding China: A guide to China's economy, history, and political culture* [3rd edition], (New York: Hill and Wang, 2010), 141.

[342] Nuclear Organisations in China", *World Nuclear Association*.

province.[343] From 2005 to 2016, CGN designed and broke ground on 20 reactors, as well as the aforementioned 5 Hualong One reactors.[344] The CPR-1000 reactor design was exclusively used by CGN until the joint-design of Hualong One was introduced.

Nuclear regulator

China's nuclear regulatory agency is the Ministry of Ecology and Environment (MEE), which is also known as the National Nuclear Safety Administration (NNSA). The MEE/NNSA was established in 1988 under the State Science and Technology Commission (SSTC).[345] The NNSA is responsible for regulation of nuclear safety, radiation safety, design, licensing, manufacture, and radiation environmental protection.[346] In 1998, China transferred its NNSA out of the SSTC and housed it in the State Environmental Protection Administration (SEPA). In 2008, the SEPA was upgraded to a higher level and became the Ministry of Environmental Protection (MEP). As such, its Minister reports directly to the State Council, which in turn reports to the National People's Congress. In 2017, the passage of the Nuclear Safety Law of China gave the NNSA more power to regulate nuclear activities.[347] In 2018, institutional reforms were made to the MEP by the State Council. The MEP was restructured as the Ministry of Ecology and the Environment (MEE).[348]

The MEE/NNSA has centralized regulatory activities and made efforts to streamline the nuclear regulatory process. The MEE/NNSA has generic inspection programs for construction, commissioning, and operations. Additionally, the MEE/NNSA combined the First Fuel Loading

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[343] "CGNPC renamed to reflect expansion", *World Nuclear News*, May 15, 2013, https://www.world-nuclear-news.org/C-CGNPC_renamed_to_reflect_expansion-1505134.html#

[344] IAEA PRIS database.

[345] "About NNSA", NNSA/MEE website, updated 2020, accessed May 4, 2021, http://nnsa.mee.gov.cn/english/nnsa/overview/.

[346] Ibid.

[347] "China's legislature passes nuclear safety law", *Reuters*, September 1, 2017, https://www.reuters.com/article/us-china-nuclearpower/chinas-legislature-passes-nuclear-safety-law-idUSKCN1BC4ER.

[348] "China's historical evolution of environmental protection along with the forty years' reform and opening-up ", Environmental Science and Ecotechnology", *Environmental Science and Ecotechnology*, Vol. 1, (January 2020), https://www.sciencedirect.com/science/article/pii/S2666498419300018.

Permit and the Operation Permit into one license to reduce administrative processing time during construction.[349]

As mentioned in the *Nuclear Regulatory Comparison* section in chapter 2, the apples-to-apples comparison of EPR design reactors being built in Finland, France, United Kingdom, and China revealed that China's design approval and construction licensing timelines were faster by one year than Finland and two years than the United Kingdom; China's timelines were equal to France's timelines in this regard.

Environmental Stewardship

Civil nuclear power only accounts for five percent of electricity generated in China.[350] Coal, on the other hand, accounts for 58 percent—and the amount generated is *vast*. China is the world's largest generator of coal-produced electricity and in 2019 it produced 22,686 Terawatt hours (81.67 Exajoules) of energy from coal alone.[351] That number is over four times the amount of the world's second largest producer—India. The amount of coal consumed exceeds fifty percent of worldwide usage, making China the leader in CO_2 emissions.

Climate change gained prominence in 2006 and quickly became a political focal point—especially for China. The same year as *An Inconvenient Truth* was released in an effort to spread the word to the masses about the dangers of greenhouse gas emissions, China surpassed the United States in greenhouse gas emissions to become the world's largest CO_2 emitter.[352] As mentioned earlier, Carbon Dioxide is not the only greenhouse gas of concern. Sulfur Dioxide (SO_2) and Fine particulate matter ($PM_{2.5}$) impact air quality which adversely impacts nearby residents' respiratory health.[353] A major source of Sulfur Dioxide is the

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[349] "China's Regulatory Practice on New Reactors Transition to Operation", U.S. NRC, accessed April 12, 2021, https://www.nrc.gov/public-involve/conference-symposia/ric/past/2019/docs/abstracts/zhous-th30-hv-r1.pdf.

[350] IAEA PRIS database.

[351] Melissa Garside, "Largest coal consumption worldwide by country 2019", *Statista*, November 5, 2020. https://www.statista.com/statistics/265510/countries-with-the-largest-coal-consumption/

[352] "China overtakes U.S. in greenhouse gas emissions", *New York* Times, June 20, 2007, https://www.nytimes.com/2007/06/20/business/worldbusiness/20iht-emit.1.6227564.html.

[353]

combustion of fossil fuels at power plants—such as coal power plants, and emissions from industrial facilities.[354] Fine particulate matter is also emitted from power plants, but a smaller share when compared to the large shares emitted from the combustion of fires, vehicle engines, residential and agricultural sources (fireplaces and burning fields).[355] Fine particulate matter that is less than or equal to 2.5 microns in diameter is dangerous to human health because it is small enough to travel through the lungs and be absorbed into the bloodstream.[356]

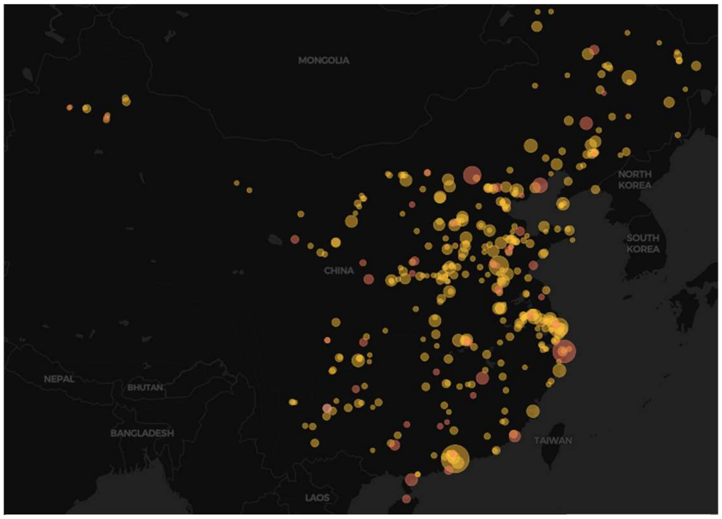

Figure 29-- Coal plants in China in 2000. The size of the circle denotes the size of the plant. Orange indicates operating plants. Source: Carbon Brief, https://www.carbonbrief.org/mapped-worlds-coal-power-plants

The cause of China's increase in greenhouse gases was due to industry expansion. From 1990 to 2017, China's economy grew rapidly, and increased their GDP by a factor of 43 (4,300 percent).[357] This growth prompted a rapid growth of electrical power generation infrastructure, and China built coal plants to meet that need. The two figures to the right illustrate the number of coal plants in China in the year 2000

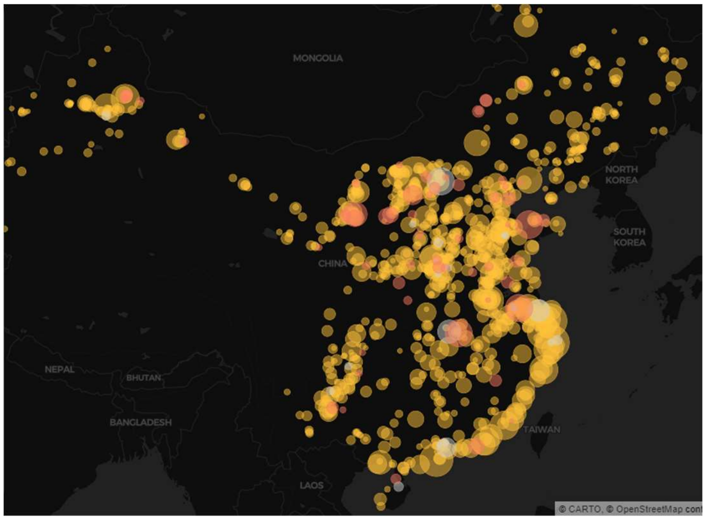

Figure 30-- Coal plants in China in 2019. Source: Carbon Brief, https://www.carbonbrief.org/mapped-worlds-coal-power-plants

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[354] "Sulfur Dioxide (SO_2) Pollution", U.S. EPA, updated April 2, 2019, https://www.epa.gov/so2-pollution/sulfur-dioxide-basics

[355] Frederico Karagulian, et al., *Attribution of anthropogenic PM2.5 to emission sources: A global analysis of source-receptor model results and measured source-apportionment data*, (Brussels, European Commission, 2017), https://publications.jrc.ec.europa.eu/repository/handle/JRC104676

[356] Dan Levin, "Study links polluted air in China to 1.6 million deaths a year", *New York Times*, August 13, 2015, https://www.nytimes.com/2015/08/14/world/asia/study-links-polluted-air-in-china-to-1-6-million-deaths-a-year.html.

[357] Xi Lu, et al., "Progress of Air Pollution Control in China and Its Challenges and Opportunities in the Ecological Civilization Era", *Engineering*, Volume 6, Issue 12, (December 2020), Pages 1423-1431, https://www.sciencedirect.com/science/article/pii/S2095809920301430#b0035

and in the year 2019. From 2000 to present, China built an extensive number of coal power plants to support the growing industrial needs of the state. With the increase in operating fossil fuel plants, came an increase in greenhouse gases and particulates.

In 2015, a study on air pollution from *Berkeley Earth* stated that China had 1.6 million deaths caused by air pollution each year.[358] One of the authors, Richard Muller, also co-authored a study on air pollution in China, which mapped out the air pollution data and put air quality in terms of smoking X number of cigarettes per day.[359] As the image to right illustrates, the areas of dark red had the most hazardous air quality on the 13th of December, 2015. This second study drew equivalencies between breathing the air of Shanghai, for example, on a given day with the harmful effects of an individual smoking 25 cigarettes that day. (See image to right.)

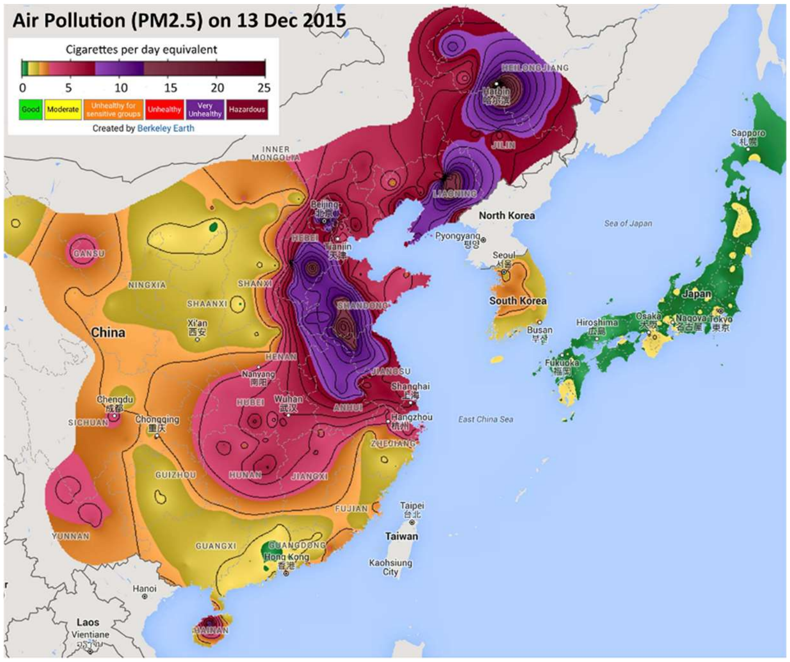

Figure 31--Air pollution map. Source: Richard Muller and Elizabeth Muller, "Air Pollution and Cigarette Equivalence", Berkeley Earth

In the mid-2000s, China saw a surge of environmental protests. Citizens protested against toxic industrial waste being dumped in the rivers, rendering their waters undrinkable for livestock and humans alike.[360] The pollution was highly evident in the cases of the Xiangbi (2018) and Yangtze (2012) rivers where the

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[358] Dan Levin, "Study links polluted air in China to 1.6 million deaths a year", *New York Times*, August 13, 2015, https://www.nytimes.com/2015/08/14/world/asia/study-links-polluted-air-in-china-to-1-6-million-deaths-a-year.html.

[359] Richard Muller and Elizabeth Muller, "Air Pollution and Cigarette Equivalence", *Berkeley Earth*, December 17, 20155, http://berkeleyearth.org/air-pollution-and-cigarette-equivalence/.

[360] Christina Larson, "China's Emerging Environmental Movement", *Yale360*, June 2, 2008, https://e360.yale.edu/features/chinas_emerging_environmental_movement

waters turned blood red.[361] Environmental protests, or ‘mass incidents’, occurred often within China.

Small groups of environmental protesters were occasionally tolerated by the government but were typically dispersed by the police. This was the case for protesters upset about the air quality in Chengdu. The protesters made a statement by putting facemasks on statues in the city center and were subsequently dispersed or detained by police.[362] Stories like environmental protests are typically downplayed by the state-run China Central Television (CCTV), as well as censorship of news on the internet.[363] The government of China, under direction of its leader Xi Jinping, is also able to filter out unwanted internet content that is not aligned with the views of the government.[364] The government’s control of the internet, also referred to as the ‘Great Firewall of China’, extends further as China prevents its citizens from accessing western sites like Google, Facebook, Instagram, Twitter, Youtube, and western banking sites.[365] The government is thus able to contain local protests and prevent them from growing into coordinated environmental movements.

When environmental protests, or ‘environmental mass incident’, occur in China, it tends to follow a pattern: Citizens complain about an environmental issue. Government ignores citizens for a period of time. Citizens openly protest on the streets. [366] Unrest seen as a threat to

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[361] Katherine Hignett, “This River Mysteriously Turned Bright Red, Baffling Locals”, *Newsweek*, July 4, 2018, https://www.newsweek.com/river-red-china-1007818#:~:text=The%20Yangtze%20has%20also%20seen,an%20unusually%20large%20algal%20bloom.

[362] Benjamin Haas, “China riot police seal off city centre after smog protesters put masks on statues”, *The* Guardian, December 12, 2016, https://www.theguardian.com/world/2016/dec/12/china-riot-police-seal-off-city-centre-after-smog-protesters-put-masks-on-statues.

[363] Beina Xu and Eleanor Albert, “Media Censorship in China”, *Council on Foreign Relations*, February 17, 2017, https://www.cfr.org/backgrounder/media-censorship-china

[364] Elizabeth Economy, “The great firewall of China: Xi Jinping’s internet shutdown”, *The* Guardian, June 29, 2018, https://www.theguardian.com/news/2018/jun/29/the-great-firewall-of-china-xi-jinpings-internet-shutdown

[365] Alice Su and Frank Shyong, “The Chinese and non-Chinese internet are two worlds. Here’s what it’s like to use both”, *Los Angeles* Times, June 3, 2019, https://www.latimes.com/world/la-fg-us-china-internet-split-20190603-story.html.

[366] Ma Tianjie, “China Environment Series”, in *Woodrow Wilson International Center for Scholars*, Issue 10, 2008/2009, ed. Jennifer Turner, https://pdf.usaid.gov/pdf_docs/pnady986.pdf#

social stability.[367] Government becomes responsive, adopts their cause as their own, and informs citizens that it will fix the environmental issue—but on a timeline decided by the government.[368] Government implements stricter industry standards—which are not fully enforced. The Shifang protest exemplified this pattern: Citizens complained about a copper plant being built near their city, and the government was not responsive. Citizens protested, and the government responded by first suspending the construction project, then later terminating the project.[369]

President Xi Jinping's administration has responded to environmental protests by imposing stricter environmental standards for industry and pledging a target goal of reaching peak CO_2 emissions by 2030 (i.e., 2031 emissions will have to be less than 2030) for the Paris Agreement. China has also pledged to reduce its 'carbon intensity' of 40 to 45 percent below 2005 levels by 2020 at the Copenhagen Accord, and pledged for China to become carbon neutral by 2060. Most recently, China called for 40 percent of vehicle sales to be electric vehicles.[370] Carbon intensity, or the amount of CO_2 produced to make 1 kW/hour of electricity, can be lowered through the reduction of operating coal plants.[371] Civil nuclear power plants, aside from their construction period, do not emit any CO_2 during operation and are considered to be of low carbon intensity.

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[367] "China paper blames poor government decisions for violent protest", *Reuters*, July 30, 2012, https://www.reuters.com/article/us-china-environment-protest/china-paper-blames-poor-government-decisions-for-violent-protest-idUSBRE86T04N20120730.

[368] Michael Standaert, "As it looks to go green, China keeps a tight lid on dissent", *Yale360*, November 2, 2017, https://e360.yale.edu/features/as-it-looks-to-go-green-china-keeps-a-tight-lid-on-dissent.

[369] "China paper blames poor government decisions for violent protest", *Reuters.*

[370] Steven Lee Myers, "China's pledge to be carbon neutral by 2060: What it means", *New York Times*, September 23, 2020, https://www.nytimes.com/2020/09/23/world/asia/china-climate-change.html.
"China: Pledges and Targets", Climate Action Tracker, September 21, 2020, https://climateactiontracker.org/countries/china/pledges-and-targets/.
"Nancy Stauffer, "China's transition to electric vehicles", *MIT News*, April 29, 2021, https://news.mit.edu/2021/chinas-transition-electric-vehicles-0429.

[371] "U.S. Energy-related carbon dioxide emissions", *EIA*, September 30, 2020, https://www.eia.gov/environment/emissions/carbon/.

Anti-nuclear political protests have not been as strongly voiced as have the protests against chemical plants. Even after the events of Fukushima, the only notable protest was a NIMBY (not in my backyard) protest against a nuclear fuel reprocessing plant (i.e., taking spent reactor fuel rods and chemically separating Plutonium from them to use to fuel reactors or produce nuclear weapons) in Jiangmen.[372] Post-Fukushima era anti-nuclear sentiment does not seem to have a strong footing in China at present; and the government is very committed to China's nuclear expansion.

Long-term strategic plan

China's government has both long-term goals and the political continuity necessary to carry them out. It plans and carries out Five-Year plans which direct the economic and social path that China takes.[373] China's 'Made in China 2025' plan of 2015 aims to shift manufacturing away from low-technology goods, and into higher technology goods during the 13th and 14th Five-Year plans.[374] China also made plans to build six to eight nuclear reactors each year from 2020 to 2025.[375]

The benefits of a government administration that plans in long-term economic goals, instead of next-term political goals is evident in China's economic expansion—both domestically and internationally.

Future

China's success with the Gen III EPR reactor at Taishan, and their current partnership at Hinkley Point C, has given China the experience to build more EPR-design reactors if they so

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[372] "'No Nukes' China's latest NIMBY protest", *Wall Street* Journal, https://www.wsj.com/articles/BL-CJB-18145

[373] "What is China's five-year plan?", *The Economist*.

[374] Elsa Kania, "Made in China 2025, Explained", *The Diplomat*, February 1, 2019, https://thediplomat.com/2019/02/made-in-china-2025-explained/.

[375] David Stanway, "China to build 6-8 nuclear reactors a year from 2020-2025 report", *Reuters*, July 8, 2020, https://www.reuters.com/article/china-nuclearpower/china-to-build-6-8-nuclear-reactors-a-year-from-2020-2025-report-idINKBN24A0DL.
Note: In 2020, China only broke ground on three civil nuclear power plants, and only one plant has broken ground in 2021.

choose, but it is more likely that China will incorporate features from the EPR into its indigenous HPR-1000. The five HPR-1000 designed reactors created by CGN and CNNC are currently being constructed at Zhangzhou, Taipingling, and Zheijiang San'ao.[376] China's State Power Investment Corp (SPIC) has recently designed and began construction on the Guohe One, CAP1400 reactor. This reactor is a larger version of Westinghouse's AP1000 design which China was able to indigenously procure 90 percent of the necessary components.[377]

There are two developments to emerge from China's civil nuclear research: Thorium molten salt reactors, and fusion reactors. The Thorium molten salt reactor uses Thorium, which is naturally abundant in China, as the fuel source. Due to molten salt being the primary coolant, the reactor can operate at higher temperatures, which increases the efficiency of the electrical power generation. China has built several small molten salt research reactors and a 100 MW Thorium molten salt reactor is planned to be operational by 2030.[378] Historically, Thorium reactors have not proved successful enough to attempt a commercial venture with, and it would be likely that China proceeds cautiously in this venture.

Findings

State-owned enterprises

China's direction of its state-owned enterprises during the construction of civil nuclear power plants achieves synergy and success. China's merger of the CNEC construction firm, and the China National Nuclear Corporation (CNNC) increased the efficiency of the construction process.

The China General Nuclear Power Group (CGN) and the CNNC joined together on the HPR-1000 project which, if successful, can lead to collaboration on future projects. Through China's

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[376] IAEA PRIS database.

[377] "China launches CAP1400 reactor design", *World Nuclear News*, September 29, 2020, https://world-nuclear-news.org/Articles/Large-scale-Chinese-reactor-design-officially-laun.

[378] "Zhimin Dai et all., "Thorium-based Molten Salt Reactor (TMSR) project in China" (India: Bhabha Atomic Research Centre, 2013), https://inis.iaea.org/search/search.aspx?orig_q=RN:44041321

application of commanding heights, and its state control of SOEs, China is able to advance its civil nuclear power program and weather political and financial bumps in the road that private corporations in the Post-Fukushima era cannot.

Secure financing

China's nuclear SOEs have access to the China Development Bank, and the China Power Investment Corporation where they can obtain the necessary capital to start and complete projects. Following Fukushima, the global nuclear industry experienced higher political risk due to the uncertainty that the public could protest or call upon their government to cancel nuclear construction projects. Having access to secure financing coupled with China's political continuity under the Communist Party gave China the certainty of its projects' success, and resulted in the completion of more civil nuclear projects.

Standardized design

China's two SOEs, the CNNC and CGN, each put forward their standardized design—the CNP-600 and CPR-1000, respectively. These standardized designs were constructed from 1996 to 2010, with a few design capacity increases following. The CNNC introduced the next generation design, the ACPR-1000, in 2013. This period culminated with the CGN and CNNC joint design of the HPR-1000. [379] The long series of standardized design built by each SOE was effectively splitting up China's indigenous nuclear supply chain, however, construction completion times were still shorter than the global average. The construction of the HPR-1000 design is still ongoing (the series of builds began in late 2019), but it is likely that the construction times for these plants will meet or surpass the previous average completion times due to this consolidation of the supply chain.

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[379] "CGN's Hualong One design certified for European use", *World Nuclear News*, November 12, 2020, https://world-nuclear-news.org/Articles/CGNs-Hualong-One-design-certified-for-European-use

Economies of scale

China excels at taking advantage of economies of scale. As indicated by the unit numbers of their reactors, China is building upwards of six reactors at each site. This takes advantage of the economies of scale as the site licensing process is streamlined, and the skilled workforce and supply chain is already in place for each site. Additionally, since China is constructing a series of four to six reactors, and constructing multiple reactors at a time, the manufacturing process is also able to take advantage of economies of scale.

Return of experience

Over the course of China's thirty-four completed indigenous builds, its average completion time was 5.4 years. With very few exceptions, China broke ground on several indigenous civil nuclear power construction projects each year from 2005 to present. In addition to the indigenous projects, China was also participating on the construction of imported civil nuclear plants. This construction tempo necessitated the maintenance of a skilled workforce, and an efficient supply chain. China benefited not only from their experience working on previous standardized designs, but also from the nuclear exporters' experience from their previous projects such as Russia's VVER, and France's EPR. As the successful EPR project at Taishan demonstrated, China benefited greatly from the experience and lessons learned at foreign sites prior to the construction on their own soil.

Project delays

China did not experience much in the way of project delays outside of first-of-its-kind builds for the Westinghouse AP-1000 and EDF EPR-1750. The Fast Breeder Reactor, BN-20, took a considerable amount of time, but historically FBRs take states longer to build. No political barriers or public protests delayed China's projects. China has the best record on completion times and completion rates out of the case studies covered in this paper.

Closing

China is well on its way to becoming the biggest nuclear state in the world. If China continues to build at its current rate, it should overtake the United States in number of operating reactors within fifteen to twenty years. If China resumes its construction pace of four to six reactors a year, it will overtake the U.S. even sooner. Standardization of one design would benefit China greatly as it would consolidate the indigenous nuclear supply chain, produce greater return of experience from standardized design, reduce construction times, and thus reduce costs. France came to prominence with their standardization of one design—the CP1, and later CP2, reactor designs. If China continues to produce CNNC/CGN joint designs, like the HPR-1000 joint design, China can potentially accelerate their construction process as there would be only one standard design constructed across China.

China has pledged to be carbon neutral by 2060 and has pledged to cap its carbon emissions by 2030. These environmental goals dovetail with China's civil nuclear power program. China's civil nuclear power plants won't contribute to greenhouse gas emission. China will reduce its greenhouse gas emissions and improve its air quality by increasing its share of electricity produced by nuclear relative to that produced by coal, as well as reducing the number of coal fired power plants.

* * *

Case Study 8: Japan

Japan's first nuclear reactor was JRR-1. It was built with assistance from the United States in 1957 under the Atoms for Peace program. [380] Three years later, Japan began construction on the Japan Power Demonstration Reactor (JPDR)--a boiling water reactor with 10 MWe design capacity. It was completed and connected to the grid in 1963, but did not commence operations until 1965.[381]

Japan currently has thirty-three reactors operational (nine currently online), twenty-seven reactors permanently shutdown, and two reactors under construction. Civil nuclear power accounts for 7.9 percent of Japan's energy production. Japan has built a total of sixty nuclear reactors over the course of fifty years.[382] The average reactor project completion time for Japan is 4.1 years.[383] No other state has averaged completed construction of full-scale nuclear reactors this quickly. (Compare to China's indigenous 5.4-year average, or France's 6.25-year average.)

Due to the events of Fukushima, Japan is currently operating only nine reactors.[384] The graph below depicts the time (in years) that each of the sixty civil nuclear reactor projects took

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[380] Kiyonobu Yamashita, *History of Nuclear Technology Development in Japan*, AIP conference proceedings, 2015-04-29, Vol.1659 (1) https://aip.scitation.org/doi/pdf/10.1063/1.4916842,
Phillip Andrews-Speed, "South Korea's nuclear power industry: Recovering from scandal", *Journal of World Energy Law and Business*, (2020), May 16, 2020, pg 48, https://watermark.silverchair.com/jwaa010.pdfs.

[381] IAEA PRIS database.

[382] Note: In total, sixty reactors were built in Japan, although Japan constructed fifty-five projects, and foreign corporations like Westinghouse and Areva constructed five of the sixty projects.

[383] IAEA PRIS database, authors own calculations.

[384] "Japan's Nuclear Power Plants in 2021", *Nippon*, March 31, 2021, https://www.nippon.com/en/japan-data/h00967/

to complete. Japan has a very consistent grouping that mostly remains in the four-to-six-year band with a few notable outliers that will be discussed in the following sections.

1960-1970

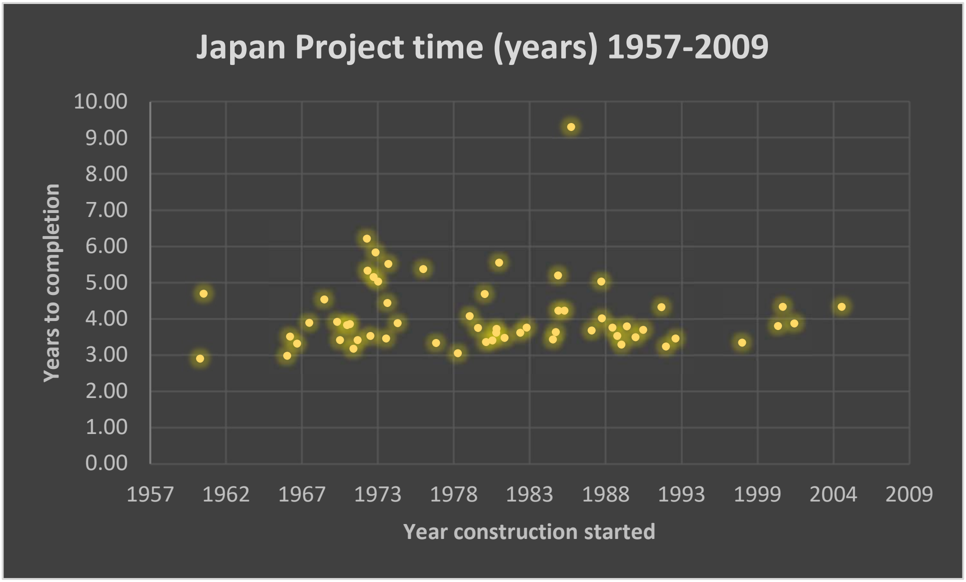

Figure 31-- Japan's project construction times. Source: IAEA PRIS database. Author's own graph.

Seven civil nuclear power reactors began construction during this period. After construction began on the 10 MWe JPDR boiling water reactor, Japan contracted with the United Kingdom's General Electric Company (GEC) to construct a Magnox reactor at Tokai 1. This 150 MWe plant was built just inside of five years. Tsuraga 1 was built by the United States' General Electric from 1966 to late 1969. Westinghouse also built a civil nuclear reactor in Japan. The Mihama 1, a PWR design, was constructed from 1967 to 1970. In the same year that Mihama 1 broke ground, Fukushima-Daiichi 1 started construction. This plant was not built by foreign nuclear contractors, but by Tokyo Electric Power Company. (TEPCO).[385] The design used was a boiling water reactor (BWR) and took only 3.3 years to complete the project. (See Appendix D.) An additional unit each at Fukushima and Mihama began construction during this period. The average time to complete these early projects was 3.69 years.[386]

1970-1985

Thirty reactors began construction during this period with an average design capacity of 813 MWe with an average completion time of 4.16 years. Fourteen PWR reactors and fifteen

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[385] IAEA PRIS database.

[386] Ibid., authors own calculations.

BWR reactors began construction during this period. The western half of Japan preferred the PWR design, and the eastern half of Japan preferred the BWR. (See Figure 12. Note: This preference will have an impact in 2011.) The outlier is the Fugen ATR. It was a prototype-advanced thermal reactor—which used heavy water moderators and boiling LWR. Prototypes and first-of-their-kind builds take a longer time to build than standard designs. (6.2 years for Fugen.)

1985- November 1992

This period saw sixteen new reactors projects break ground. The projects seemed evenly split between Mitsubishi M(4-loop) designs in the west, and BWR-5/6/7/8 designs in the east. The average time to complete a reactor build during this period was 4.29. That number seems a little higher than average due to a major outlier (See Figure 13 below.) The Monju reactor project that began in 1986 took over nine years to complete (9.3 years.) This was owing to the fact that the design was cutting edge—a sodium-cooled fast reactor.

November 1992-present

November of 1992 marked the entrance of Gen III reactors to Japan's nuclear portfolio. General Electric (U.S.) designed four ABWR units for Kashiwazaki-Kariwa (6 and 7), Hamaoka (5), and Shika (2). France's Areva (formerly Framatome, and later EDF) designed a Gen III reactor that combined aspects from Mitsubishi PWRs and Areva's EPR—namely their steam generator.[387] While nine projects broke ground during this period, at the time of writing, only seven have been completed.

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[387] "EDF and MHI to collaborate on Atmea joint Venture", *World Nuclear News*, January 5, 2018, https://www.world-nuclear-news.org/C-EDF-and-MHI-to-collaborate-on-Atmea-joint-venture-0501184.html

2011 Fukushima

Figure 32--Tohoku earthquake and Fukushima plant location. Source: The Guardian, https://www.theguardian.com/world/2014/jul/15/japan-mount-fuji-eruption-earthquake-pressure

As previously described in the U.S. case study, the Fukushima accident occurred on March 11, 2011 when a 9.0-magnitude earthquake caused units 1, 2, and 3 at the Fukushima-Daiichi plant in Japan to automatically shut down. The tsunami event caused a loss of external power (no power coming from the electric grid), and since the reactors were shut down, the turbines were not supplying on-site power for plant operations. Additionally, the tsunami waves flooded the diesel generators, which are the designed back-up power for situations where on-site and external power is lost. This all resulted in the coolant pumps having no electricity to operate, which created a loss of coolant casualty in the three reactor cores. The three reactor units' fuel rods melted due to the high temperatures.[388] (See Appendix E: Three Mile Island for an illustration of a core meltdown.) Radiation was released into the atmosphere and 100,000 citizens that lived in a 12-mile radius of the plant were forced to evacuate.

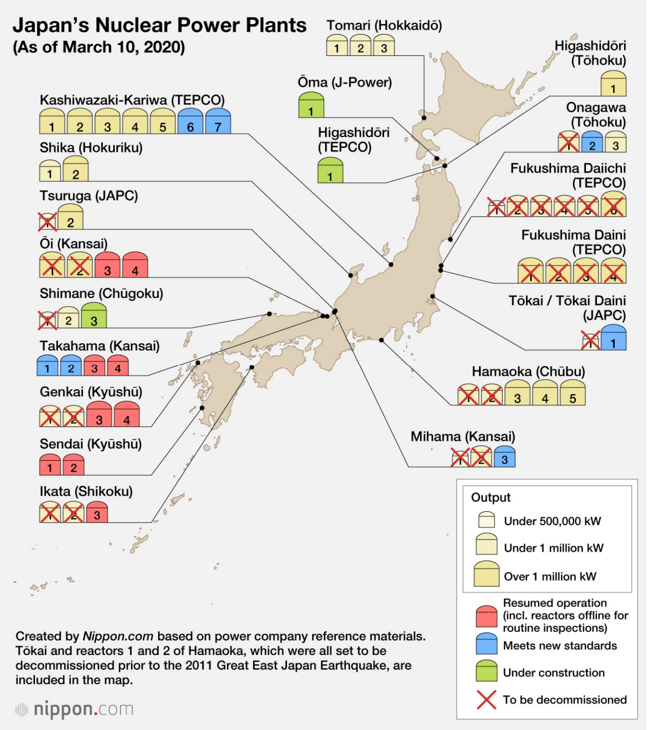

Figure 33-- Japan's nuclear power plant map. Source: Nippon.com https://www.nippon.com/en/japan-data/h00967/

In response to the accident, the Japanese government shutdown all fifty-four reactors.[389] All the reactors remained shutdown for nearly four years. In

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[388] "Backgrounder on NRC Response to Lessons Learned from Fukushima", U.S. NRC, accessed April 15, 2021, https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/japan-events.html#accident

[389] "Five and half years after Fukushima, 3 of Japan's 54 reactors are operating", *EIA*, September 13, 2016, https://www.eia.gov/todayinenergy/detail.php?id=27912

2015, Sendai 1 was the first reactor to restart, followed by Sendai 2 three months later.[390] At the time of writing, seven more reactors have restarted. (See Figure 33 above. Red shapes indicate a reactor is online.)

The seven that came online are all PWR design—since a BWR design was used at Fukushima-Daiichi, the PWR designed units were chosen for restarts. An additional sixteen reactors are planned to restart once inspected and approved by the Nuclear Regulatory Authority (NRA).[391] Each plant will have to pass new post-Fukushima safety standards put in place by the NRA following the accident.[392] Among those sixteen are TEPCO's Kashiwazaki-Kariwa units 6 and 7. These are the first BWR reactors, and the first reactors owned by Tokyo Electric Power Co. (TEPCO)—the same owners as Fukushima—to have their safety upgrades and restart application approved by the NRA.[393]

Since the Fukushima accident, Japan has permanently shut down twenty-two plants. All six units at Fukushima Daiichi, and four units at the sister plant, Fukushima Daini, 12 km to the south were shut down. Twelve other reactors were shut down in addition to those at Fukushima. The remaining twenty-four operable reactors are at various stages of their restart applications with the NRA. If the plants cannot meet the updated safety standards they will not come back online until they come into compliance.[394]

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[390] "Japan restarts second nuclear reactor despite public opposition", *The* Guardian, October 15, 2015, https://www.theguardian.com/world/2015/oct/15/japan-restarts-second-nuclear-reactor-despite-public-opposition#.

[391] "Nuclear Power in Japan", *World Nuclear News*, February 2021, accessed February 15, 2021, https://world-nuclear.org/information-library/country-profiles/countries-g-n/japan-nuclear-power.aspx

[392] Osamu Tsukimori and Aaron Sheldrick, "Japan regulator grants safety approval to TEPCO's first reactor restart since Fukushima", *Reuters*, October 3, 2017, https://www.reuters.com/article/us-japan-nuclear-tepco/japan-regulator-grants-safety-approval-to-tepcos-first-reactor-restart-since-fukushima-idUSKCN1C908B.

[393] "Kashiwazaki-Kariwa plant passes restart review", *World Nuclear News*, October 30, 2020, https://www.world-nuclear-news.org/Articles/Kashiwazaki-Kariwa-plant-passes-restart-review

[394] "Japanese industry leaders call for nuclear restarts", *World Nuclear News*, January 08, 2021, https://world-nuclear-news.org/Articles/Japanese-industry-leaders-call-for-nuclear-restart.

Twenty-five reactors are anticipated to be in operation by 2030 and will be responsible for generating 20 percent of electricity in Japan. (Down from the pre-Fukushima share of 30 percent.)[395]

Nuclear Regulators

The Nuclear and Industrial Safety Agency (NISA) was created in 2001. NISA was housed under the Ministry of Economy, Trade, and Industry (METI)—which is also the body responsible for the promotion of nuclear industry in Japan.[396]

Japan's regulators had a streamlined permitting process. Japan had three permits associated with nuclear power plant construction and pant licensing: One permit for site, basic design, and environmental impacts, one permit for construction, and one permit for reactor plant operation (once construction is complete).[397]

NISA's nuclear safety regulations were not as stringent as those found in the United States. NISA did not enforce safety regulations, but instead relied upon civil nuclear plant operators to voluntarily perform safety measures.[398] Additionally, the scope of probability safety assessments was limited to internal plant events and excluded external events such as earthquakes or tsunamis.[399]

The National Diet (Japan's legislature) issued an after-accident investigation report which stated that there was a conflict of interest with the NISA having been organized within the

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[395] "Nuclear Power in Japan", *World Nuclear News*

[396] Hideaki Shiroyama, "Nuclear Safety Regulation in Japan and Impacts of the Fukushima Daiichi Accident", in *Reflections on the Fukushima Daiichi Nuclear Accident*, eds. Ahn J., Carson C. et al., (Cham: Springer, 2015), https://doi.org/10.1007/978-3-319-12090-4_14.

[397] Pedro Crajilescov and Joao Moreira, "Construction time of PWRs", *2011 International Nuclear Atlantic Conference*, https://inis.iaea.org/collection/NCLCollectionStore/_Public/42/105/42105221.pdf

[398] Phillip Andrews-Speed, "Governing nuclear safety in Japan after the Fukushima nuclear accident: incremental or radical change?", in *Journal of Energy & Natural Resources Law*, 38:2, 161-181, DOI: 10.1080/02646811.2020.1741990.

Warren Young, "Atomic Energy: From 'Public' to 'Private' Power—the US, UK, and Japan in Comparative Perspective" in *Annales historiques de l'electricite*, 2003,133-153, https://www.cairn.info/revue-annales-historiques-de-l-electricite-2003-1-page-133.htm.

[399] Hideaki Shiroyama, "Nuclear Safety Regulation in Japan and Impacts of the Fukushima Daiichi Accident"

METI.[400] Subsequently, the Japanese government reorganized the newly formed Nuclear Regulation Authority (NRA) under the Ministry of the Environment.[401]

Environmental Stewardship

Japan is a signatory of the Kyoto Protocol, Paris Agreement, Copenhagen Accord, and pledges to be Carbon neutral by 2050.[402] Japan's Paris Agreement pledge is to reduce its greenhouse gas emission 26 percent below 2013 levels by the year 2030; and pledged in Copenhagen to reduce its carbon intensity to 3.8 percent less than 2005 usage by the year 2020.[403] Given Japan's reduction in operating civil nuclear power plants, and its new energy mix of only 7 percent share of nuclear, it will be more difficult for Japan to achieve the above pledged goals.[404] (Pre-Fukushima, Japan's nuclear energy share was 30 percent.)[405]

Future

The future of Japan's nuclear industry is uncertain. Japan will likely have to make a choice between achieving its Paris Agreement and Carbon neutral pledges, or further reducing its remaining civil nuclear power plants.

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[400] "Fukushima Nuclear Accident Independent Investigation Commission", National Diet of Japan, 2012
40, accessed May 1, 2021, https://www.nirs.org/wp-content/uploads/fukushima/naiic_report.pdf.
Charles D. Ferguson and Mark Jansson, "Regulating Japanese Nuclear Power in the Wake of the Fukushima Daiichi Accident", Federation of American Scientists, May 2013, 10, accessed April 9, 2021, https://fas.org/wp-content/uploads/2013/05/Regulating_Japanese_Nuclear_13May131.pdf

[401] New Japanese regulator takes over, *World Nuclear News*, 19SEP2012 https://www.world-nuclear-news.org/RS-New_Japanese_regulator_takes_over-1909125.html

[402] Reese Oxner, "'A Decarbonized society': Japan pledges to be carbon neutral by 2050", *NPR*, October 26, 2020, https://www.npr.org/2020/10/26/927846739/a-decarbonized-society-japan-pledges-to-be-carbon-neutral-by-2050

[403] "Japan: Pledges and Targets", Climate Action Tracker, September 22, 2020, https://climateactiontracker.org/countries/japan/pledges-and-targets/#.

[404] Katharina Bucholz, "How Fukushima Changed Japan's Energy Mix", *Statista*, March 11, 2021, https://www.statista.com/chart/18679/electricity-generated-in-japan-by-source/

[405] "Nuclear Power in Japan", *World Nuclear Association*, February 2021, https://world-nuclear.org/information-library/country-profiles/countries-g-n/japan-nuclear-power.aspx

Findings

State-owned enterprises

Japan is an interesting case study with regard to state-owned enterprises. Japan's early nuclear plant construction, research, design, and major nuclear promoter is the Japan Atomic Power Company. JAPC is a Special Purpose Company (SPC), which is essentially the same as a Limited Liability Corporation (LLC), but with a limited scope—typically designed for the duration of a large project. The JAPC is a joint venture owned by a consortium of the major electric companies of Japan: TEPCO 28.23 percent, Kansai 18.54, Chubu 15.12, Hokuriku 13.05, Tohoku 6.12, J-Power 5.37. The rest of the shares are owned by investors. It should be noted that J-Power, although a minority shareholder, was owned by the Japanese government until 1997.[406] (TEPCO, the majority shareholder, was recently nationalized by the Japanese government in 2012.[407] In 2020, TEPCO gave financial support to JAPC to make necessary safety upgrades to Tokai 2.)[408]

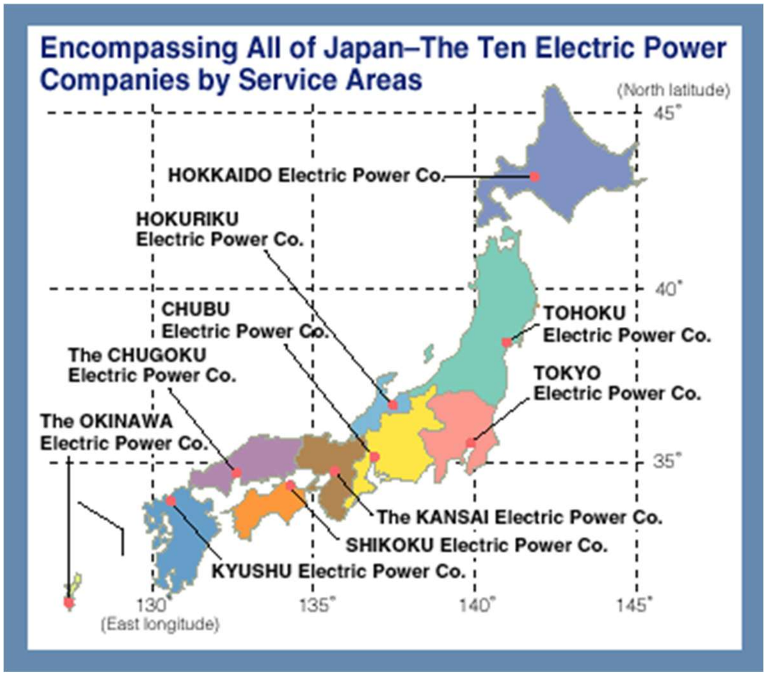

Figure 32—Japan's electric companies. Source: The Federation of Electric Power Companies of Japan. https://www.fepc.or.jp/english/about_us/service_areas/index.html

What makes this case study interesting is the connection between the JAPC, and the Ministry of Economy, Trade, and Industry (METI). METI is a government ministry that funds

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[406] "Toward the complete privatization of J-Power", J-Power corporate website, June 11, 2003, https://www.jpower.co.jp/english/news_release/news/news177.pdf.

[407] Osamu Tsukimori, "Japan's TEPCO works hard to pull out from government control", *Reuters*, February 7, 2016 https://www.reuters.com/article/us-japan-tepco/japans-tepco-works-hard-to-pull-out-from-government-control-idUSKCN0VG0V8

[408] Clarist Zablan, "TEPCO greenlights reboot funding for 1,100 MW nuclear plant", *Asian Power*, accessed April 9, 2021, https://asian-power.com/project/news/tepco-greenlights-reboot-funding-1100mw-nuclear-plant

nuclear research and directs the progress of the nuclear industry. In 1975, METI, originally the Ministry of International Trade and Industry (MITI), and the nuclear industry (e.g., JAPC) created the Light Water Reactor (LWR) Improvement and Standardization Program. The program's purpose was to standardize the reactor design and shorten plant construction lead time.[409] The research and design carried out by METI was critical to Japan's quick average construction times.

Another integral part of Japan's low average construction time was the fact that the nuclear regulatory agency was housed under METI--the ministry responsible for the promotion of nuclear research and nuclear industry. METI was also responsible for regulating and enforcing nuclear plant activity. As discussed above in the nuclear regulatory section, nuclear safety standards were not enforced, and the electric companies that operated the plants were left to regulate their own safety. This absence of strict safety oversight enabled construction projects to proceed at pace.

There are two other significant touchpoints between the government and the nuclear power industry. Japan's J- Power (also referred to as Electric Power Development Company), a government owned enterprise until 1997, also has ties to the JAPC.[410] The electric companies and J- Power both financially support the JAPC's endeavors.[411] The second touchpoint is related to the nuclear fuel cycle. Japan operates one state-owned enterprise in the nuclear industry related to nuclear fuel production, and reactor research and design--the Power Reactor and Nuclear Fuel Development Corporation (PNC).[412]

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[409] Thomas Lowinger, "Japan's nuclear energy development policies: An overview" in *The Journal of Energy and Development*, Vol. 15, no. 2, (Spring 1990), 221, https://www.jstor.org/stable/24807916.
Note: The usage of 'construction lead time' is also used to describe the front end of the construction process.

[410] "EPDC Expands Abroad as Japan Deregulates Power Market", *Bloomberg*, October 30, 2001, https://www.bloomberg.com/news/articles/2001-10-31/epdc-expands-abroad-as-japan-deregulates-power-market

[411] Richard Gilbert and Edward Kahn, "The Japanese electric utility industry" in *International Comparisons of Electrical Regulation*, (Cambridge: Cambridge University Press, 2010), 239.

[412] Kiyonobu Yamashita, "History of nuclear technology development in Japan", *AIP Conference Proceedings 1659*, 020003 (2015) https://doi.org/10.1063/1.4916842

There are additional interactions between state banks and the nuclear industry that will be discussed in the 'secure financial' section below.

Standardized Design

Japan collectively built twenty-seven PWRs, thirty BWRs, five ABWRs, and one FBR, GCR, and HWLWR each. Japan's domestic manufacturing corporations—Hitachi, Mitsubishi, Toshiba, and JAPC—preferred either the PWR or BWR design. Hitachi-General Electric preferred a BWR design, as did Toshiba. Mitsubishi preferred a PWR design, and the imported technology from Westinghouse was PWR.[413] Regardless of which PWR or BWR design was preferred, these firms used a LWR standardized design that was researched and developed by METI.

As discussed in the 'State-owned Enterprises' section above, the government of Japan instituted a LWR Improvement and Standardization program. In Phase 1 (1975-1977) and Phase 2 (1978–1980) of the program, the BWR and PWR designs—both being LWRs due to their moderator usage—were improved upon for better operation. Phase 3 of the program (1981-1985) focused on increased design capacity and the development of advanced LWRs.[414]

Due to the standardization of reactor plant design under METI's LWR program, Japan's utility consortium was able to benefit greatly from shorter construction times. At 4.1 years, Japan's average plant construction times are the lowest of any other states from the case studies.

Economies of scale

If a firm does not begin construction on several reactor units on the same site in the same year, it cannot take full advantage of economies of scale. In Japan's fifty-year civil nuclear history, it has constructed plants on-site in series (i.e., one after another). Japan's nuclear industry has rarely constructed plants in parallel (several reactors beginning construction

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[413] IAEA PRIS database.

[414] Thomas Lowinger, "Japan's nuclear energy development policies: An overview", 215

concurrently on a site.). Only five civil nuclear reactors were constructed in parallel: Ōi 1 and 2 in 1972 (Westinghouse), Fukushima Daiichi units 4 and 6 in 1973, Fukushima Daini 3 and 4 in 1981, Takahama 3 and 4 in December 1980/March 1981, and Tomari 1 and 2 in 1985.[415] Japan's economies of scale are limited when compared to states like Canada, France and China. Canada's Pickering site where its eight reactors began parallel construction in groups of four, or France's Dampieer and Gravelines sites where four units began in the same year, or China's constructing four to six units by two-unit pairs (e.g., two units at Fangchenggang in 2010 and another two units in 2015) at almost all sites in China.[416] While Japan built additional units at civil nuclear plant sites, it did so with several year gaps in between construction periods. Japan's nuclear firms were also not able to take advantage of economies of scale possible in the manufacturing and supply chain. The supply chain was divided to specialize in the several different reactor technologies, which made the supply chain suboptimal.

Secure financing

Japan's nuclear corporations, not being wholly or majority owned by the government, did not receive government funding for their projects. As such, the Japanese nuclear firms were not as advantaged as an SOE when larger scale projects were undertaken and had to seek loans from banks and investors. Japan's Development Bank of Japan (DBJ) is an SOE, and its stock is wholly owned by the government of Japan. The DBJ has offered guaranteed loans and low interest rates to Japan's nuclear firms, specifically the Japan Atomic Power Company (JAPC), Mitsubishi, Hitachi, and Toshiba.

A recent example of a problem related to secure financing is the recent Hitachi nuclear export project planned for the United Kingdom. Hitachi had begun contracting with the United Kingdom for a civil nuclear plant construction project in Wylfa Newydd. While Hitachi had been offered guaranteed loans from the Development Bank of Japan, they still required a significant

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[415] IAEA PRIS database.

[416] Ibid.

amount of additional funds from the United Kingdom in order to undertake such a large project.[417] As discussed in chapter 2 and the U.K. case study, the Wylfa Newydd project stalled due to finance negotiations between Hitachi and the United Kingdom.[418] Ultimately, Hitachi thought the project was too expensive to complete without additional funding from the U.K. government, and the two parties were not able to come to an agreement as to the amount and structure of funding. This is another example of the disadvantages of private corporations building civil nuclear power plants. State-owned enterprises have secure financing from the government sufficient to cover the costs of a large undertaking.

Return of experience

The usage of standardized LWR reactor plant designs enabled Japan to benefit from return of experience. However, that return of experience was not fully realized due to the division of experience among Japan's firms—those who preferred BWR and those who preferred PWR. The lessons learned from constructing a Mitsubishi PWR designed plant are not directly applicable to constructing a Hitachi BWR designed plant. Even the lessons learned from a Toshiba BWR would not translate well for a Hitachi BWR plant project.

Project delays

Until the events at Fukushima, Japan did not suffer from project delays like those experienced by its fellow non-SOEs states like the United States, United Kingdom, and Germany. The Monju reactor was a fast breeder reactor, and like the other states that have constructed prototype reactors (e.g., FBRs in the U.K., and HTGR in Germany) it experienced significant delays.

Following the events of the Fukushima nuclear accident, Japan's remaining two construction projects—Shimane 3 and Ōma-- were put on hold. Shimane 3, owned by Chugoku

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[417] "Japanese gov't to guarantee bank loans for Hitachi's nuclear plant project in Britain", *Mainichi news*, January 3, 2018, https://mainichi.jp/english/articles/20180103/p2a/00m/0na/004000c.

[418] "Wylfa Newydd planning decision delayed again", *NEI*, April 6, 2020, https://www.neimagazine.com/news/newswylfa-newydd-planning-decision-delayed-again-7859280

electric power company, and Ōma, owned by J-Power (no longer an SOE), are awaiting review and determination from the NRA on their post-Fukushima safety modifications.[419]

Closing

Japan was able to construct nuclear power plants in a very short timeline even though it did not operate a nuclear SOE. The factors that contributed to this were the federation of the electrical companies and their joint enterprise—JAPC. Since the JAPC was funded by all the electric companies, and partially by the government (through J-Power), it was able to achieve results similar to that of an SOE. Additionally, since JAPC was owned by all the utilities, and the utilities were granted regional monopolies on electric power, there was no need to compete with one another on design. (These monopolies were later deregulated in 2016.)[420] The JAPC could focus on making the LWR designs more efficient, and Japan's electric firms benefited through reduced construction times.

Another factor that contributed to Japan's short construction timelines was the nuclear regulator being housed under METI—the nuclear promoter. Less regulations, enforcement, and less permitting and licensing red tape contributed to lower construction times. This type of government-to-nuclear-firm alignment of purpose mirrored those found in SOEs.

Japan's nuclear industry benefited from this pseudo-nuclear-SOE-type organization and experienced shorter licensing and construction times. Japan's slow, but cautious, restarting of its nuclear reactors indicates that they might again advance their nuclear industry in a post-Fukushima world.

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[419] "Ohma start-up delayed by a further two years", *World Nuclear News*, September 5, 2018, https://www.world-nuclear-news.org/Articles/Ohma-start-up-delayed-by-a-further-two-years
"Japanese utility seeks to start up new reactor", *World Nuclear News*, May 22, 2018, https://www.world-nuclear-news.org/RS-Japanese-utility-seeks-to-start-up-new-reactor-2205184.html

[420] Yuka Obayashi and Osamu Tsukimori, "Japan's power monopolies face reform jolt", *Reuters*, March 31, 2016, https://www.reuters.com/article/us-japan-power-reforms/japans-power-monopolies-face-major-reform-jolt-idUSKCN0WX0G1

Case Study 9: South Korea

South Korea started their civil nuclear program through participating in the U.S. Atoms for Peace program. South Korea was supplied with a Training, Research, Isotope, General Atomics (TRIGA) reactor in 1962.[421] Within a decade, South Korea contracted for, and began instruction on, a 558 MWe turnkey-reactor project from Westinghouse—Kori 1 reactor. In less than five years, Kori 1 was supplying electricity to the grid.[422] South Korea currently has twenty-four operational reactors, four reactors under construction, and two permanently shutdown. Given its size and number of reactors, South Korea has the highest density of nuclear reactors in the world.[423] The average reactor project completion time is 5.16 years.[424] Civil nuclear power accounts for 26.2 percent of South Korea's energy production.

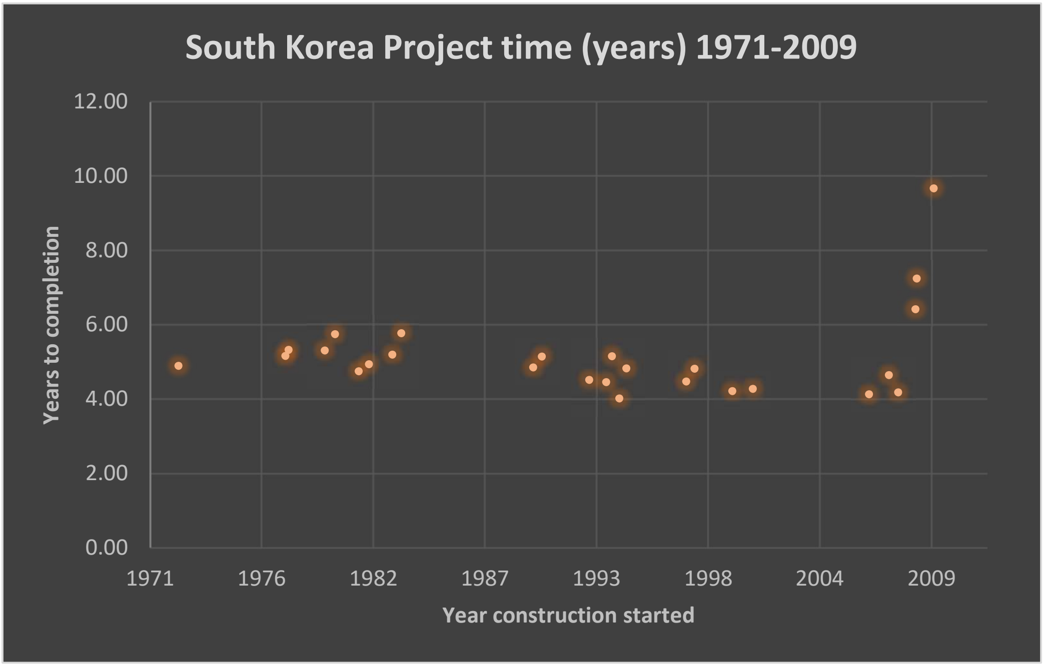

Figure 33-- South Korea's project construction completion times. Source: data from IAEA PRIS. Author's own graph.

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[421] "History, Development, and Future of TRIGA Research Reactors", IAEA, accessed May 7, 2021, https://www-pub.iaea.org/MTCD/Publications/PDF/trs482web-68751096.pdf

[422] IAEA PRIS database.

[423] "South Korea is one of the world's largest nuclear power producers", *EIA*, August 27, 2020, https://www.eia.gov/todayinenergy/detail.php?id=44916#

[424] IAEA PRIS. Author's own calculations.

South Korea’s production of 139 Terawatt hours makes it the fifth-highest civil nuclear power producer in the world.[425]

The graph above shows that South Korea was very consistent throughout their builds until 2008. The three conspicuous outliers warranted research, and one answer was found to address all three—a forgery scandal. In 2013, the Nuclear Safety and Security Commission (NSSC) discovered that the quality control documents for nuclear components had been forged. It was discovered that this was not a singular incident, and that quality control certificates for components safety tests had been forged going back ten years for components installed across fourteen civil nuclear plants.[426] The Korea Hydro and Nuclear Power Co (KNHP), a subsidiary of the Korea Electric Power Company (KEPCO) admitted that it had known about the forgeries from the nuclear supply groups.[427] The Energy of the Ministry had shut down the projects for investigation in 2013, thus causing the two year-long delays. Shin Wolsong 2 was completed in 2013, but could not go online until the scandal was fully investigated.[428]

1972-1986

Following the construction of Kori 1, eight additional plants were constructed in this period. This period was comprised of turnkey plants made by Westinghouse and Canada’s AECL. Westinghouse and Framatome also provided reactors and components as part of a technology transfer which allowed the Korean nuclear corporations to build the Hanbit, Hanul, and Kori civil nuclear plants. The designs used during this period were PWRs with an average design capacity of 825 MWe. The average time to complete a reactor project was 5.17 years.[429]

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[425] “South Korea is one of the world’s largest nuclear power producers”, *EIA*.

[426] Choe Sang-Hun, “Scandal in South Korea Over Nuclear Revelations”, *New York Times*, Aug 3, 2013, https://www.nytimes.com/2013/08/04/world/asia/scandal-in-south-korea-over-nuclear-revelations.html

[427] “Two Years Later, S. Korea Finally Puts Shin-Wolsong 2 Online”, *POWER*, https://www.powermag.com/two-years-later-s-korea-finally-puts-shin-wolsong-2-online/

[428] Ibid.

[429] IAEA PRIS database. Author’s own calculations.

1986- October 2008

KEPCO's *Nuclear Power Plant Construction Technology Independent Plan* was set forth with the goal of producing indigenous design, component manufacture, and construction.[430] After having gained experience in the previous period by constructing reactor units with foreign components, South Korea was ready for its nuclear industry to become self-reliant.[431] Indigenous construction in the period was solely focused on one design—the OPR1000. The OPR1000 design is a Gen II, 1,000 MWe two-loop PWR. Its design was based off Combustion Engineering's (CE) Arkansas Nuclear One unit 2 design. South Korea obtained the design through a technology transfer agreement with CE.[432] While South Korea was constructing OPR1000 reactors, there was also building activity from foreign nuclear corporations. Three turnkey CANDU reactors built by AECL at the Wolsong plant during this period.

October 2008- present

This period saw South Korea's nuclear industry introduce Gen III nuclear technology. The APR1400 reactor was designed, making optimal improvements to the preceding OPR1000 design. Six APR1400 units began construction from 2008 to 2018. Due to the 2013 quality control scandal addressed earlier, the projects were delayed by upwards of two years.[433] The projects at Shin Hanul 1 and 2, as well as Shin Kori 5 and 6 are still ongoing.[434]

State-owned enterprises

South Korea's state-owned enterprise is the Korean Electric Power Corporation (KEPCO). KEPCO was founded by the government under the Korean Electric Power

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[430] "OPR1000", KEPCO, accessed April 10, 2021, https://www.kepco-enc.com/eng/contents.do?key=1532

[431] Ibid.

[432] Mark Holt, "U.S. and South Korean Cooperation in the World Nuclear Energy Market", Congressional Research Service, January 21, 2010, https://www.hsdl.org/?view&did=29900

[433] "Two Years Later, S. Korea Finally Puts Shin-Wolsong 2 Online", *POWER*, April 1, 2015, https://www.powermag.com/two-years-later-s-korea-finally-puts-shin-wolsong-2-online/

[434] Note: The Korean word 'Shin' means 'new'.

Corporation Act of 1982. The South Korean government owns 51.11 percent share of KEPCO.[435] Additionally, KEPCO Engineering and Construction (KEPCO E&C) is majority owned by KEPCO and is responsible for designing and constructing South Korea's nuclear plants.[436]

Nuclear regulators

Prior to 2011, nuclear regulation in South Korea was executed by the Nuclear Safety Commission (NSC), which was administered by the Ministry of Trade, Industry and Energy (MOTIE).[437] This situation was similar to that seen in the Japan case study. Nuclear promotion and nuclear regulation housed in close proximity.

In response to the Fukushima accident, South Korea made shifts to their regulatory structure.[438] In October 2011, the Nuclear Safety and Security Commission (NSSC) was established under the office of the President, and the nuclear promotion, and research and development arms were located under the Prime Minister.[439]

Future

The future for South Korea is focused on expanding its nuclear exporting industry. South Korea is currently constructing four APR-1400 reactors in the United Arab Emirates (UAE) at Barakah. All four are a standardized design—the same as used in Shin Kori and Shin Hanul. This design is also approved by the U.S. NRC for use in the United States should Korea

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[435] "Overview", KEPCO website, accessed April 17, 2021, https://home.kepco.co.kr/kepco/EN/A/htmlView/ENAAHP001.do?menuCd=EN010101

[436] "Business/R&D", KEPCO website, accessed April 17, 2021, https://www.kepco-enc.com/eng/contents.do?key=1531

[437] "Nuclear Power in South Korea", *World Nuclear Association*, accessed April 17, 2021, https://world-nuclear.org/information-library/country-profiles/countries-o-s/south-korea.aspx

[438] "Country Nuclear Power Profiles 2012 Republic of Korea", IAEA, accessed April 12, 2021, https://www-pub.iaea.org/MTCD/Publications/PDF/CNPP2012_CD/countryprofiles/KoreaRepublicof/KoreaRepublicof.htm

[439] "About NSSC", Nuclear Safety and Security Commission, accessed April 12, 2021, https://www.nssc.go.kr/en/cms/FR_CON/index.do?MENU_ID=280

contract to build there.[440] South Korea has also contracted with Saudi Arabia to form a joint venture to construct SMRs in the Middle East.[441]

South Korea's current President, Moon Jae-in, has an anti-nuclear/pro-renewable stance and has promoted phasing out nuclear power.[442] At the time of writing, South Korea's two oldest nuclear plants, Kori 1 and Wolsong 1 (forty and thirty-seven years old, respectively) have been permanently shut down during the President Moon's first term in office. Public support of civil nuclear programs stopped government plans for nuclear phase out.[443] It is uncertain whether the Moon administration will pursue a phase out at a later time.

Findings

Standardized design

The standardized OPR1000 and APR1400 designs have enabled South Korea to advance their nuclear program. Their average construction completion time of 5.16 years is markedly lower than all other civil nuclear power states—save Japan.

Economies of scale

South Korea took full advantage of economies of scale. In addition to only building one standardized design, the OPR1000 design followed by the APR1400, KEPCO built four to six reactor units at the majority of their sites. Six reactors each were constructed at Hanbit, Hanul, and Shin Kori; and four reactors each were contructed at Kori, Wolsong; Shin Hanul and Shin Wolsong are also being constructed adjacent to the Hanul and Wolsong sites, respectively.

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[440] Note: In 2013, South Korea submitted its standardized design to the U.S. Nuclear Regulatory Commission (NRC) for approval. The APR1400 was approved and certified for use in the US in 2019. "Korean reactor design certified for use in USA", *World Nuclear News,* August 27, 2019, https://www.world-nuclear-news.org/Articles/Korean-reactor-design-certified-for-use-in-USA#

[441] "Korea, Saudi Arabia progress with SMART collaboration", *World Nuclear News*, January 7, 2020, https://world-nuclear-news.org/Articles/Korea-Saudi-Arabia-progress-with-SMART-collaborati

[442] Darrell Proctor, "South Korea continues nuclear phase-out", *POWER*, February 3, 2020, https://www.powermag.com/south-korea-continues-nuclear-phase-out/

[443] Jane Chung, "South Koreans support for nuclear projects deal blow to government energy plan", *Reuters*, October 19, 2017, https://www.reuters.com/article/us-southkorea-nuclear/south-koreans-support-for-nuclear-projects-deals-blow-to-government-energy-plan-idUSKBN1CP06F

Return of experience

The return of experience from the standardized design is evident in the gradual reduction in time required to complete the project—from 5.14 years down to 4.19 years for the OPR1000 design.

Project delays

As noted above, the significant construction delays experienced at Shin Kori 3 and 4, and the final licensing delay at Shin Wolsong 2 were caused by the regulator scandal. The delays caused South Korea's average construction time to increase significantly. Excluding the three delayed projects, the average construction time for South Korea would be 4.82.[444]

Environmental Stewardship

South Korea has not made any pledges to reach net zero carbon emissions by a specific year. South Korea pledged to reduce its greenhouse gas emissions by 24 percent below 2017 levels (Other states make their reduction goals relative to 2005 levels, etc) for the Paris Agreement.[445]

Closing

South Korea's civil nuclear industry is positioned for success both internationally and domestically. KEPCO's standardized design and use of economies of scale, both at home and abroad, enable it to construct plants efficiently and yield a greater return of experience from its projects. South Korea's overseas projects also provide the opportunity to increase their nuclear workforce's skillsets, and maintain perishable skills that will be needed for future domestic projects.

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[444] IAEA PRIS database. Author's own calculations.

[445] "South Korea", Climate Action Tracker, July 30, 2020, https://climateactiontracker.org/countries/south-korea/

Case Study 10: India

In 1956, the United Kingdom supplied India with its first nuclear reactor, Aspara—a 1 MWt LWR. Canada built India's second nuclear plant, the 40 MW Canadian Indian Reactor Utility Services (CIRUS), in 1960.[446] On May 18, 1974, India conducted the *Smiling Buddha* nuclear weapons test. The nuclear bomb was constructed with plutonium generated from the reprocessed fuel of the CIRUS reactor.[447] After the test, Secretary of State Henry Kissinger convened the first meeting of the (London) Nuclear Suppliers Group to discuss preventing nuclear technology from being exported to India.[448] This nuclear technology embargo, so to speak, forced India to develop not only their nuclear weapons program indigenously, but also their civil nuclear power program. From 1974 until October 1, 2008 when the U.S. Congress agreed to the U.S.-India Nuclear Deal, India had no access to international nuclear trade.[449]

India currently has twenty-three reactors operational, and six reactors under construction. Civil nuclear power accounts for 3.2 percent of India's energy production. The average reactor completion time is 9.39 years.[450]

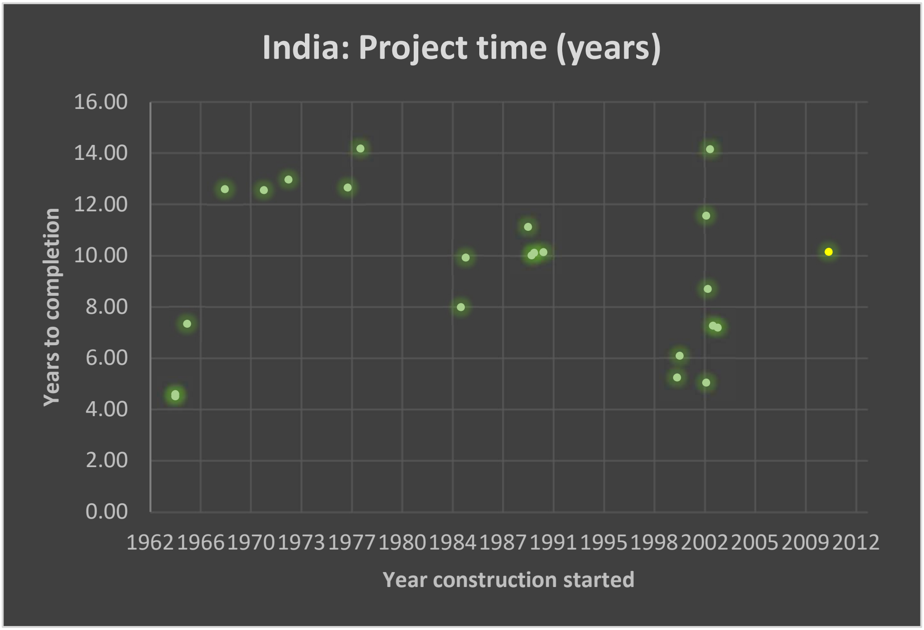

Figure 34--India's project completion times. Source: data from IAEA PRIS. Author's own graph.

1964-2000

India's civil nuclear program started similar to

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[446] Perkovich, *India's Nuclear Bomb*, 27

[447] Graham, Thomas, *Seeing the Light: The case for nuclear power in the 21st century*.

[448] Perkovich, *India's Nuclear Bomb*, 191.

[449] Peter Baker, "Senate Approves Indian Nuclear Deal", *New York Times*, October 1, 2008, https://www.nytimes.com/2008/10/02/washington/02webnuke.html

[450] IAEA PRIS database. Author's own calculation.

China, Japan, and South Korea. They obtained early assistance from states that had civilian nuclear power technology. Although India obtained its first research reactors from the United Kingdom and Canada, they courted the United States for a full-scale reactor. In 1960, representatives from the U.S. visited India to discuss the possibility of a nuclear reactor agreement. Dr. Homi Bhabha, nuclear physicist and director of India's nuclear program, met with them and asked for an Export-Import Bank loan with deferred payments to finance the deal. The Eisenhower administration agreed to the terms and agreed for General Electric (U.S.) to construct two 200 MWe BWRs at Tarapur.[451]

Tarapur 1 and 2 started construction in 1964 and were both completed within five years. Twelve other 200 MWe plants began construction during this time period. The reactor design shifted from the BWRs used at Tarapur, to a Pressurized Heavy Water Reactor (PHWR) design called a Horizontal Pressure Tube (HPT). This shift in design was largely owing to the limited nuclear technology options following the political aftermath of Smiling Buddha, and the establishment of the London Nuclear Suppliers Group. The average time to construct a nuclear reactor, indigenously, during this period was 10.96 years.

2000-2010

After a ten-year break in new construction, units 3 and 4 began construction at Tarapur. The reactors were a PHWR design, but the average design capacity more than doubled during this period (457 MWe.) Of the nine reactors that began construction, two were 502 MWe, four were the standard 200 MWe from the previous period, and two Russian-built 917 MWe VVER designs built by Atomstroyexport. The VVER plants faced serious delays—243 days behind on construction of the turbine building for Unit 1, and 396 days behind for Unit 2. Over two thousand days behind schedule for attaining first criticality for Unit 1, and over three thousand behind for Unit 2. Similar to the financial loan agreement struck before the Tarapur project, India

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[451] Perkovich, *India's Nuclear Bomb*, 52.

obtained financing from Russia to pay for the Kudankulam nuclear plant. India's Comptroller and Auditor General (CAG) audited the project and stated that since the delays were caused by the Russian labor force, the loan repayment schedule should have been revised.[452] The result of revising the payment schedule is that India was made to pay interest for years in which they should have been collecting operating revenue. CAG stated it cost India an additional 449.92 crore ($60M in 2017 USD.)

Only one of the nine reactors that began construction during this period was not complete at the time of writing. The Prototype Fast-Breeder Reactor (PFBR) is expected to be completed within the next year. The PFBR project has experienced long delays, similar to large delays at Dounreay in the U.K., Super Phenix [sic] in France, CEFR in China, and Monju in Japan. The delays are reported as due to it being a first-of-its-kind reactor. The average completion time for reactor projects from this period is 8.15 years.[453]

2010-present

This period was similar to the last period except for the shift in design towards a larger capacity reactor. Construction began on two PHWR-700s each at Kakrapar 3 and 4, as well as Rajasthan 7 and 8. Additionally, two more Russian 1,000 MWe VVERs began construction at Kundankulam units 3 and 4. As of this writing, only Kakrapar 3 has been completed.

Environmental Stewardship

India, much like China, is experiencing heavy air pollution related to fossil fuel emissions. In 2019, India had an estimated 1.67 million deaths related to toxic air pollution.[454]

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[452] "Kudankulam: CAG faults NPCIL for plant delays, cost overruns", *The Hindu*, https://www.thehindu.com/news/national/tamil-nadu/kudankulam-cag-faults-npcil-for-plant-delays-cost-overruns/article22289052.ece

[453] IAEA PRIS database. Author's own calculations.

[454] "Pollution deaths in India rose to 1.67 million in 2019 -Lancet", *Reuters*, December 22, 2020, https://www.reuters.com/article/us-india-pollution/pollution-deaths-in-india-rose-to-1-67-million-in-2019-lancet-idUSKBN28W158

This number exceeds China's 2015 number of deaths from air pollution (1.6M). The cause for this amount of air pollution is that coal represents fifty-five percent (2020) of India's energy mix[455] Reports on air pollution from 2020 show that India is home to twenty-two of the top thirty polluted cities in the world (based on PM2.5.)[456] India is party to the Paris Agreement, and Copenhagen Accord, but has made no net zero emissions pledge to date. India's Paris Agreement pledge was to reduce its carbon emissions to thirty-three percent below its 2005 levels by the year 2030.[457]

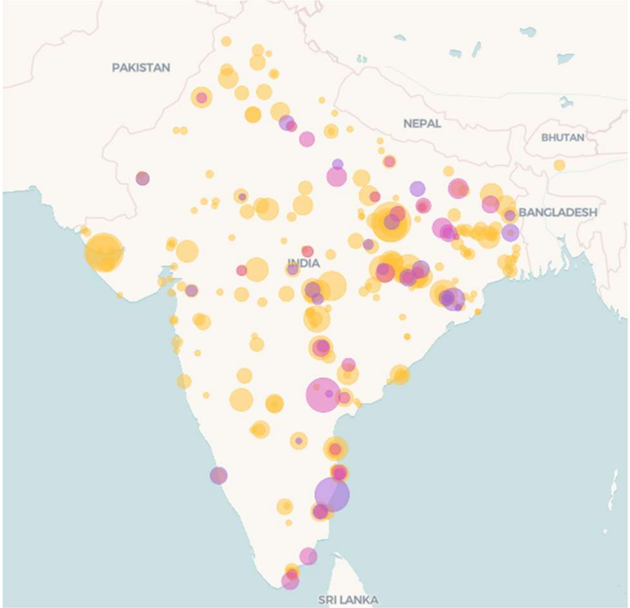

Figure 35--India's coal plants. Orange circles denote currently operating, and purple colors denote planned. Source: Carbon Brief, https://www.carbonbrief.org/mapped-worlds-coal-power-plants

Future

India could reduce their carbon emissions by building more nuclear plants as well as renewable energy plants. India is currently constructing four 630 MWe PHWR reactors, and Rosatom is currently constructing two VVER 917 MWe reactors. Given that the PHWR took 10.14 years for the first build, and Rosatom's VVER V-412 reactors took 12 and 14 years to complete, it will take several more builds before the return of experience reduces the time down to five or six years. India may want to pursue quicker renewable energy sources and small modular reactor technology to fill the gap until its nuclear industry is more experienced with Gen III reactor technology.

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[455] "India country analysis", EIA, September 30, 2020, https://www.eia.gov/international/analysis/country/IND

[456] Disha Shetty, "22 out of top 30 world's most polluted cities in India", *Forbes*, March 16, 2021, https://www.forbes.com/sites/dishashetty/2021/03/16/22-out-of-top-30-worlds-most-polluted-cities-in-india/?sh=6195b7f175ad
"World's most polluted cities 2020 (PM2.5)", IQ Air, accessed April 21, 2021, https://www.iqair.com/us/world-most-polluted-cities.

[457] "India: Pledges and Targets", Climate Action Tracker, September 22, 2020, https://climateactiontracker.org/countries/india/pledges-and-targets/

Findings

State-owned enterprises

The Nuclear Power Corporation of India Limited (NPCIL) was established in 1956 as an SOE wholly owned by the Indian government.[458] NPCIL is responsible for design and construction of civil nuclear power plants in India. It also operates those civil nuclear plants once they are completed.

Standardized design

India has constructed nineteen Horizontal Pressure Tube PHWR reactor units, with another three under construction at the time of writing.[459] These HPT plants have an average construction time of 9.53 years. When compared to standardized design projects in China and South Korea, India's projects seem prolonged. The twelve HPT reactor projects that were undertaken from 1965-2000 had an average completion time of 11.29 years.[460] During this time period, India had two military conflicts with Pakistan—the Indo-Pakistan Wars of 1965 and 1971.[461] India also experienced three economic recessions: 1965-1966, 1972-1973, and 1979-1980.[462] India's GDP in 1965 was $59.55B (2021 USD), compared to the U.S. GDP of $743.7B in the same year.[463] By 2000, India's GDP had grown to $468.4B, and their average reactor completion time for HPT reactor projects that began in 2000-2003 was 6.58 years.[464]

Once India's economy grew, it was better able to take advantage of standardized design.

Economies of scale

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[458] "About NPCIL", NPCIL website, accessed April 19, 2021, https://www.npcil.nic.in/content/328_1_AboutNPCIL.aspx

[459] IAEA PRIS database.

[460] Ibid.

[461] "The India-Pakistan War of 1965", Office of the Historian, accessed April 20, 2021, https://history.state.gov/milestones/1961-1968/india-pakistan-war

[462] Anilesh Mahajan, "Why India's present economic crisis is different from the recession of 1979", *India Today*, September 2, 2020, https://www.indiatoday.in/india-today-insight/story/why-india-s-present-economic-crisis-is-different-from-the-recession-of-1979-1718003-2020-09-02

[463] "India country profile", World Bank, updated 2021, accessed April 20, 2021, https://data.worldbank.org/country/india

[464] IAEA PRIS database. Author's own calculations.

India was able to take advantage of economies of scale by constructing multiple reactor units at each site. India constructed two nuclear plants at a time at each nuclear site. (e.g., two units at Kaiga in 1989, followed by two units in 2002.)

Project delays

One of the largest factors for project delays in India from 1965 to 2008 was due to the aforementioned nuclear trade supply cutoff from the London/Nuclear Suppliers Group. Other reasons for construction project delays were a lack of industrial infrastructure in India and financial issues.[465]Additionally, two VVER design reactor units were imported and constructed by Russia, with another two units currently under construction. The final start-up of the nearly completed Kundankulam was delayed six months due to protesters blockading the site.[466]

Secure financing

NPCIL being a SOE afforded it access to government funding, but India's GDP from 1965 to 2000 limited the speed of India's civil nuclear program advancement. India relied upon Russia's export bank for loans in order for Russia to construct its VVER V-412 plants at Kundankulam.[467]

Return of experience

Due to India's experience constructing a standardized design for eighteen HPT reactors, it benefited from a greater return of experience. The return of experience led to shorter average completion times for this design (from 10.25 to 6.58 years.)

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[465] "Madras Atomic Power Project", Indian Department of Atomic Energy, April 27, 1989, accessed April 20, 2021, https://eparlib.nic.in/bitstream/123456789/4067/1/pac_8_162_1989.pdf

[466] "Kudankulam delays mount up", *World Nuclear News*, January 18, 2012, https://www.world-nuclear-news.org/NN_Kudankulam_delays_mount_up_1701121.html

[467] Anil Sasi, "NPCIL gets big funding push after payments delay to Russians", *The Indian Express*, February 7, 2019, https://indianexpress.com/article/business/npcil-gets-big-funding-push-after-payments-delay-to-russians-5572797/

Closing

India is advancing its nuclear power program, but progress is slow due to India's economic constraints. Over the course of the last fifty years, India has developed good habits in the civil nuclear power industry—using standardized design and economies of scale, and continuously constructing projects which maintains the skills of their specialized workforce. These habits are likely to generate larger dividends in a stronger economy. With India's economic growth rate, that time is likely several years away. Without international aide, India will likely continue to construct more coal plants to meet immediate power needs and construct civil nuclear power projects when international financing is favorable.

* * *

Case Study: Findings

Conclusion

The post-Fukushima era is a period of uncertainty for the nuclear industry. Nuclear power programs across the industry are either advancing, declining, or stalling. The findings from this paper indicate that civil nuclear power programs are on the decline in states without nuclear state-owned enterprises. The United States, Canada, United Kingdom, Germany, and Japan do not have nuclear SOEs, and their civil nuclear power programs are in a state of decline. While states that have nuclear SOEs—Russia, France, China, South Korea, and India—are advancing their nuclear programs in the post-Fukushima era.

Declining civil nuclear power states

While the United States and the United Kingdom are both in the process of constructing Gen III reactors, both are experiencing significant delays. Recently, both states experienced civil nuclear plant projects falling through (Wylfa Newdd) or abandoned mid-construction (Virgil C. Summer). Additionally, both states were once strong nuclear export states, but neither has exported nuclear technology in over a decade. The U.S. nuclear export firm, Westinghouse, went bankrupt during the Virgil C. Summer project, and the U.K. is importing nuclear technology from France. Both states experienced significant project issues related to financing, a lack of an experienced workforce, project management, and dried up supply chains. Due to the age of the nuclear reactors in the U.K. and U.S., and concerns for air pollution and climate change, civil nuclear power will likely remain a strong option for both states. It is feasible that both states' nuclear industries will regain their momentum following the completion of their current civil nuclear projects. Resulting from the Vogtle and Hinkley Point C projects both being significantly overbudget and overschedule, it is likely that both states will pursue small module reactors in lieu of large-scale reactors due to lower capital costs and quicker (estimated) construction times.

Canada too, has an aging nuclear fleet. Its nineteen operational reactors have an average age of forty-five years old (1976 average year).[468] Canada has focused its efforts on extending its reactors' plant life (refurbishment).[469] The privatization of AECL in 2011, Canada's exit from the nuclear export industry, and the nearly thirty-year lapse in domestic civil nuclear power plant construction led to the decline of Canada's civil nuclear program. Canada, no longer operating a nuclear SOE, is currently pursuing the usage of SMR technology to advance their civil nuclear program.

For all three states, Canada, U.S., and U.K., the resumption of civil nuclear power plant projects (both new construction and refurbishment) following long hiatuses/moratoriums indicates that the level of public reservations about nuclear power has decreased.

Germany and Japan, however, still have strong reservations about civil nuclear power. Both states moved away from nuclear following the events of Fukushima. Germany is on its way to being a nuclear free state by the year 2030. Japan is slowly restarting its nuclear fleet and its citizens are divided on the nuclear debate. Both states have returned to a reliance on coal and other fossil fuels following Fukushima. Germany's majority of energy comes from renewable energy and moves towards a carbon free future. Japan will not likely pursue any further large-scale reactors after the completion of their current projects; they will likely pursue renewables and allow their nuclear fleet to retire.

Advancing civil nuclear power states

Russia's civil nuclear power program held strong throughout the nearly twenty-year lapse in domestic builds during the post-Chernobyl and post-Soviet eras. Russia's nuclear program reemerged during a new era of prosperity fueled by Russia's 2008 oil boom, and the

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[468] IAEA PRIS database. Author's own calculations.

[469] "Current fleet refurbishment", CAN, updated 2021, accessed April 15, 2021, https://cna.ca/research-and-advocacy/refurbishment/

direction of President Putin. Russia also continued the promotion of its nuclear exports. Russia's mastery of the nuclear fuel cycle, its usage of standardized design and economies of scale, coupled with the return of experience gained from domestic and international projects will continue to drive advancement of its civil nuclear power program.

France's civil nuclear power program is advancing, but perhaps a better word would be *persevering*. France is staying the course, even in the face of significant financial and project timeline setbacks. It is able to persevere because it is a state-owned enterprise. Its long string of successes leading up to the delays and failures it experienced at Olkiluoto, Flamanville, and Hinkley Point demonstrate that France has learned the formula for success with civil nuclear power, but needs more experience with this new design and scale. If France continues to build the same design, with a refreshed supply chain and a (recently) experienced civil nuclear power plant construction workforce, it will likely advance its nuclear program much quicker and much more efficiently.

China's nuclear program is advancing by leaps and bounds over its peers. China is constructing nuclear plants at an accelerated rate, and they are using modern designs that no other state has successfully completed constructing to date. China was able to do so by learning from the experience of more advanced nuclear states. China's phased approach of having plants built, then building plants themselves with foreign nuclear technology, and culminating with indigenous design, manufacturing, and construction was well thought out and well executed. China's late entry into civil nuclear power programs (relative to then-mature nuclear states) was turned into an advantage. By the time the first nuclear states' aging fleets needed to be replaced with Gen III technology, the advanced nuclear states had lost their experience, dried out their supply chain, and privatized their nuclear industry. China, on the other hand, had fresh experience, a fresh supply chain, and state-owned enterprises to drive its nuclear program advancement. The next step for China is to master the back end of the fuel cycle—spent fuel rods—and become party to the IAEA Vienna Convention on Civil Liability for Nuclear Damage. At which point, China would be able to become nuclear exporters.[470]

South Korea is following in China's footsteps in their advancement of civil nuclear power. The phased approach is also being taken. South Korea imported nuclear technology and learned from its design. They then designed, manufactured, and constructed civil nuclear power technology indigenously. South Korea's mastery of the fuel cycle, and its usage of standardized design and economies of scale enabled South Korea to go a step further than China—they began exporting nuclear technology and constructing civil nuclear power plants in the Middle East. The return of experience from the APR-1400 design from both domestic builds, and international builds in UAE, can benefit future projects by increasing workforce experience and reducing construction times and costs.

India is slowly advancing its civil nuclear power projects but running into difficulty with financing its projects. Although India uses standardized design, takes advantage of economies of scale, and has a nuclear state-owned enterprise, they are dependent upon international financing to construct civil nuclear power plants. India's civil nuclear power program will progress, but slower than China, France, Russia, and South Korea.

The Decline of Civil Nuclear Power

While some states are advancing their civil nuclear power programs in the post-Fukushima era, civil nuclear power is declining in the aggregate. The greatest period of advancement for civil nuclear power was the twenty-year period between 1965 and 1985 when over four-hundred civil nuclear plants began construction worldwide. This figure is almost double the number of civil nuclear power plant projects that began both before and following this twenty-year period.[471] (See Figure 36 below for a graph of completed projects from 1965-1985.)

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[470] "Nuclear Power in China", *World Nuclear* Association, updated May 2021, https://www.world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx

[471] IAEA PRIS database. Author's own calculations. 421 nuclear power plant projects started from 1965-1985, 263 projects in preceding and following years.

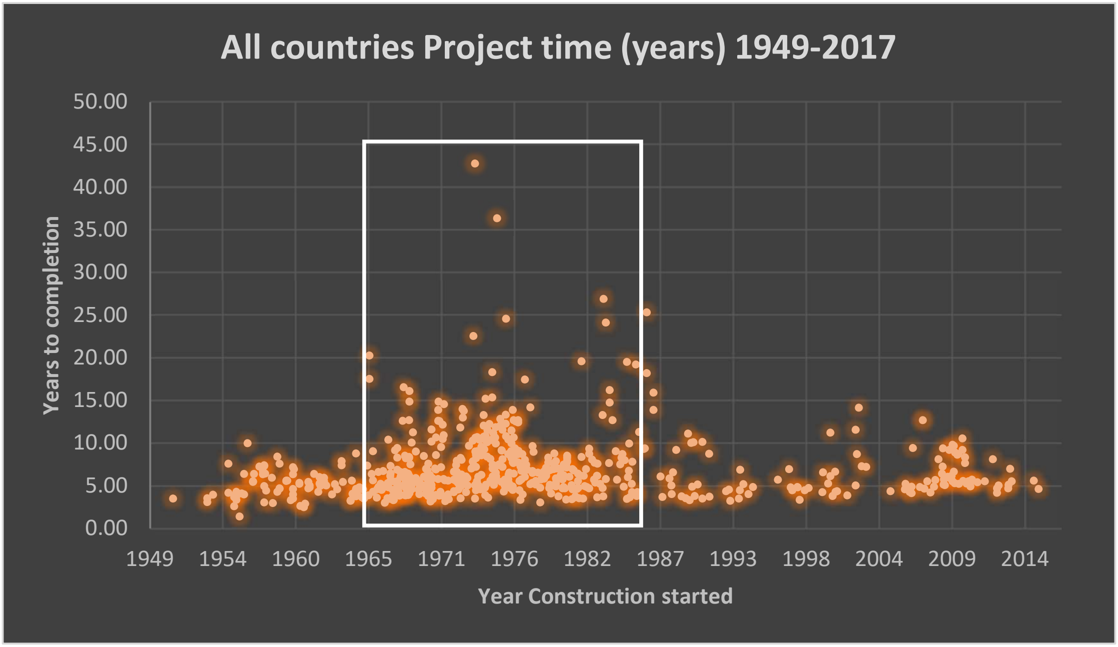

Figure 36-- Project completion times for 10 case studies. Source: Data from IAEA PRIS database. Author's own graph. Note: White box indicates twenty-year span from 1965-1985.

The heavy concentration of civil nuclear power projects constructed from 1965 to 1985 carries with it a significant problem for mature nuclear states—plants that are constructed in the same period generally retired alongside others from that period. The median year of the data set is 1975—which puts the average age of the global nuclear fleet at 38 years old (45 years from 1975 to present, minus the seven years for the average construction completion time and connection to the electrical grid—the connection to grid date marking the beginning of operational life of the plant.)[472] Contrary to popular belief, nuclear plants do not have thirty-year operating lives. Civil nuclear plants can operate up to 60 years, most needing refurbishment (i.e., technological and safety feature upgrades) to achieve an operating life of that length.[473] Additionally, nuclear regulatory agencies require extension licenses past a certain operating life. (Varies by state.) The United States, for example, has a 20-year license extension application

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[472] IAEA PRIS database. Author's own calculations.

[473] Note: See Canada's refurbishment program. Page 72 of this paper.

for nuclear plants following the initial 40-year license.[474] Plants that were constructed at the beginning of the construction boom in 1965, which connected to the electrical grid five to seven years later, will reach their sixtieth year in 2030. Those constructed in 1975 and connected to the grid in 1980 will reach sixty years in 2040; and those constructed at the tail end, near 1985, and connected to the grid in 1990 will reach sixty in 2050.

This sixty-year operating life only holds true if states or private energy companies opt to spend the time and money to refurbish the nuclear plants—a significant number of plants are retired well before they reach thirty years of operation. When older plants are found technologically incompatible with modern replacement parts, or when its systems do not meet modern safety standards (e.g., containment structures not able to withstand aircraft collision, lack of passive safety features for emergency core cooling following Fukushima, etc.), the plant operator is faced with the choice to refurbish or retire the plant. The United States retired twenty-seven civil nuclear power plants before they reached thirty years of operation. [475] The U.S. retired twelve more plants ranging from thirty years to forty-nine years of operation. U.S. states, such as California, have shut down their civil nuclear power plants prior to the plants reaching the end of its operating life. Rancho Seco plant was shut down just shy of the fifteen-year mark, San Onofre plants at the twenty-five and thirty-year marks, and California plans to shut down their last remaining plant—Diablo Canyon—at the forty-year mark.[476] Canada has not shut down a large percentage of its nuclear reactors, and as mentioned earlier in this paper, Canada is in the process of refurbishing many of its existing reactors. Of the six reactors it has retired, they were retired (on average) at their twenty-fifth year of operation; those currently in

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[474] "Status of Subsequent License Renewal Applications", U.S. NRC, accessed May 5, 2021, https://www.nrc.gov/reactors/operating/licensing/renewal/subsequent-license-renewal.html

[475] Note: One additional reactor was permanently shut down-Three Mile Island unit 2—due to it suffering a partial meltdown.

[476] "Voters, in a First, Shut Down Nuclear Reactor", *New York Times*, June 8, 1989.
Sonal Patel, "PG&E moves to retire 2.3-GW Diablo Canyon Nuclear Plant", *Power,* June 21, 2016, https://www.powermag.com/pge-moves-to-retire-2-3-gw-diablo-canyon-nuclear-plant/

operation are exceeding that average.[477] What is notable in Canada's case is that, much like the United States, it constructed the bulk of its reactors between 1965 and 1985.Britain has retired thirty out of its forty-five constructed reactors at the average plant operating life of thirty-five years. The remaining fifteen operational plants are thirty-eight years old.[478] Germany has retired their nuclear plants early as well—at an average of 15.72 years of operating life for the East German Soviet-built reactors, and 23.60 years on average for those built in West Germany.[479] Germany intends to retire its remaining six reactors in 2021 and 2022—which nears the thirty-five-year mark of operating life for those reactors. Japan has shut down twenty-seven reactors—twenty-two of which following the events of Fukushima. Average plant operating life: 35.62 years. Japan's current operating plants have an average age of 30-year age. Even with refurbishment, the operating reactors from the above states will reach their sixty-year operating lives 2030, 2040, and 2050.

The decline of civil nuclear power in states without SOEs is compounded by the approaching retirement of a large percentage of their civil nuclear power plants. As posited in the argument of this paper, states that do not have nuclear SOEs, or maintain a controlling interest in a private civil nuclear power corporation, are not able to take advantage of secure financing, standardized design, economies of scale, return of experience, or able to mitigate the effects of project delays. These states are not able to advance their civil nuclear power projects, and as a result, nuclear power plants are not being constructed at a rate suitable to replace an aging nuclear fleet. Mature nuclear states are more susceptible to this compounded problem as many of their civil nuclear power plants were completed nearly forty years ago, and a large percentage of their nuclear fleet will soon be due for retirement. Since the number of aging plants that need to be replaced significantly outweigh the number of plants currently under

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[477] Ibid. Author's own calculations.
[478] Ibid. Author's own calculations.
[479] IAEA PRIS. Author's own calculations.

construction, a future reduction in the share of electricity generated by nuclear power plants can be expected.

The decline of civil nuclear power programs in non-SOE states presents a challenge for future energy production. And since nuclear energy represents a significant percentage of a state's carbon-free energy production, a decline in civil nuclear power programs will also limit a state's ability to meet its climate change / greenhouse gas reduction goals.

Recommendations for future research

Given that small modular reactor projects are scalable, and the projects would become affordable to private utility companies, or even large cities, civil nuclear interests could be advanced without the aid of state-owned enterprises. Future research could be conducted on the impact of SMRs on the nuclear energy industry—specifically centered on state-owned enterprises and the ability of private firms to compete against SOEs.

The NuScale-Shearwater Energy project proposed in the U.K. at Wylfa presents an opportunity to conduct a technical study on the effectiveness of using SMRs in hybrid-energy systems that combine nuclear with wind and or solar. Additionally, the nuclear industry's cutting-edge proposals to use SMRs and molten-salt energy storage systems in tandem for energy production and storage for peak demand hours would be an excellent topic of study.

Studies could also be conducted on the impact of small modular reactors potentially being used for small-distributed power projects to create microgrids in geographically distant towns, and what impact the microgrids might have on the national grid, and utility corporations.

Academic contribution

This paper provides data analysis on state-owned enterprises and private corporations operating in the nuclear industry. Ten data points were collected from six-hundred and thirty-six civil nuclear power reactor unit projects constructed or planned throughout the world. These points were analyzed to determine which factors could offer possible explanations to the phenomenon in the research question: Why are certain states able to advance their civil nuclear power programs in the post-Fukushima era, and other states not? There are no studies discovered during the literature review that focus on the nexus of the subjects of state-owned enterprises and the nuclear industry.

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APPENDIX A: Simplified nuclear Power Plant design

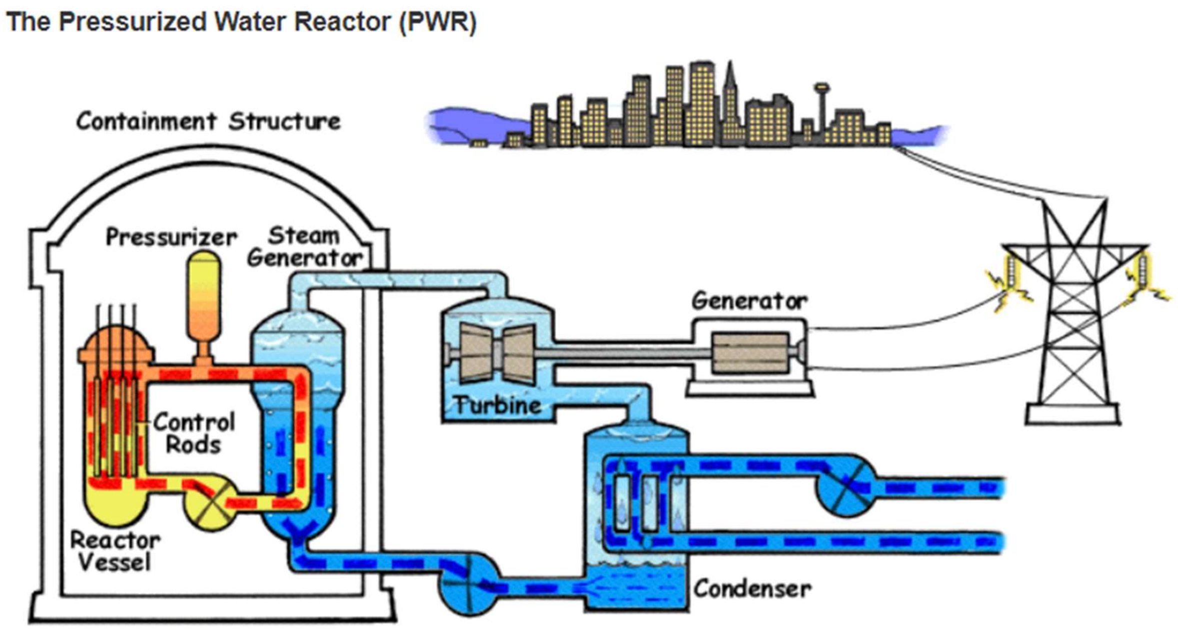
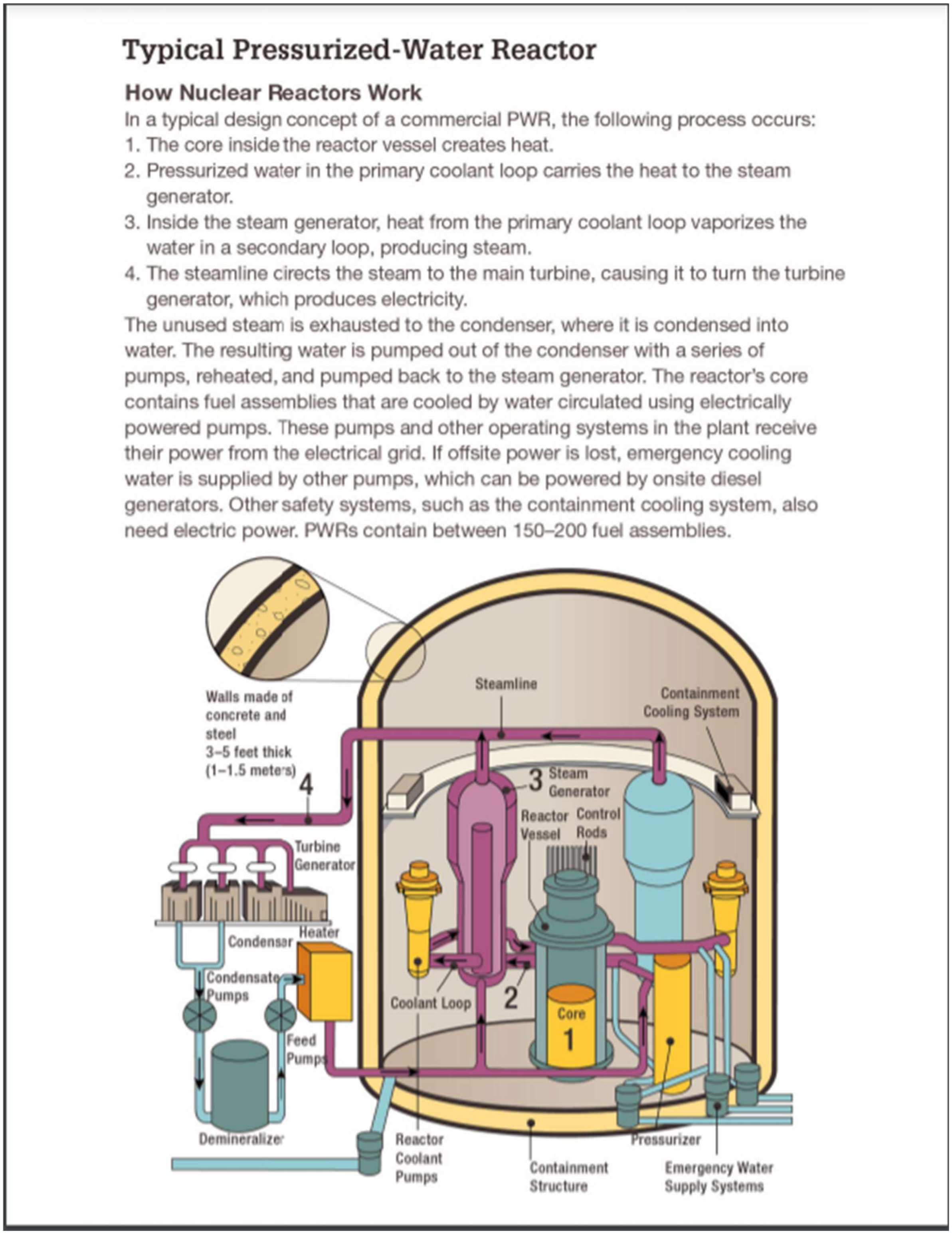


Figure 37: Basic diagram of a nuclear power plant (PWR). Source: U.S. NRC https://www.nrc.gov/reading-rm/basic-ref/students/animated-pwr.html

The major difference between a nuclear reactor and nuclear power plant is the addition of three components: steam generator, turbine, and generator. The nuclear power plant has primary coolant water flowing through the reactor core (inside reactor vessel), which in turn flows in pipes passing through a steam generator. These pipes, made hot from the primary coolant water flowing through them, heat up and vaporize the secondary water (water inside the steam generator). The vaporized water (steam) then moves in pipes leaving the steam generator and passes through turbine generators making the blades turn, the rotation of which turns a turbine generator shaft. The generator shaft has a rotor attached, which interacts with the stator of the generator, creating electricity. This process is what generates electrical power supplied to the commercial electric grid.

It should be noted that in PWRs, the primary water from the reactor core **never** comes in contact with the secondary water in the steam generator. In BWRs, there is no secondary coolant system. The coolant water flowing through the reactor core is turned into steam and that same steam passes through turbines.

APPENDIX B: Pressurized Water Reactor design (PWR)



Typical Pressurized-Water Reactor

How Nuclear Reactors Work

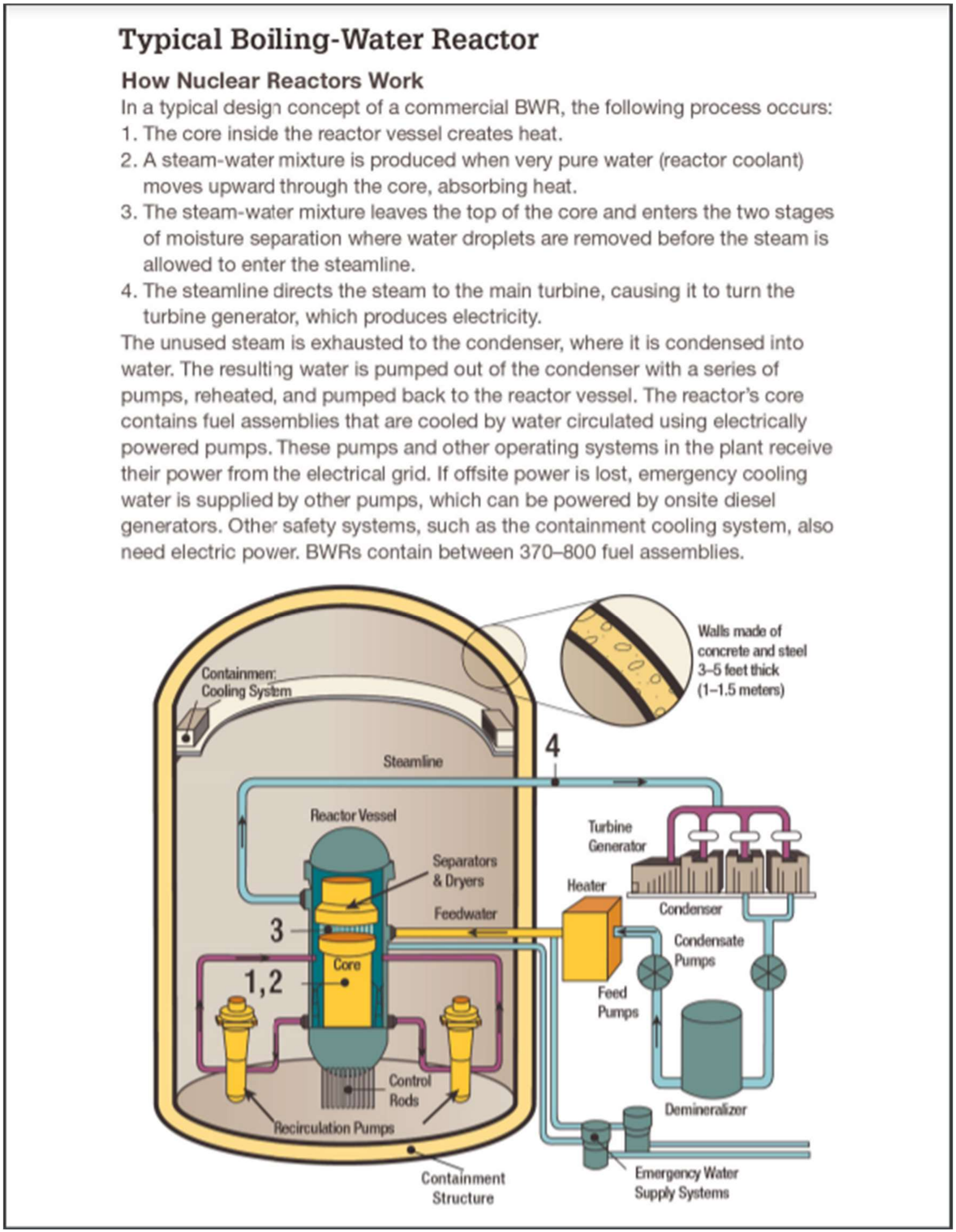
In a typical design concept of a commercial PWR, the following process occurs:

1. The core inside the reactor vessel creates heat.
2. Pressurized water in the primary coolant loop carries the heat to the steam generator.
3. Inside the steam generator, heat from the primary coolant loop vaporizes the water in a secondary loop, producing steam.
4. The steamline directs the steam to the main turbine, causing it to turn the turbine generator, which produces electricity.

The unused steam is exhausted to the condenser, where it is condensed into water. The resulting water is pumped out of the condenser with a series of pumps, reheated, and pumped back to the steam generator. The reactor's core contains fuel assemblies that are cooled by water circulated using electrically powered pumps. These pumps and other operating systems in the plant receive their power from the electrical grid. If offsite power is lost, emergency cooling water is supplied by other pumps, which can be powered by onsite diesel generators. Other safety systems, such as the containment cooling system, also need electric power. PWRs contain between 150–200 fuel assemblies.

Figure 38- Basic Pressurized Water Reactor (PWR) design. Source: US NRC, https://www.nrc.gov/reactors/pwrs.html

APPENDIX C: Boiling Water Reactor design (BWR)



Typical Boiling-Water Reactor

How Nuclear Reactors Work

In a typical design concept of a commercial BWR, the following process occurs:

1. The core inside the reactor vessel creates heat.
2. A steam-water mixture is produced when very pure water (reactor coolant) moves upward through the core, absorbing heat.
3. The steam-water mixture leaves the top of the core and enters the two stages of moisture separation where water droplets are removed before the steam is allowed to enter the steamline.
4. The steamline directs the steam to the main turbine, causing it to turn the turbine generator, which produces electricity.

The unused steam is exhausted to the condenser, where it is condensed into water. The resulting water is pumped out of the condenser with a series of pumps, reheated, and pumped back to the reactor vessel. The reactor's core contains fuel assemblies that are cooled by water circulated using electrically powered pumps. These pumps and other operating systems in the plant receive their power from the electrical grid. If offsite power is lost, emergency cooling water is supplied by other pumps, which can be powered by onsite diesel generators. Other safety systems, such as the containment cooling system, also need electric power. BWRs contain between 370–800 fuel assemblies.

Figure 39- Basic Boiling Water Reactor (BWR) design. Source: NRC, https://www.nrc.gov/reactors/bwrs.html

APPENDIX D: Fukushima-Daiichi boiling water reactor cutaway

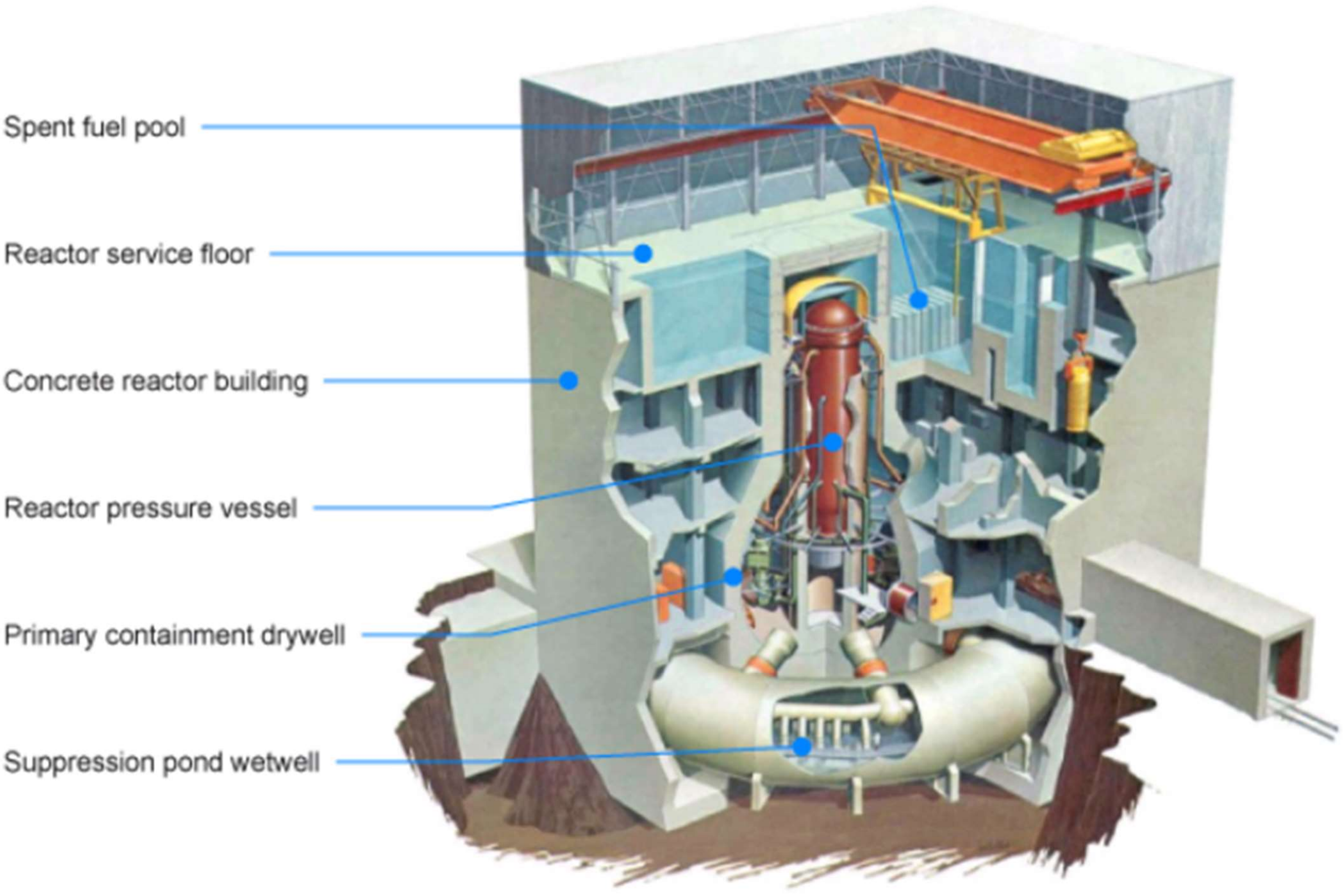


Figure 40--BWR cutaway illustration; Source: "Fukushima: Background on Reactors", World Nuclear Association, https://www.world-nuclear.org/information-library/safety-and-security/safety-of-plants/appendices/fukushima-reactor-background.aspx

APPENDIX E: Three-mile island end-state of reactor core-partial meltdown

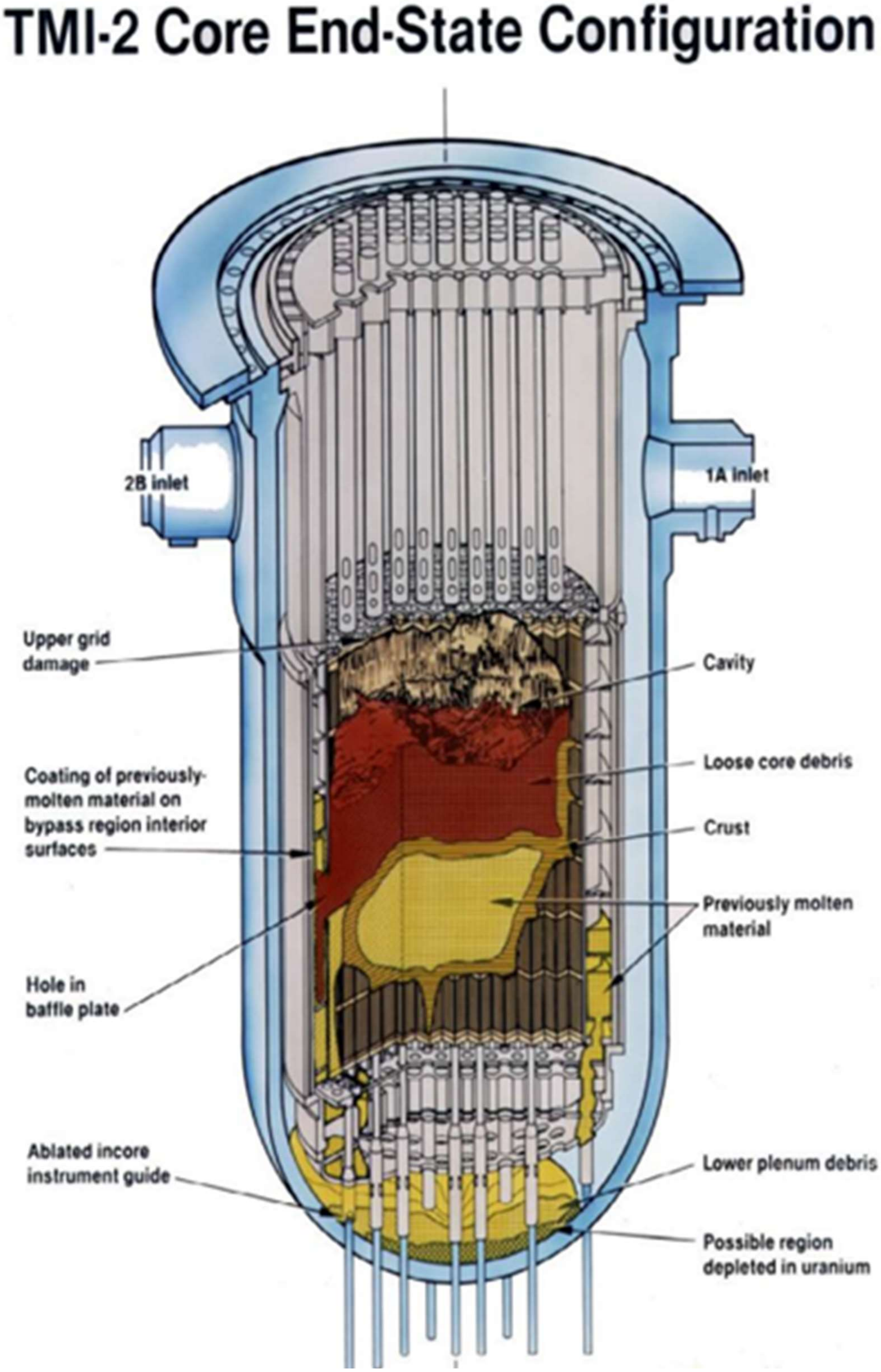
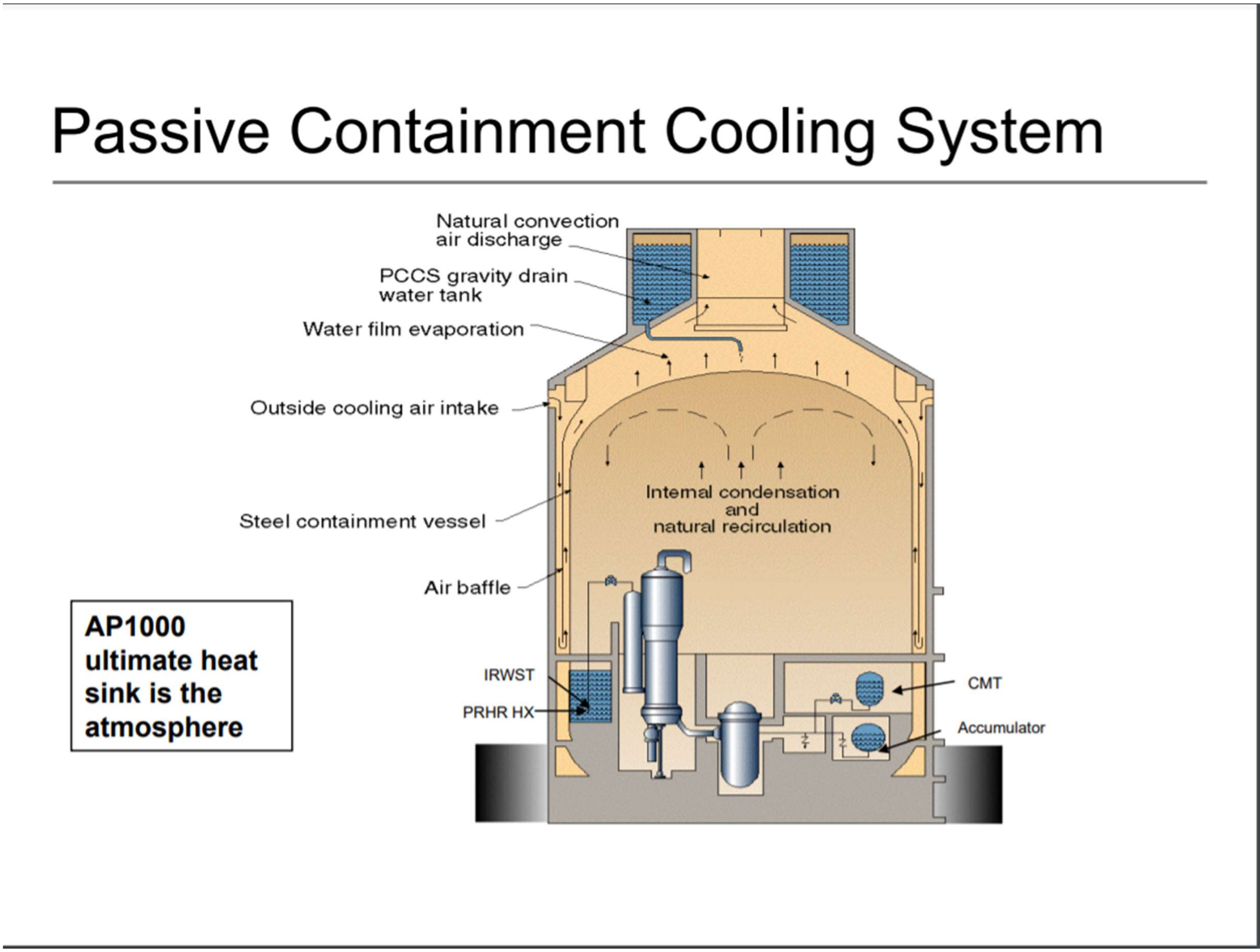


Figure 41: Partial core meltdown of Three Mile Island. Source: U.S. Nuclear Regulatory Commission https://www.nrc.gov/docs/ML1616/ML16166A358.pdf

APPENDIX F: Westinghouse AP1000 passive safety design features

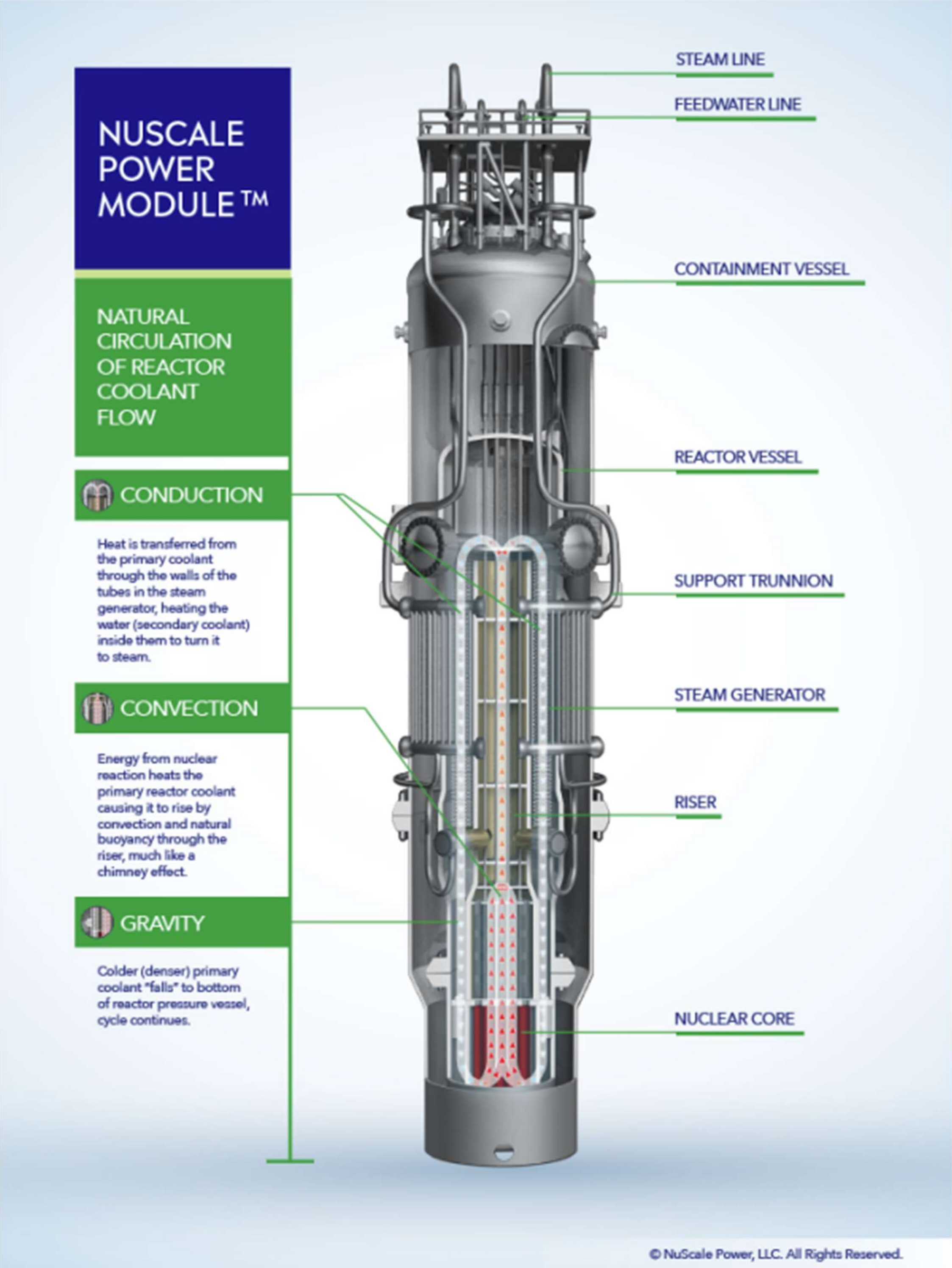


Passive Containment Cooling System

AP1000 ultimate heat sink is the atmosphere

Figure 42: Passive safety features of the Westinghouse AP1000. Image source: "The Westinghouse Advanced Passive Pressurized Water Reactor, AP1000", Westinghouse, https://inis.iaea.org/collection/NCLCollectionStore/_Public/42/026/42026956.pdf

APPENDIX G: NuScale reactor unit design



CONDUCTION

Heat is transferred from the primary coolant through the walls of the tubes in the steam generator, heating the water (secondary coolant) inside them to turn it to steam.

CONVECTION

Energy from nuclear reaction heats the primary reactor coolant causing it to rise by convection and natural buoyancy through the riser, much like a chimney effect.

GRAVITY

Colder (denser) primary coolant "falls" to bottom of reactor pressure vessel, cycle continues.

Figure 43—NuScale reactor unit design, Source: NuScale website, accessed May 27, 2021, https://www.nuscalepower.com/benefits/simplified-design

APPENDIX H: European Pressurized Reactor design

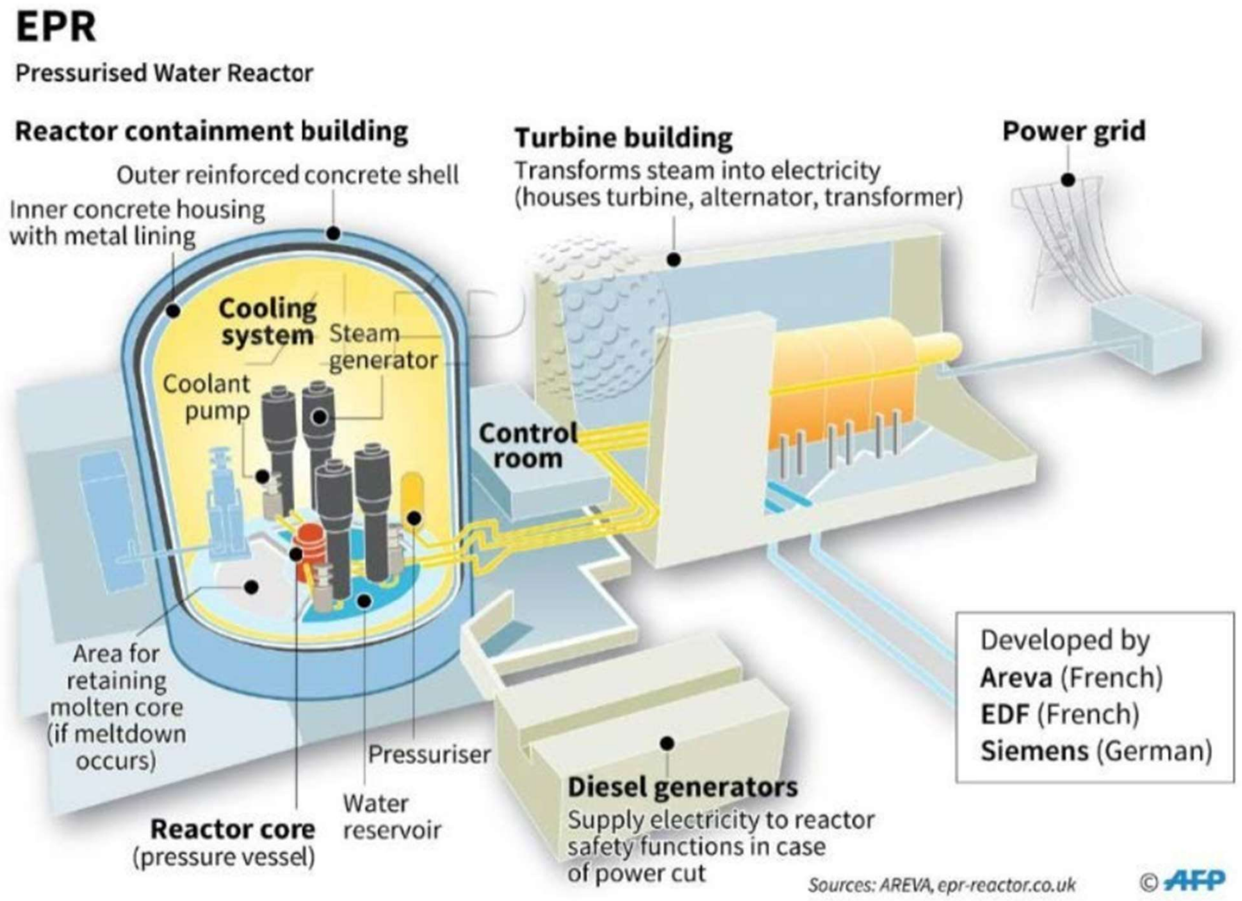


Figure 44-European Pressurized Reactor. Source: Agency France-Presse, https://twitter.com/AFP/status/1005766525272379397/photo/1

APPENDIX I: Pebble-bed sphere design

A pebble-bed reactor is different than previously discussed reactors in that its nuclear fuel source travels through the reactor active zone, suspended in moderator fluid or traveling within a moderator gas. The ‘pebble’ refers to a sphere containing a kernel of fissile material (e.g., U-233, U-235, Pu-239) that is coated in carbon and silicon carbide. A recent Generation IV design of the pebble can withstand extreme temperatures—up to 3,000 degrees Fahrenheit.[480] The pebble design is illustrated below in Figure 44.

Figure 45-- TRISO pebble sphere. Source: U.S. Department of Energy, https://www.energy.gov/ne/articles/triso-particles-most-robust-nuclear-fuel-earth

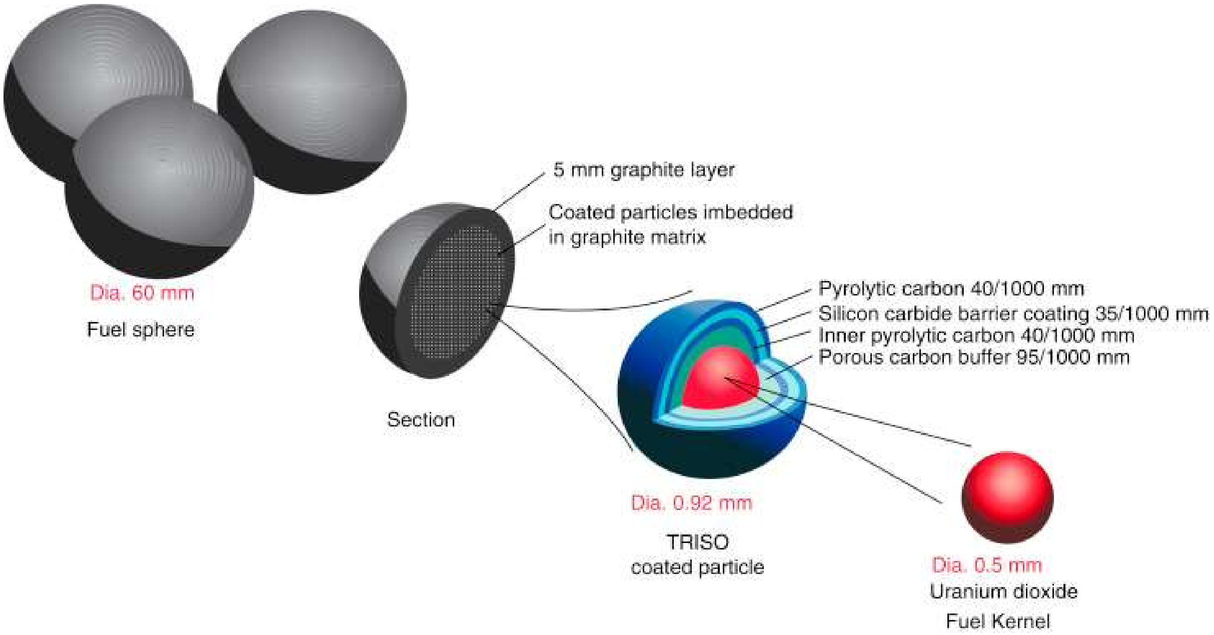


Figure 436-- TRISO pebble composition, Source: Brian Boer, "Optimized Core Design and Fuel Management of a Pebble-Bed Type Nuclear Reactor", IAEA, https://inis.iaea.org/collection/NCLCollectionStore/_Public/43/066/43066439.pdf

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[480] “TRISO Particles: The most robust nuclear fuel on Earth”, Office of Nuclear Energy DOE, July 9, 2019, https://www.energy.gov/ne/articles/triso-particles-most-robust-nuclear-fuel-earth

APPENDIX J: Pebble-bed reactor design

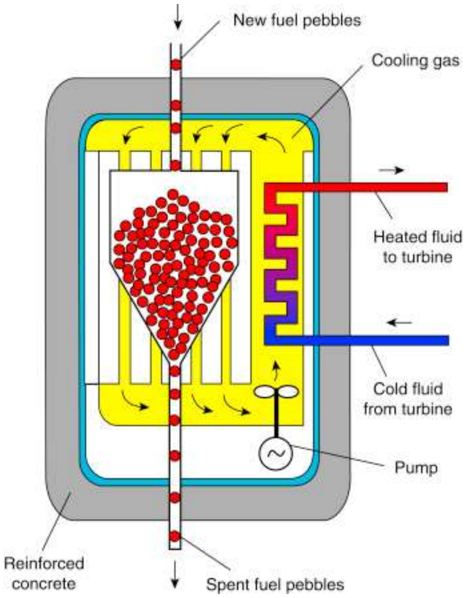


Figure 47--simplified Pebble-bed reactor design, Source: Bahman Zohuri, "Small Modular Reactors as Renewable Energy Sources" in Nuclear Energy Research and Development Roadmap, (Springer, 2019) https://doi.org/10.1007/978-3-319-92594-3_3

The basic operation of this reactor design is that the pebbles travel through the feeder tube and settle in the reactor active zone. Once the pellet's fissile material is spent, the pellet exits the active zone via a tube and is collected. The cycle then repeats, and new pellets are introduced at the top. No need for reactor downtime that typical PWR or BWR designed reactors need for replacing fuel rods.

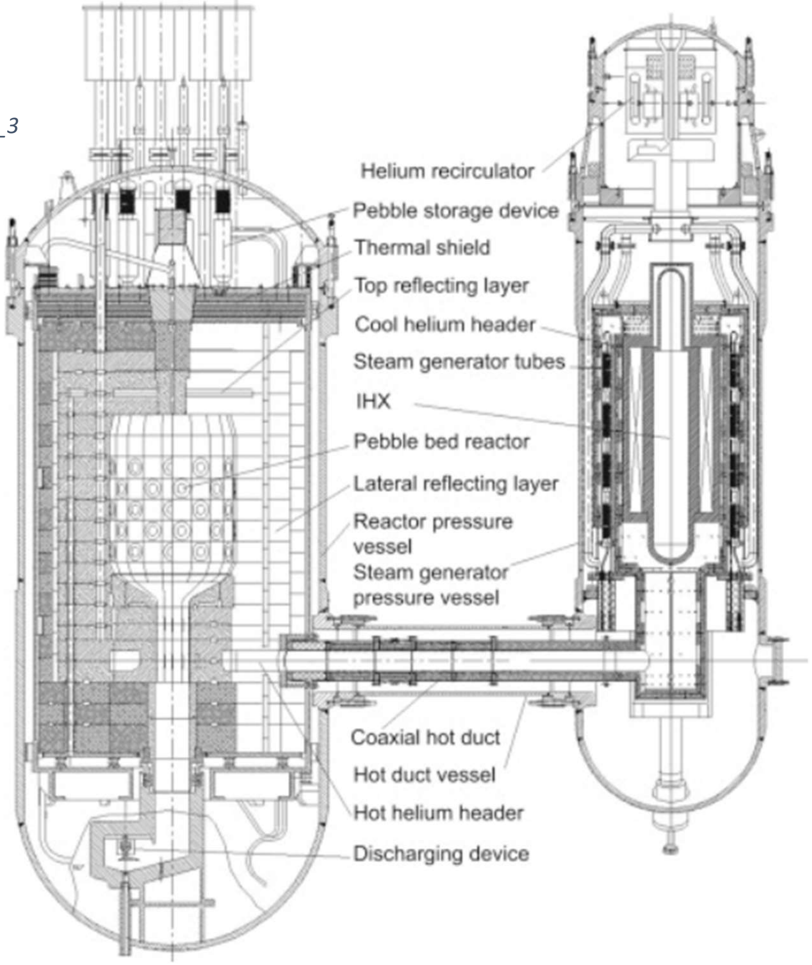


Figure 48-- Cutaway diagram of a Pebble-bed reactor, Source: D. Zhang, "Generation IV concepts" in Handbook of Generation IV Nucear Reactors, (Woodhead Publishing: 2016) https://www.sciencedirect.com/book/9780081001493/handbook-of-generation-iv-nuclear-reactors#b

APPENDIX K: CANDU/ Horizontal Pressure Tube reactor design

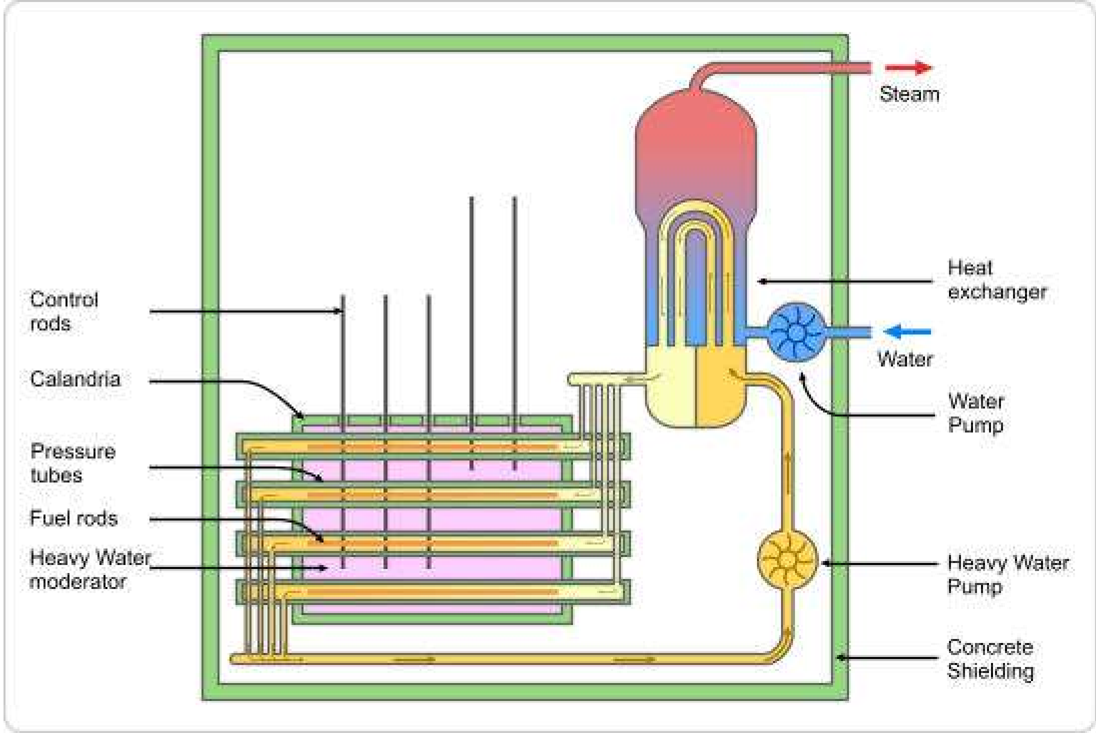
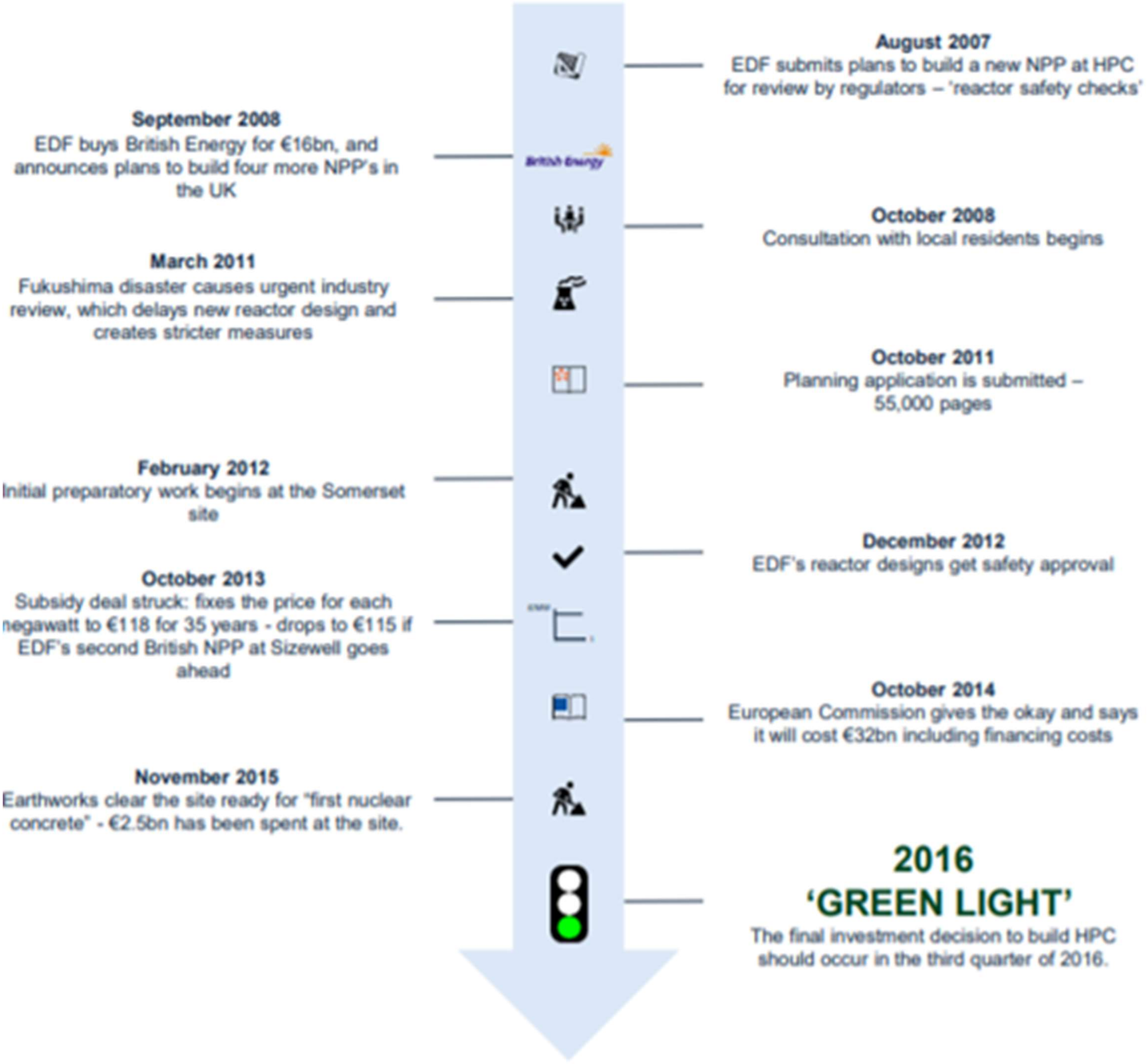


Figure 49- CANDU / Horizontal Pressure Tube reactor design. Source: https://www.researchgate.net/publication/330571584_Neutronic_analysis_of_mixed_thorium-uranium_fuel_bundle_for_CANDU_reactors

The CANDU design is similar to that of a PWR design except that the reactor vessel has pressure tubes running horizontally through it, and its *moderator* is full of *heavy water* (also called deuterium, D_2O.)

APPENDIX L: Hinkley Point C Timeline



August 2007
EDF submits plans to build a new NPP at HPC for review by regulators – 'reactor safety checks'

September 2008
EDF buys British Energy for €16bn, and announces plans to build four more NPP's in the UK

October 2008
Consultation with local residents begins

March 2011
Fukushima disaster causes urgent industry review, which delays new reactor design and creates stricter measures

October 2011
Planning application is submitted – 55,000 pages

February 2012
Initial preparatory work begins at the Somerset site

December 2012
EDF's reactor designs get safety approval

October 2013
Subsidy deal struck: fixes the price for each negawatt to €118 for 35 years - drops to €115 if EDF's second British NPP at Sizewell goes ahead

October 2014
European Commission gives the okay and says it will cost €32bn including financing costs

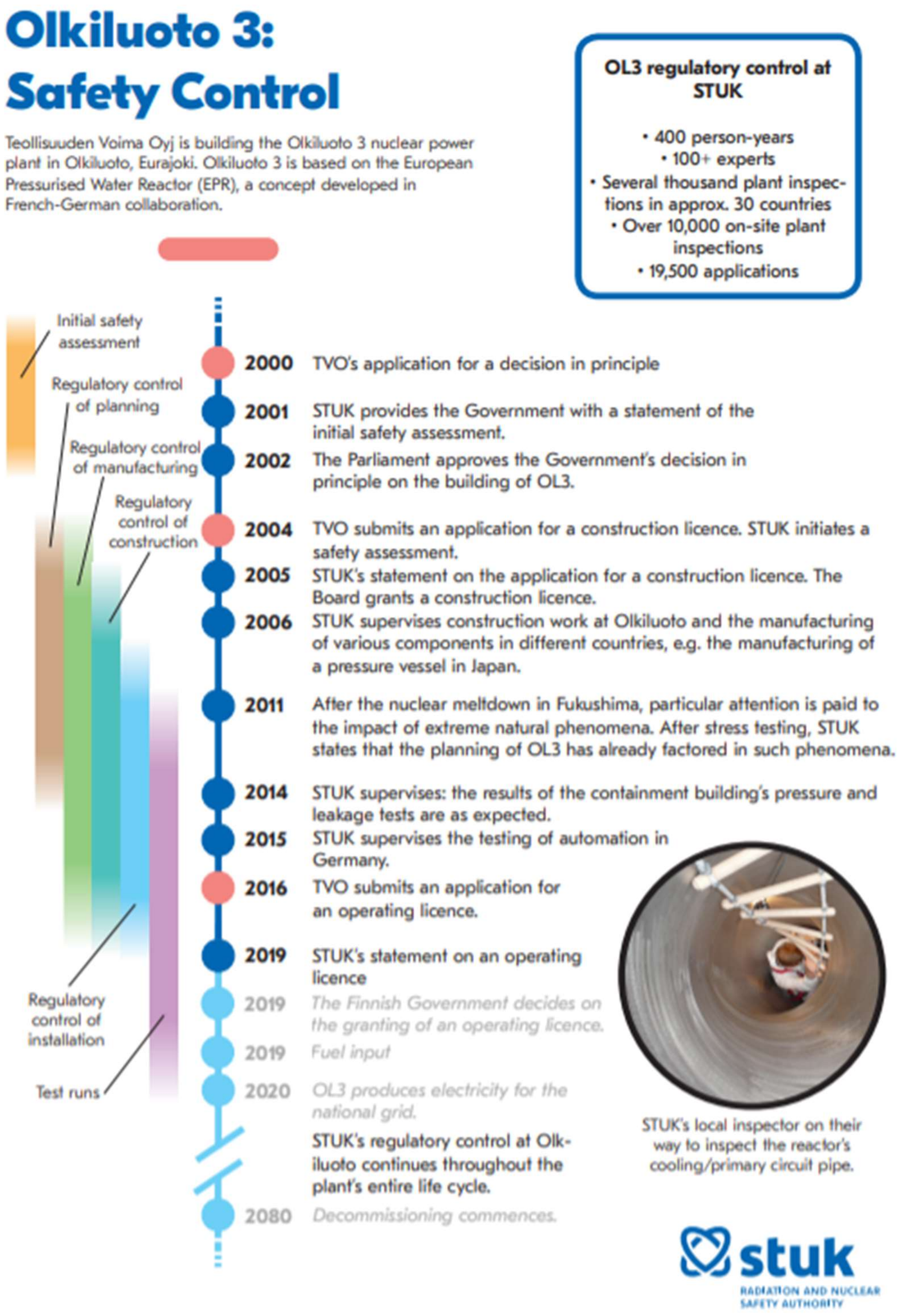
November 2015
Earthworks clear the site ready for "first nuclear concrete" - €2.5bn has been spent at the site.

2016
'GREEN LIGHT'
The final investment decision to build HPC should occur in the third quarter of 2016.

Figure 50: Capitalmind corporate finance advisory: Hinkley Point C 2016/2017

https://capitalmind.com/wp-content/uploads/2018/12/16-03-29-HPC-final_-E-CMv2.pdf

APPENDIX M: Finland’s nuclear license / STUK regulatory timeline



Olkiluoto 3: Safety Control

Teollisuuden Voima Oyj is building the Olkiluoto 3 nuclear power plant in Olkiluoto, Eurajoki. Olkiluoto 3 is based on the European Pressurised Water Reactor (EPR), a concept developed in French-German collaboration.

OL3 regulatory control at STUK

- 400 person-years
- 100+ experts
- Several thousand plant inspections in approx. 30 countries
- Over 10,000 on-site plant inspections
- 19,500 applications

2000	TVO’s application for a decision in principle
2001	STUK provides the Government with a statement of the initial safety assessment.
2002	The Parliament approves the Government’s decision in principle on the building of OL3.
2004	TVO submits an application for a construction licence. STUK initiates a safety assessment.
2005	STUK’s statement on the application for a construction licence. The Board grants a construction licence.
2006	STUK supervises construction work at Olkiluoto and the manufacturing of various components in different countries, e.g. the manufacturing of a pressure vessel in Japan.
2011	After the nuclear meltdown in Fukushima, particular attention is paid to the impact of extreme natural phenomena. After stress testing, STUK states that the planning of OL3 has already factored in such phenomena.
2014	STUK supervises: the results of the containment building’s pressure and leakage tests are as expected.
2015	STUK supervises the testing of automation in Germany.
2016	TVO submits an application for an operating licence.
2019	STUK’s statement on an operating licence
2019	*The Finnish Government decides on the granting of an operating licence.*
2019	*Fuel input*
2020	*OL3 produces electricity for the national grid.*
	STUK’s regulatory control at Olkiluoto continues throughout the plant’s entire life cycle.
2080	*Decommissioning commences.*

STUK’s local inspector on their way to inspect the reactor’s cooling/primary circuit pipe.

stuk
RADIATION AND NUCLEAR SAFETY AUTHORITY

Figure 441—Olkilouto 3 project timeline, Source: Radiation and Nuclear Safety Authority (STUK) website, https://www.stuk.fi/documents/12547/8995921/Olkiluoto3-timeline-EN.pdf/895bbe88-8575-776e-b3f6-246d6a3fcdae

APPENDIX N Glossary

Nuclear Reactor technology Glossary:

ABWR—Advanced Boling Water reactor

AGR—Advanced Gas reactor

BWR—Boiling Water Reactor

CANDU—Canadian Deuterium Uranium

EPR-- European Pressurized Reactor/Evolutionary Power Reactor

FBR—Fast Breeder reactor

GCR—Gas-cooled reactor

HTGR—High Temperature Gas-cooled reactor

HWGCR—Heavy Water Gas-cooled reactor

HWLWR—Heavy Water-moderated, Light-water-cooled reactor

LWGR—Light Water-cooled Graphite-moderated reactor

MAGNOX—Magnesium Alloy Graphite Moderated Gas-cooled Uranium Oxide reactor

PHWR—Pressurized Heavy-water reactor

PFR-- prototype fast breeder reactor

SGHWR-- steam generating heavy water reactor

PWR—Pressurized Water Reactor

VVER—Voda-Vodyanoi Energetichesky Reaktor (Water-water energy reactor)

Project Delivery Methods Glossary:

BOO—build, own, operate. A firm builds, operates, but does not transfer the project to owner.

BOT—build, operate, transfer. A firm builds it, and get to operate it for X years, then transfers it back to owner.

BOOT –build, own, operate, transfer. This is a longer-term BOT.

DBFO—design, build, finance, operate. A firm does not keep the project after it is built, but it may be paid by gov't to operate it—in addition to rents collected.

EPC—engineering, procurement, and construction. A firm is contracted to construct a design.

LSTK-- lump sum, turnkey. A firm builds the project then transfers it directly to the owner.

PFI-- private finance initiative. This delivery method is common to the United Kingdom.

PPP—private-public partnership. A firm forms a partnership with owner to share in profits by leasing, rents collected, etc.