Journal of Infrastructure, Policy and Development 2024, 8(11), 8715.
https://doi.org/10.24294/jipd.v8i11.8715

Article

Can the European nuclear power industry compete with the Chinese nuclear power industry?

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CITATION

Rothwell G. (2024). Can the European nuclear power Industry compete with the Chinese nuclear power industry?. Journal of Infrastructure, Policy and Development. 8(11): 8715. https://doi.org/10.24294/jipd.v8i11.8715

ARTICLE INFO

Received: 29 September 2024
Accepted: 30 October 2024
Available online: 21 October 2024

Abstract: European commissioner for the Internal Market, Thierry Breton, told Le Journal du Dimanche in January 2022, “Existing nuclear plants alone will need 50 billion euros of investment from now until 2030. And new generation ones will need 500 billion”. This paper considers whether these values are realistic. Further, it asks whether these investments would yield an internationally competitive European nuclear power infrastructure given that the nuclear power industries in the Organization for Economic Cooperation and Development member countries have lost global nuclear market share to Russian and Chinese firms since 1995.The paper investigates whether the European nuclear industry even with massive investment can compete with the Chinese nuclear industries. It concludes that the European (in particular, the French) nuclear power industry will be unlikely to be cost competitive with the Chinese nuclear power industry unless financing and new plant orders are immediately forthcoming. To achieve carbon neutrality, the issue becomes whether European Union countries can afford indigenous nuclear technologies or will need to import nuclear power plants from Asia.

Keywords: China; European Union; standardization; nuclear power plants; nuclear supply chain

1. Introduction

The European Commissioner for the Internal Market, Thierry Breton, told Le Journal du Dimanche in January 2022 (Gröndahl, 2022) for the European Union (EU) to achieve carbon neutrality, “Existing nuclear plants alone will need 50 billion euros of investment before 2030. And new generation ones will need 500 billion” by 2050 (in cumulative nominal dollars). Further, “To achieve carbon neutrality, according to all the experts, and taking into account the transition process undertaken, as well as the existing fleet of power plants, nuclear power will represent at least 15% of the whole in 2050–depending on the availability of other energies. Since the needs for carbon-free energy will increase considerably, it will therefore be necessary to proportionally increase the production of nuclear energy, especially since certain aging power stations will close in the years to come. Far from ideological debates, I stick to facts and arithmetic reality”.

This paper investigates whether these estimates for nuclear power investment in the EU are realistic. In addition, it asks whether these investments would yield a competitive European nuclear power industry in light of the nuclear power industries in the Organization for Economic Cooperation and Development (OECD) member countries (except the Republic of Korea, ROK) having lost global nuclear market share to Russian and Chinese firms since 1995.

The comparison of European and Chinese technologies is based on cost information available from OECD (2020) and Rothwell (2022), and construction lead times from IAEA (2024a, 2024b). The next section discusses the size of nuclear power industry investments required to maintain the European nuclear power infrastructure. Section 3 examines the development of the Chinese nuclear power industry. Section 4 compares construction lead times of the French and Chinese nuclear power plants (NPPs). The final section offers some conclusions and poses key questions, such as whether members of the EU should build Chinese NPPs. Throughout this discussion it should be remembered that the privately held American company, Westinghouse (which has had many owners), developed the Pressurized Water Reactor (PWR) technology that became the basis for the Chinese, French, and Korean PWRs deployed by state-owned enterprises (SOEs) that now compete with Westinghouse.

2. Assumptions to evaluate European Union nuclear power plant investment

First, consider the total net EU electricity generation was 2780 Terawatt-hours (TWh) in 2019 (Eurostat, 2022). If this were to double by 2050 and nuclear power were to supply 15% of this, NPPs would be required to produce 834 TWh per year, or a capacity of 112 GW (gigawatts, net), assuming a lifetime capacity factor of 85%, as in OECD (2020). According to IAEA (2024b), in 2024 there were 96.3 GW (net) of NPPs operating in the EU. While there are two units under construction, the EU NPPs have a mean age of 38.5 years with a median age of 40 years and a modal age of 44.5 years.

Second, to evaluate Commissioner Breton’s cost estimates additional assumptions must be made:

1) “Existing” NPPs refer to those that were operating in mid-2022. In mid-2024, there were only two units under active construction in the EU: Flamanville-3 (France, 1630 megawatts-electric, MWe, started in December 2007) and Mochovce-4 (Slovakia, started in January 1987). If these plants achieve commercial operation in 2024, there will be no NPPs under construction in the EU. (There are two European Pressurised Reactors, EPRs, under construction in the United Kingdom, UK: Hinkley Point C, where construction began in December 2018). However, until Flamanville-3 achieves commercial operation it would be difficult to determine how many more Euros will be required to bring Flamanville-3 into operation.
2) EDF (“Électricité de France”) estimates that it would cost €56B to build six 1630 MW (net) EPRs in France, i.e., a total of approximately 10,000 MW, or €5000/kWe overnight capital cost to which must be added financing costs (EDF, 2020). (The French parlement approved this plan and site preparation has begun at Penly (WNA, 2024a)). If the new EPRs are built as rapidly as those in China (Taishan 1 and 2 (NEA, 2015)), they would require 9 years from the first concrete date (i.e., not including the period to plan and license them) to criticality. If the average weighted cost of capital were 5% (real, i.e., not including inflation), following Rothwell (2016, p. 87), financing costs would be approximately €1400/kWe, or a €6400/kWe total capital investment cost. (If €5000/kWe

included financing costs, overnight capital cost would be approximately €3900/kWe, which is below all projected estimates for countries in the EU in OECD, 2020). Therefore, 10 GW of new capacity (e.g., EPR) would be approximately €64B when the financing costs are considered.

3) The next task is to determine whether €50 billion will adequately cover the existing NPPs. For example, the French "Grand Carenage" to extend the lives of 34 French nuclear units has been estimated at €50 billion (RTE, 2021). With 56 currently operating units, the Grand Carenage implies the life extension for French PWRs known as CP2 (Contrat Programme 2) 10 units coming into commercial operation between 1983 and 1988), P4 and P'4 ("pressurisé" or "pressurized" 4-loop PWR, where the prime refers to an updated version of the P4, 8 and 12 units, respectively, coming into commercial operation between 1985 and 1994), and N4 ("Nouveau 4 boucles primaires" or "New 4-loop", 4 units coming into commercial operation between 2000 and 2002). (A "loop" refers to a primary cooling circuit of pressurized steam running through the reactor to a steam generator where heat is transferred to a secondary circuit creating steam to drive the turbine generators.) The other 22 operating units would be retired. Commissioner Breton's implicit assumption is that these units (40 GW) will not need to be replaced until after 2050.
4) This implies that the earlier units CP0 ("Contrat Programme zéro", 6 units coming into commercial operation in 1978 and 1979, 2 of which have been retired) and CP1 (Contrat Programme 1:900 MWe with 3 steam generators, 18 units coming into commercial operation between 1980 and 1985) will need to be replaced by 2050. These 24 units account for 20 GW of net generating capacity. Assuming that these units are also replaced with EPRs, using the same values as above implies a total capital construction cost of about €128B.
5) Although other European units could have their lives extended, even if their lives could be extended 10 or 20 years, all but two (Olkiluoto 3 and Flamanville 3, both EPRs) will need to be replaced by 2050. This accounts for 40 GW. Assuming that these units are replaced with EPRs, implies a total capital construction cost of €256B.
6) At the same time, there are 90 GW of retired NPPs in the EU. The cost of decontamination and demolition, not including the cost of nuclear used fuel management (including reprocessing and disposal (Rothwell, 2016, pp. 187–197; Rothwell, 2021)) could be €100B (NEA, 2016), i.e., ~€1B/GW, including used nuclear fuel management.

The total capital construction cost to replace 70 GW with the only European nuclear technology currently available would be about €450B, ignoring economies of scale in serial production (i.e., "learning", see Rothwell (2016, pp. 96–100)). (Compare this with the estimate of $440B for 150 units in China (Bloomberg, 2021; Bloomberg, 2023)). If the newer French units with life extension would need to be replaced before 2050, another €256B might be required. If the newer French units do not need to be replaced, there would be €50B (out of a total of €500B) available for investment in Small Modular Reactors (SMRs (Hernandez, 2024)) and advanced (non-light water reactors) nuclear technologies (so-called "Generation IV" technologies, such as fast reactors and gas reactors).

Recently, the European Commission approved the French government's allocation of €300 million to support an EDF subsidiary to develop SMRs (EC, 2024). NEA (2024) assessed the progress of 56 SMR designs. In 2024 there were two small reactors producing electricity: one in China and one in Russia. They were "stick-built" like all larger NPPs, i.e., not manufactured in series with modular construction. Thus, while many countries in the EU have expressed interest in building SMRs, particularly those countries without operating NPPs, it will be at least a decade before they will be economically competitive with larger reactors (Rothwell, 2016, pp. 91–95), but they might not be competitive at that time with other low carbon generating alternatives.

Until they are competitive, the Chinese would like to export their Hualong One/HPR1000 to the EU and the UK. Can the EPR compete with the HPR1000? (This ignores competition from the Westinghouse Advanced Passive AP1000 and the Korean Advanced PWR, the APR1400, as well as prohibiting all Russian nuclear power technologies in the EU). How did China develop their nuclear power industry such that it can now compete with the more mature European nuclear power industry?

3. The development of a competitive Chinese nuclear power industry

The West's commercial nuclear power industry had its origins in the United States (US) Manhattan Project during World War II. After the war and the start of the Cold War with the Soviet Union and China, there was a bifurcation in the global nuclear power industry between the "West" (US, Western Europe, and their allies, including Japan and ROK) and the "East" (Soviet Union, Eastern Europe, and their allies, including India and Pakistan (Wealer et al., 2018)). With the passage of the *US Atomic Energy Act of 1946*, the British, Canadians, and French who had participated in the Manhattan Project, were denied access to the nuclear technologies they had helped develop. Competition among these countries led to a further fracturing of the Western nuclear power industry.

To continue the development of nuclear power and compact nuclear naval propulsion technologies the US Atomic Energy Commission (US AEC) developed several reactor technologies. The *Atomic Energy Act of 1954* was designed to encourage the entry of private enterprise into atomic energy development. In particular, the Power Demonstration Reactor Program (PDRP, US AEC and US DOJ, 1968, p. 117) offered three rounds of industrial group selection to allow access to US AEC-funded technologies, where "Reactor projects resulting from the PDRP are to have primary technical and financial responsibility rested in the industrial group making the proposal" (ANS, 2014). The policy of encouraging private enterprise to develop commercial nuclear technology has not changed in the US, for example, the same policy is prevailing with advanced nuclear technology development (SMRs and non-light water reactors).

The first round of PDRP funding included the Westinghouse PWR at the Yankee Nuclear Power Station (167 MWe) in Massachusetts, operating from 1961 to 1991, similar to the PWR in the nuclear submarine, Nautilus. Westinghouse built 58 units in the US (48 units are still operating), 18 units in Western Europe, 11 units in Asia, 4 AP1000s in China, 2 AP1000s in the US, and a unit in Brazil. While these units were similar, because of utility requirements and regulation changes, most Westinghouse units were one-of-a-kind or two-of-a-kind. Some were built before and after the Three Mile Island accident, which required design changes by the US NRC. Since 2000, it was hoped the AP1000 would be standardized and constructed in modules, but construction was started before the standardized design was finished. Also, design changes were made after the Fukushima accident.

France and the UK developed technologies to extract plutonium from used nuclear fuel from Gas-Cooled, graphite-moderated Reactors (GCRs, 34 units; all these early units are retired). To avoid the cost of developing another reactor to generate electricity, the French decided to build a fleet of standardized NPPs under license from Westinghouse. In the 1970s, Framatome began constructing two 3-loop (3 steam generator) 900 MW PWRs at Fessenheim (known as CP0). These units started operating in 1978 and were retired by 2020. Four more CP0 units were finished in 1978 and are still operating. By 1985, EDF had built 18 CP1s, similar in size to the CP0 units. By 1988 10 more follow-on CP2s (Contrat Programme 2) were built. Together these 34 units are known by the designation "CPY". This technology was exported to South Africa (2 units), ROK (2 units), and China (4 units). Twenty 4-loop 1,300 MW units, extending the CPY design, were built by 1994. Four larger 4-loop units, the N4, were operating by 2002, i.e., EDF built 58 similar PWRs (with different numbers of reactor sizes, steam generators, and various upgrades). The French strategy showed how to standardize units in a nuclear fleet. David and Rothwell (1996) define and compare the levels of standardization in France and the US.

By mid-2024, China was operating 57 nuclear units, including 4 French CP1s (M312), 1 one-loop CNP300 (Chinese Nuclear Plant-300 MW, with 4 exported to Pakistan), 6 two-loop CNP600s, 18 three-loop CPR1000s (Chinese Power Reactor-1000 MWe), 4 three-loop ACPR1000s (Advanced CPR1000), 6 three-loop CNP1000s, 4 Westinghouse AP1000s (NEA, 2015, pp. 209–217), 4 Russian VVER1000s, 4 HPR1000s (with 2 more operating in Pakistan), 2 French EPRs, 2 heavy-water moderated CANDUs (Canadian Deuterium Uranium), one 20 MW fast reactor (BN-20), and one high-temperature gas reactor with a pebble bed fuel system (HTR-PM, a single power plant with 4 reactors feeding heat to two steam turbine generators); Xin (2024). (The VVER is a pressurized Water, in Russia Voda, moderated, and Water, Voda, cooled Energy, or Electricity, Reactor).

Further, in mid-2024 China was building 29 units, including 12 HPR1000s, 8 CAP1000s, 4 VVER1200s, 2 CAP1400s, 2 fast reactors (CFR600s), and 1 small reactor (ACP100). See **Figures 1** and **2**. Also, there are many lists of planned and proposed units in China, e.g., WNA (2024b) with 37 planned units (39 GW) and 82 "firmly" proposed units (98 GW).

Figures 1 and **2** depict the complex process of moving toward a set of standardized units in China following a continuous "technology digestion, absorption, and re-innovation" (TDARI) strategy, as described by DRC (2010). See Xu (2020) and Gangyang et al. (2021) for discussions of standardization in the Chinese nuclear power industry. There are three SOEs digesting and innovating in the Chinese nuclear sector: (1) CGN (China General Nuclear), (2) CNNC (Chinese National Nuclear Corporation), and (3) the State Nuclear Power Technology Corporation (SNPTC), which became the State Power Investment Corporation (SPIC) in the merger with

China Power Investment (CPI), NicobarGroup (2017). All three NPP suppliers rely on a single SOE constructor, China Nuclear Engineering & Construction (CNEC), the builder of the Hualong One unit in Pakistan.

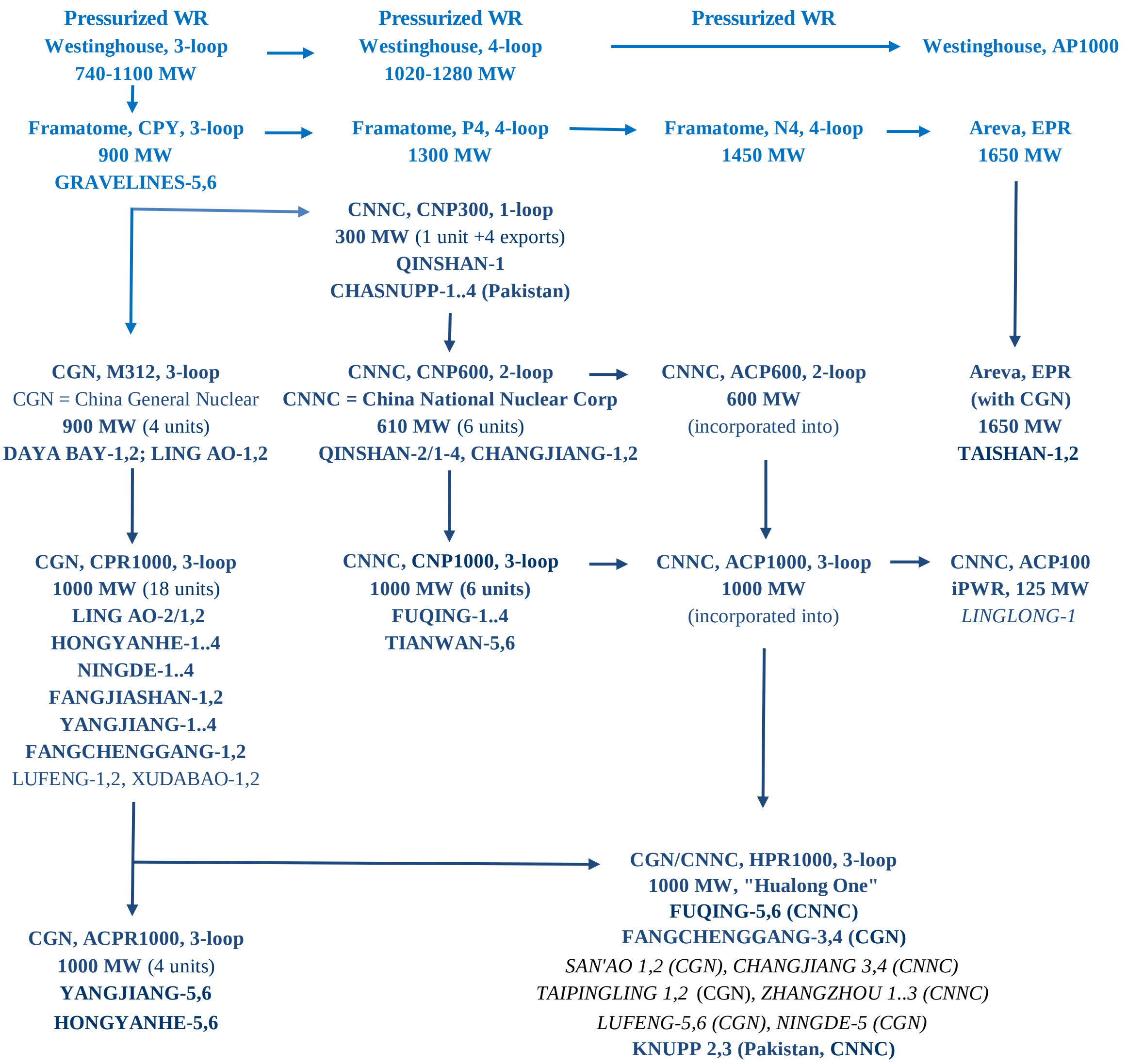

Figure 1. Evolution from the Westinghouse PWR to the Hualong PWR.

Notes: Completed units are in bold and units under construction are in italic.
Sources: update of Rothwell (2003, Table 1) with IAEA (2024b).

CGN built a majority of the NPPs in China (NEI, 2014). The company provides design and engineering through its subsidiaries CNPDC (China Nuclear Power Design Company) and CNPEC (China Nuclear Power Engineering Company), and operation & maintenance (O&M) services, as well as component manufacturing infrastructure. Under a different corporate name, the CGN began China's acquisition of a Framatome CP1 900 MW PWR, based on Westinghouse technology when American firms were restricted from selling nuclear technology to China because of non-proliferation concerns (Burt, 1978). Two units were built at Daya Bay between 1987 and 1994 after ROK's construction of a French CP1 between 1983 and 1989.

The CPR1000 is an upgraded version of the (French based on Westinghouse licenses) M310; hence, some of the intellectual property rights are owned by

Framatome and Westinghouse, limiting export negotiations (WNA, 2024b). The CPR1000 was to be the Chinese standard until a review of the Fukushima accident suggested that an advanced version, the ACPR1000, should be deployed. As a result, 18 CPR1000 units were built between 2005 and 2017, and 4 ACPR1000s were built between 2013 and 2022.

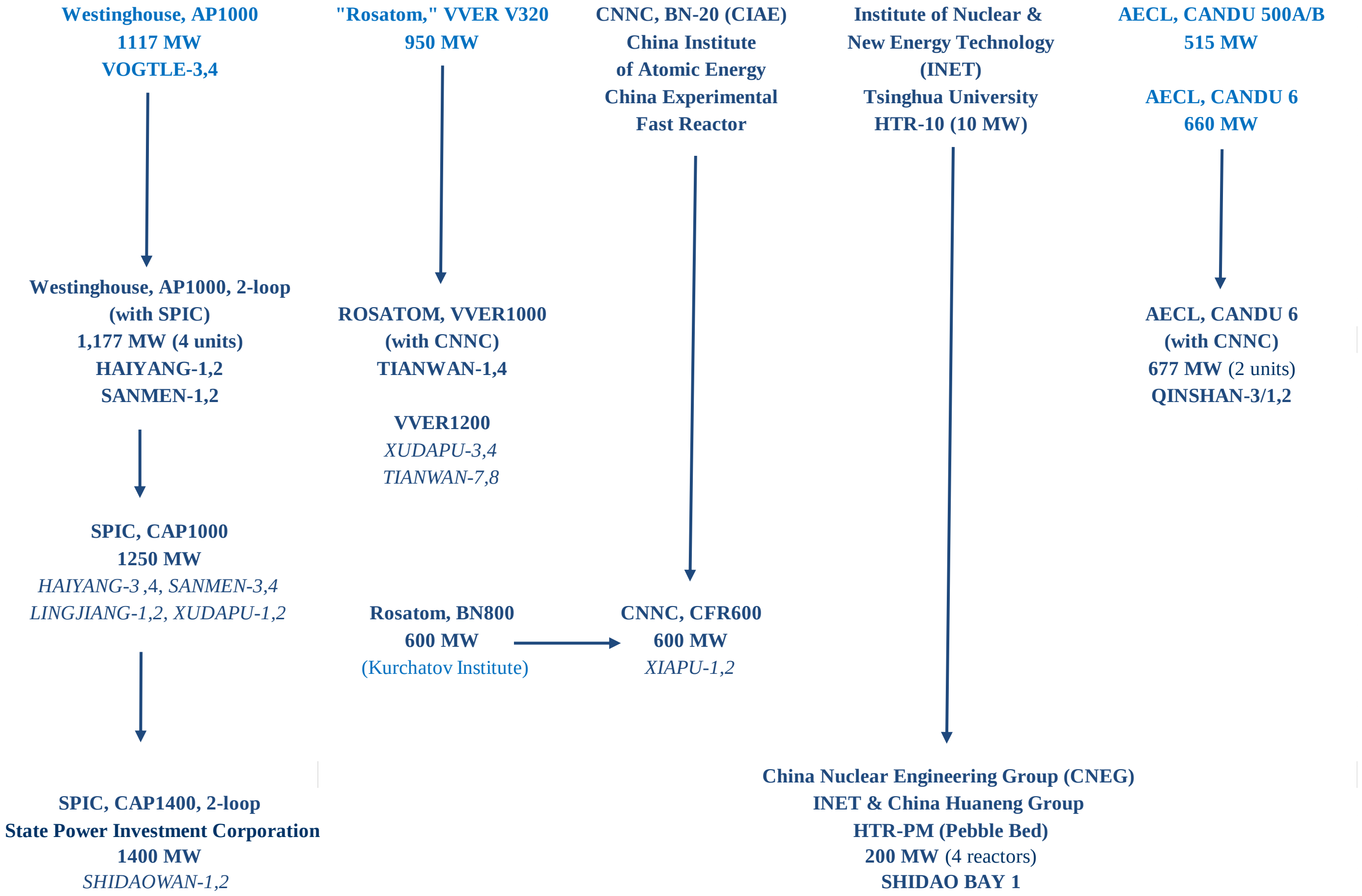

Figure 2. Evolution of other Chinese nuclear technologies.

Notes: Completed units are in bold and units under construction are in italic.
Sources: update of Rothwell (2003, Table 1) with IAEA (2024b).

Parallel to the development of the CPR1000, CNNC worked with Framatome to develop a competing CNP1000. This was developed in three stages: a one-loop CNP300, a two-loop CNP600, and a three-loop CNP1000 (6 units were built in China between 2009 and 2021). Also, parallel to these has been the design of an advanced series, the ACP600, the ACP1000, and the ACP100. The ACP600 and ACP1000 were incorporated into a joint venture with CGN. (The APR100, "Ling Lóng", or "exquisite", is the Chinese demonstration small reactor.) The CNNC version of the ACP1000 is known as the "Hua-lóng One" (or "Chinese Dragon #1"). The CGN version is known as HPR1000 (certified by the European as well as the UK's generic design assessment) with a domestic benchmark construction cost of less than \$2650 per kilowatt (WNA, 2024b), i.e., about \$5B for a two-unit plant. The first Hualong One went into commercial operation on 30 January 2021 and 12 units are under construction. CGN states that it does not rely on any foreign-owned intellectual property, so the "HPR1000" can be exported without agreement of a foreign party (2 units have been built in Pakistan). The Hualong One/HPR1000 is likely to be the "Chinese standard", however a competing design could be the CAP1400.

SPIC is "re-innovating" the Chinese version of the AP1000 as the CAP1400 (the "Guò-hé One", a Chinese idiom implying "the next step"). Westinghouse agreed to transfer technology to SPIC over the first 4 AP1000 units so that SPIC could build the following units on its own. Agreements with Westinghouse stipulated that SPIC would own the intellectual property rights for any derivatives over 1350 MW (WNA, 2024b). About 80%-90% of the components for the CAP1400 demonstration project are expected to be made in China. In November 2018 successors of these companies, SPIC and Westinghouse (under new ownership), signed a cooperation agreement to jointly promote international sales of the AP1000. Following the "TDARI" strategy, the SPIC (SNPTC) worked with Westinghouse to build 2 AP1000s (Haiyang-1&2) and CNNC built 2 units at Sanmen (Units 1&2). The site for the first two-unit CAP1400 is at Shidaowan near the HTR-PM at Shidao Bay (WNA, 2024b).

Also, there were 4 Russian VVER1000s built in China between 1999 and 2018. The Russians could continue to build VVERs in China, but it does not appear as if they are the basis of another standardized Chinese design. On the other hand, the Chinese are relying on Russian technology for their fast reactors (CFR600).

If the EU is going to invest in new PWR capacity, the cost of this capacity should be competitive with other electricity generating alternatives. Rothwell (2022) discusses the projected costs of nuclear capacity. Construction lead times are comparable across countries. Achieving overnight costs of $5000/kWe, as assumed by Commissioner Breton, lead times for EPRs must be lower than those at Olkiluoto 3 (with a lead time of 16.4 years) and Flamanville 3 (with a lead time of 16.8 years). Because there is a high correlation between total capital construction costs (TCIC) and construction lead time (Rothwell, 1986), getting lead times under control could imply costs could be under control. Using TCIC per kilowatt of capacity from the data appendix to Koomey and Hultman (2007), the correlation of lead time with TCIC in 2004 dollars was 86% for Westinghouse 3-loop nuclear power units built in the US.

There are at least three causal relationships between TCIC and lead time: (1) the longer the lead time, the greater the total cost of construction and administrative labor (NEA & IAEA, 2018), because it is difficult to layoff and rehire skilled labor during construction; (2) the longer the lead time, the greater the real escalation in input costs and the higher the probability that there will be a change in regulations requiring reworking plant systems; and (3) the longer the lead time, the higher the total cost of financing (known as "Interest During Construction"). While larger NPPs enjoy economies of scale, larger units take longer to build, hence it is not obvious whether there are scale economies in levelized costs per MWh (Rothwell 2022). The next section compares French and Chinese construction lead times for standardized units.

4. Comparing the French and Chinese nuclear plant construction experience

Can the long construction lead times of new nuclear in the EU be reduced, reducing costs? The purpose of standardization is to simplify construction and design changes during construction, reducing overnight costs and the time to build a nuclear unit. Construction lead time is defined by IAEA (2024b, p. 3) as the time between the "First Concrete Date" (FCD) and either (1) reactor criticality, (2) NPP grid connection, or (3) NPP commercial operation. Here, lead time is measured as the time between FCD and criticality, because the pre-construction and the post-criticality periods can vary by regulatory regime. Lead times are available for all nuclear units in IAEA (2024a).

Units that started just before the accident at Three Mile Island (TMI, 28 March 1979) were likely finished after the accident, thus experiencing an increase in their lead times while the US NRC updated their regulations. After each accident, TMI, Chernobyl (26 April 1986), and Fukushima (11 March 2011), there was a drop in the number of units under construction. There was a general lull in new nuclear in the 1990s (no construction started in 1995), followed by a discussion of a "nuclear renaissance" around 1996, e.g., Blix (1996) stated, "We clearly need to have coherent energy strategies to get from here to there. Many countries are going to have to face up to this hard fact of life in the coming years, and that may well bring about a nuclear renaissance". However, much of this rebirth took place with Chinese, Korean, and Russian technologies.

Many studies have attempted to compare construction costs and lead times, for example, Lovering et al. (2016, p. 372) state in their literature review, "Berthélemy and Escobar-Rangel (2015) performed a regression analysis to isolate hypothetical cost drivers, including learning effects, using a combined dataset of French and US reactors. They find that standardization of reactor designs is key for decreasing lead times and costs". (However, Lovering, Yip, and Nordhaus do not discuss the problem of how they assigned construction expenditures to particular years to address the problem of summing mixed-year currency or how financing costs were calculated).

Among the units currently operating, there are several sets of "standardized" units. Consider the 34 CPY units built in France coming online between 1978 and 1988 and the 20 P4/P'4 units coming online between 1985 and 1994 plus the 4 follow-on N4 units coming online between 2000 and 2002. Compare with the 18 CPR1000 units built in China coming online between 2010 and 2017, and the 4 advanced CPR1000 with 4 units coming online between 2019 and 2022. This series was continued as the HPR1000 with 4 units coming online in China and Pakistan in 2021 and 2022.

The French series of CP0, CP1, and CP2 had the same average lead time as the Chinese series CPR1000, ACPR1000, and HPR1000, i.e., 5.4 years. On the other hand, the French series P4/P'4 and N4 had average lead times of 7.0 years and 10.4 years, respectively, whereas the 2 EPRs built in China took 9 years and those built in the EU have taken more than 16 years to complete. The common wisdom explaining these differences is that there are economies in series construction, such that the original French series and the current Chinese series are being built as Nth-of-a-Kind (NOAK) units, whereas the EPRs in China and the EU have been First-of-a-Kind (FOAK) units; see GIF (2007, p. 46) on the definition of FOAK units. (While the P4/P'4 series took longer to build, they were larger than the CPY series; when adjusted for size, 3817 MWth/2785 MWth = 1.37 × 5.4 years = 7.4 years, the MWth at the P4/P'4 units were not significantly longer to construct than those at the CPY units). However, on average the N4 units took longer and were more costly, like the later American units, leading

Berthélemy and Escobar-Rangel (2015, p. 118) to conclude “contrary to other energy technologies, innovation leads to construction costs increases”.

Figure 3 also plots the construction lead times of the EPRs built in China and France and the AP1000s built in China and the US. The EPRs built in Europe (Olkiluoto-3 in Finland, started in 2005, with criticality on 21 December 2021 and Flamanville-3 in France, started in 2007 and achieving criticality on 3 September 2024 (SFEN, 2024)), whereas the 2 units (Taishan 1&2) in China, started in 2009 and 2010, took an average of 8.8 years to complete. Also, the AP1000s built in China (Sanmen 1&2 and Haiyang 1&2) also took an average of 8.8 years and those built in the US (Vogtle 3&4 (NEA 2015, pp. 108–121)) took 10.1 years to complete. (Another set of AP1000s, Summer 1&2, with construction started in 2013, were cancelled after 4 years (NEA, 2015, pp. 218–227). Therefore, the French must show that they can build the larger EPR NPPs as fast as the Chinese built their EPRs.

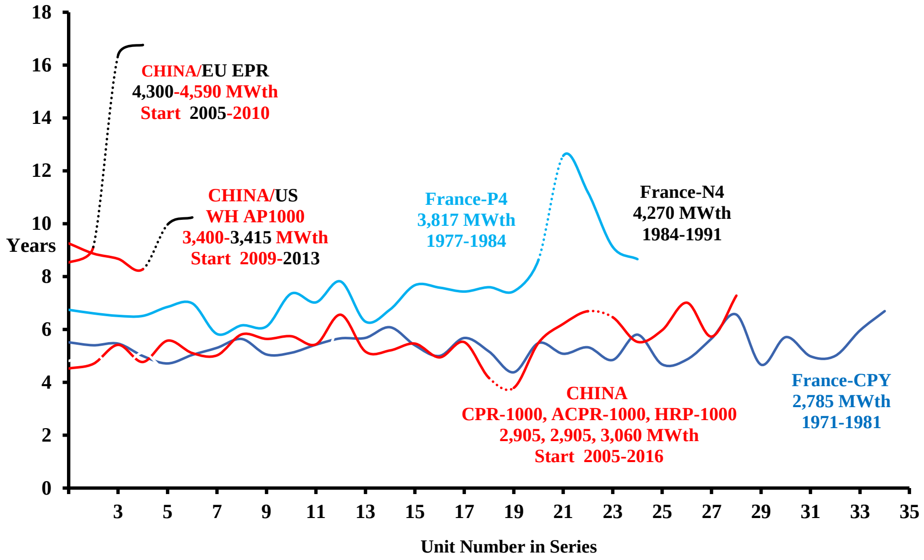

Figure 3. Construction lead times for standardized PWRs.

Source: IAEA, 2024a.

One of the reasons why the Summer AP1000 was cancelled was the complexity of its global supply chain, portrayed in NEA (2015, Figure 56, “Global supply chain for VC Summer components”). The figure lists seven Korean and two Japanese suppliers of primary components, such as the reactor pressure vessel and steam generators; five Italian and two Swiss suppliers of piping and tanks; 25 US suppliers of pumps and valves; and a Brazilian supplier of cooling tower fans. One of the problems of manufacturing NPPs, including the NuScale SMR, according to Stein and Nordhaus (2023) is, “The materials used in a nuclear reactor need to be tracked from the mine head to the forge or manufacturer, manufacturers of components need to be certified to stamp components for use in nuclear reactors by the American Society of Mechanical Engineers (ASME), and the manufacturing needs to meet documented quality assurance standards monitored by the NRC”. Over time the Chinese have developed in-country suppliers such that they can now claim that the HPR1000 is “100% Chinese”. Most of these are well-coordinated SOEs that can adjust to changes in input prices and bottlenecks more quickly than privately-owned firms in competitive markets.

While Chinese authorities claim that the HPR1000s Nth-of-a-Kind overnight costs should be $2650/kWe (WNA, 2024b), the First-of-a-Kind HPR1000s in Pakistan were closer to $4500/kWe (Power Technology, 2020). Because “more than 80% of the estimated project cost is being financed through a loan from China’s state-owned Export-Import (Exim) Bank”, it is likely that these project costs included financing in Pakistan. It is difficult to know the total capital construction costs of the EPR. In 2020 Finnish authorities estimated the cost of Olkiluoto 3 at €11B or about €7000/kWe (but this does not necessarily account for the cost of capital to Areva, who was forced to pay €5.5B due to their fixed price contract with the Finnish owner). In 2022 EDF announced the costs of Flamanville would be over €12.8 billion or €8000/kWe. (It is unlikely that these estimates include financing costs). Returning to the discussion above, the total capital construction cost to replace 70 GW with the only European nuclear technology currently available could be greater than €500B. However, if the 70 GW are replaced with Chinese technology, it is possible that the estimate of €450B could be realized, leaving funds to build SMRs and advanced nuclear technologies. It is unlikely that the future SMRs or advanced non-light water reactors will be cost competitive with the HPR1000, although the SMRs’ smaller sizes might make them easier to finance (Rothwell, 2016, p. 171).

5. Results and conclusions

At this time, the EU has designated nuclear energy as a “sustainable” technology in the EU taxonomy (although this is contested by Austria and Luxembourg). However, the current law requires progress on a spent (used) nuclear fuel disposal strategy by 2050 and the use of “Accident Tolerant Fuels” (AFTs, Yadav et al., 2023) in new NPPs (although ATFs have not yet been deployed). These requirements could necessitate investments not currently considered in Commissioner Breton’s calculations. It is likely that the required total cumulative investment in European nuclear capacity will be greater than €550 billion by 2050 to achieve carbon neutrality.

To replace and expand the nuclear power infrastructure and the number of NPPs in the EU by 2050, difficult decisions must be made:

(1) How many and which small and advanced technologies should be developed?

(2) How much will the countries and utilities in the EU spend on decommissioning retired and retiring nuclear plants?

(3) How much will countries and utilities spend on managing, reprocessing, and disposing of used nuclear fuel and reprocessing residuals?

(4) Will the EU electric utilities build non-EU based, e.g., Chinese HPR1000s, nuclear technologies given renewed interest in climate change and energy security?

Responses to these policy questions are unlikely to coincide with those that Americans might give. For example, one American policy analyst (Ezell, 2024, p. 25) suggests, “China has become America’s leading geostrategic competitor, and America needs to completely cease any sharing of its nuclear technologies with the country. Lastly, the United States needs to be working more closely with its own allies, including France, Germany, Japan, South Korea, and Sweden (among others), to collaborate on R&D for advanced nuclear technologies and to help promote nuclear exports from techno-democracies to third-party markets".

While this might be the predominant view in the American policy community in 2024, these nuclear technologies are owned by private companies. Westinghouse has licensing agreements with SOEs in China, France, and ROK (among others). The American government restricted access to American nuclear technology in the late 20th century. In response, French SOEs licensed these technologies to Chinese SOEs. The issue is whether the EU will finance key nuclear infrastructure development or build Asian (Chinese or Korean) NPPs. The "arithmetic reality" is that presently the EU cannot compete with the Chinese nuclear power industry and its supply chain infrastructure.

Acknowledgments: An earlier version of this paper, Financing Nuclear Power in Europe to 2050, was presented at GLOBAL 2022, Reims, France (6–8 July 2022). That paper was prepared in association with the production of a podcast, Sharing the Atom: NPT Talk. I thank M. Berthélemy, P. Chew, M-K Lee, J. Lovering, T. Wood, and two anonymous referees for their earlier work, comments, and references. However, the paper reflects the author's errors, biases, and conclusions.

Conflict of interest: The author declares no conflict of interest.

References

ANS (American Nuclear Society). (2014). Eisenhower's Atomic Power for Peace III: CAP and Power Demonstration Reactors. Available online: https://www.ans.org/news/article-1537/eisenhowers-atomic-power-for-peace-iii-cap-and-power-demonstration-reactors/ (accessed on 4 February 2021).

Berthélemy, M., & Escobar-Rangel, L. (2015). Nuclear reactors' construction costs: the role of lead-time, standardization and technological progress. Energy Policy, 82, 118–130. http://dx.doi.org/10.1016/j.enpol.2015.03.015

Blix, H. (1996). The peaceful and safe uses of nuclear energy: An address by the IAEA Director General. International Atomic Energy Agency.

Bloomberg. (2021). China's Climate Goals Hinge on a $440 Billion Nuclear Buildout. Available online: https://www.bloomberg.com/news/features/2021-11-02/china-climate-goals-hinge-on-440-billion-nuclear-power-plan-to-rival-u-s (accessed on 20 August 2024).

Bloomberg. (2023). China's Fast and Cheap Nuclear Gives Its Climate Ambitions a Boost. Available online: https://www.bloomberg.com/news/newsletters/2023–08–28/china-s-fast-and-cheap-nuclear-gives-its-climate-ambitions-a-boost (accessed on 28 August 2024).

Burt, R. (1978). White House Endorses French Sale of a Nuclear Power Plant to China. The New York Times, 25 November 1978.

David, P., & Rothwell, G. S. (1996). Measuring Standardization: An Application to the American and French Nuclear Power Industries. European Journal of Political Economy, 12, 291–308. https://doi.org/10.1016/0176-2680(95)00018-6

DRC (Development Research Center of the State Council of the People's Republic of China). (2010). Mechanism and Experiences for Technology Digestion, Absorption and Re-innovation in China's Railway Equipment Manufacturing Industry. Available online: https://www.chinadaily.com.cn/m/drc/2010-07/28/content_22163873.htm (accessed on 25 May 2021).

EC (European Commission). (2024). Commission approves €300 million French State aid measure to support Nuward in researching and developing small modular nuclear reactors. Available online: https://ec.europa.eu/commission/presscorner/detail/en/ip_24_2228 (accessed on 11 September 2024).

EDF (Électricité de France). (2020). EDF adjusts the cost of the "Grand Carénage" program (French). EDF communiqué de presse.

Eurostat. (2022). Electricity production, consumption and market overview. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_production,_consumption_and_market_overview (accessed on 11 September 2022).

Ezell, S. (2024). How Innovative is China in Nuclear Power. Information Technology & Innovation Foundation.

Gangyang, Z., Xianke, P., Xiaozhen, L., et al. (2021). Research on the standardization strategy of China's nuclear industry. Energy Policy, 155, 112314. https://doi.org/10.1016/j.enpol.2021.112314

GIF (Generation IV International Forum). (2007). Cost Estimating Guidelines for Generation IV Nuclear Energy Systems. Economic Modeling Working Group

Gröndahl, M.-P. (2022). 500 billion euros will have to be invested in new-generation nuclear power plants (French). Le Journal de Dimanche.

Hernandez, A. (2024). France's EDF to redraft small modular reactor design amid cost, technology concerns. Reuters.

IAEA (International Atomic Energy Agency). (2024a). Power Reactor Information System (PRIS). Available online: https://pris.iaea.org/pris/ (accessed on 20 August 2024).

IAEA (International Atomic Energy Agency). (2024b). Nuclear Power Reactors in the World. Available online: https://www-pub.iaea.org/MTCD/Publications/PDF/p15748-RDS-2-44_web.pdf (accessed on 20 August 2024).

Koomey, J., & Hultman, N. (2007). A reactor-level analysis of busbar costs for US nuclear plants, 1970–2005. Energy Policy, 35, 5630–5642. https://doi.org/10.1016/j.enpol.2007.06.005

Lovering, J.R., Yip, A., & Nordhaus, T. (2016). Historical construction costs of global nuclear power reactors. Energy Policy, 91, 371–382. https://doi.org/10.1016/j.enpol.2016.01.011

NEA & IAEA (Nuclear Energy Agency & International Atomic Energy Agency). (2018). Measuring Employment Generated by the Nuclear Power Sector. Available online: https://www.oecd-nea.org/jcms/pl_14912/measuring-employment-generated-by-the-nuclear-power-sector?details=true (accessed on 24 March 2019).

NEA (Nuclear Energy Agency). (2015). Nuclear New Build: Insights into Financing and Project Management. Available online: https://www.oecd-nea.org/jcms/pl_14904/nuclear-new-build-insights-into-financing-and-project-management (accessed on 22 October 2015).

NEA (Nuclear Energy Agency). (2016). The Costs of Nuclear Power Plant Decommissioning. Available online: https://www.oecd-nea.org/jcms/pl_14910/costs-of-decommissioning-nuclear-power-plants?details=true (accessed on 5 February 2016).

NEA (Nuclear Energy Agency). (2024). The NEA Small Modular Reactor Dashboard: Second Edition. Nuclear Technology Development and Economics Division, Available online: https://www.oecd-nea.org/jcms/pl_90816/the-nea-small-modular-reactor-dashboard-second-edition (accessed on 11 September 2024).

NEI (Nuclear Engineering International). (2014). China Reactor Design Evolution. NEI Magazine.

Nicobar Group. (2017). China's Nuclear Industry 2017–2018: A Tightly Coiled Spring. US Department of Commerce-International Trade Administration.

OECD (Nuclear Energy Agency & International Energy Agency). (2020). Projected Costs of Generating Electricity. Available online: https://www.oecd-nea.org/jcms/pl_51110/projected-costs-of-generating-electricity-2020-edition (accessed on 19 December 2020).

Power Technology. (2020). Karachi Nuclear Power Plant (KANUPP) Expansion. Power Technology. Available online: https://www.power-technology.com/projects/karachi-nuclear-power-plant-expansion/ (accessed on 25 May 2021).

Rothwell, G. S. (1986). Steam−Electric Scale Economies and Construction Lead Times. California Institute of Technology, Social Science Working. p.627.

Rothwell, G. S. (2003). History Matters: Essays on Economic Growth, Technology, and Demographic Change. Standardization, Diversity, and Learning in China's Nuclear Power Program. In: Sunstrom, W. A., Guinnane, T. W., Whatley, W. C. (editors). Stanford University Press. pp. 221–242.

Rothwell, G. S. (2016). Economics of Nuclear Power. Routledge Publishers.

Rothwell, G. S. (2021). Spent nuclear fuel storage: What are the relationships between size and cost of the alternatives? Energy Policy, 150, 112126. https://doi.org/10.1016/j.enpol.2020.112126

Rothwell, G. S. (2022). Projected Electricity Costs in International Nuclear Power Markets. Energy Policy, 164, 112905. https://doi.org/10.1016/j.enpol.2022.112905

RTE (Réseau de Transport d'Électricité). (2021). Economic analysis: Costing of scenarios to compare different transition options

(French). Energy Futures.

SFEN (Société Française d'Energie Nucléaire). 2024. Insights on Flamanville 3 EPR first criticality. Available online: https://www.sfen.org/replay/replay-insights-on-flamanville-3-epr-first-criticality/ (accessed on 11 September 2024).

Stein, A., & Nordhaus, T. (2023). Advanced Nuclear Energy Is in Trouble: NuScale Cancellation Should Be Wake-Up Call for Advocates. The Breakthrough Institute.

US AEC (Atomic Energy Commission) and US DOJ (Department of Justice). (1968). Competition in the Nuclear Power Supply Industry. US Government Printing Office.

Wealer, B., Bauer, S., Landry, N., et al. (2018). Nuclear Power Reactors Worldwide–Technology Developments, Diffusion Patterns, and Country-by-Country Analysis of Implementation (1951–2017). Deutsches Institut für Wirtschaftsforschung.

WNA (World Nuclear Association). (2024a). Nuclear Power in France. Available online: https://world-nuclear.org/information-library/country-profiles/countries-a-f/france (accessed on 28 August 2024).

WNA (World Nuclear Association). (2024b). Nuclear Power in China. Available online: https://www.world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx (accessed on 28 August 2024).

Xin, Z. (2024). Nuclear power's share in energy mix on the rise. China Daily Global.

Xu, Q. (2020). Situation and Suggestion of Nuclear Industry Standardization in China. In: Innovative Computing. Lecture Notes in Electrical Engineering. Springer. pp. 1699–1705.

Yadav, K. K., Pal, U., & Karthikeyan, R. (2023). Concept of accident tolerant fuel in nuclear reactors. Nuclear and Particle Physics Proceedings, 341, 62–66. https://doi.org/10.1016/j.nuclphysbps.2023.09.026