Pulaski Policy Papers
Pulaski's International Commentary
ISSN 2080-8852
Warsaw, 23.06.2021

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Costs and timeframes of construction of nuclear power plants carried out by potential nuclear technology suppliers for Poland

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In recent months, nuclear energy has been an increasingly debated topic on the Polish political scene. This growing popularity of the Polish Nuclear Program concept is a direct consequence of the need to implement this type of energy into the Polish energy mix in order to fully decarbonise the Polish energy sector and thus achieve the climate objectives adopted as part of the European Green Deal. Increased popularity of nuclear energy is manifested primarily by more frequent statements of politicians and experts, as well as promotional activities of potential nuclear technology suppliers to Poland. Clearly, selection of the right supplier is crucial for timely and cost-effective implementation of nuclear power in Poland. There are three main candidates in the race to build Poland's first nuclear power plant: the US company Westinghouse for the AP1000, Korea's KEPCO for the APR1400, and France's EDF for the EPR.

The most important question related to the implementation of nuclear power in Poland is the total cost and construction time for the first Polish nuclear facility. Predictability in both of these areas is dependent on a number of variables and the costs and timeframes presented in this publication are based on data publicly released by investors and the media. However, certain trends can be identified from past experience of technology providers, which is also included in the publication below.

This analysis is intended to compare the experience of potential vendors of nuclear technology, primarily with respect to cost and construction schedule. The following analysis, based on these two evaluation criteria, may be used to indicate the optimum technology for the Polish nuclear power program. However, each nuclear project is complex and depends on a number of individual contracting needs. In the absence of publicly available information on the exact requirements of the

Polish side, and given the lack of details in the preliminary bids submitted to Warsaw, the following analysis is based on publicly available data and should not be treated as a formal evaluation of the bids of individual vendors.

Construction costs

The detailed cost estimates for building a nuclear power plant are covered by investor secrecy, so the component costs of the various stages of construction are not known. Therefore, the analysis includes open-source information: originally planned construction costs (those announced to the public before construction commenced), currently projected costs (those revised over time to reflect the costs originally planned for the plant during construction), and actual costs (those actually incurred to build the plant up to commercial operation). In the case of abandoned construction, costs incurred up to the point of abandonment are shown. It is worth noting that construction costs often refer to the overall construction of a power plant and not just to the construction of individual units. For ease of interpretation, the costs have been converted into millions of US dollars per MWel of net installed capacity. The construction cost data for the AP1000, APR1400 and EPR units are shown in Table 1.

No.	Country	Reactor type	Power plant	Initial costs planned [B USD]	Actual costs [B USD]	Power [$MW_{el,net}$]	Initial costs planned [M USD/ $MW_{el,net}$]	Actual costs [M USD /$MW_{el,net}$]	Actual costs/Initial costs planned
1	China	AP1000	Sanmen-1	5.84	7.30	2314	2.52	3.15	1.25
2	China	AP1000	Sanmen-2						
3	China	AP1000	Haiyang-1	No data	Increase by1.50	2340	No data	No data	No data
4	China	AP1000	Haiyang-2						
5	US	AP1000	Vogtle-3	14.30	26.00*	2234	6.40	11.64*	1.82*
6	US	AP1000	Vogtle-4						
7	US	AP1000	Summer-2	9.80	25.00**	2234	4.39	ND	2.55*
8	US	AP1000	Summer-3						
9	Korea	APR1400	Shin-Kori-3	4.89	6.46	2832	1.73	2.28	1.32
10	Korea	APR1400	Shin-Kori-4						
11	Korea	APR1400	Shin-Kori-5	7.58	8.80*	2680	2.83	3.28*	1.16*
12	Korea	APR1400	Shin-Kori-6						
13	Korea	APR1400	Shin-Hanul-1	6.26	7.60*	2680	2.34	2.84*	1.21*
14	Korea	APR1400	Shin-Hanul-2						
15	UAE	APR1400	Barakah-1	24.40	24.40*	5380	4.54	4.54*	1.00*

16	UAE	APR1400	Barakah-2						
17	UAE	APR1400	Barakah-3						
18	UAE	APR1400	Barakah-4						
19	Finland	EPR	Olkiluoto-3	3.55	9.40*	1600	2.22	5.88*	2.65*
20	France	EPR	Flamanvile-3	3.60	13.60*	1650	2.18	8.24*	3.78*
21	China	EPR	Taishan-1	7.50	9.10	3320	2.26	2.74	1.21
22	China	EPR	Taishan-2						
23	UK	EPR	Hinkley Point C-1	30.60	31.30*	3260	9.39	9.60*	1.02*
24	UK	EPR	Hinkley Point C-2						

Table 1. Construction costs for nuclear reactors of a given type (*Costs currently projected; **Costs incurred until construction was abandoned).

Construction schedule

The stages of construction of a nuclear power plant are determined by a series of milestones. The actual start date of construction is usually considered to be the pouring of the first concrete for the reactor building foundation, and the completion date is considered to be the start of commercial electricity production after connection to the power system. Both of these dates were included in the analysis as the start and end of nuclear unit construction. Intermediate milestones not included in the analysis involve: assembly of key plant components, physical completion of construction, cold and hot commissioning tests, first criticality, and first power connection to the grid. In addition, the analysis takes into account the planned original date of commercial operation of the nuclear unit, from which construction schedule delays were calculated. If only the planned commissioning year of the nuclear unit is provided, it is assumed that the actual commissioning will occur in the middle of that year. Construction schedule data for the AP1000, APR1400, and EPR units are shown in Table 2.

No	Country	Power plant	Reactor type	Construction commencement	Planned commercial operation date	Actual commercial operation date	Actual construction time [years].	Planned construction time [years].	Delay [years]
1	China	Sanmen-1	AP1000	19.04.2009	01.08.2013	21.09.2018	9.4	4.3	5.1
2	China	Sanmen-2	AP1000	15.12.2009	01.06.2014	05.11.2018	8.9	4.5	4.4
3	China	Haiyang-1	AP1000	24.09.2009	01.05.2014	22.10.2018	9.1	4.6	4.5
4	China	Haiyang-2	AP1000	20.06.2010	01.03.2015	09.01.2019	8.6	4.7	3.9
5	US	Vogtle-3	AP1000	12.03.2013	01.07.2016	01.07.2022*	9.3**	3.3	6.0
6	US	Vogtle-4	AP1000	19.11.2013	01.07.2017	01.06.2023*	9.5**	3.6	5.9
7	US	Summer-2	AP1000	11.03.2013	01.07.2017	31.07.2017***	4.4****	4.3	ND
8	US	Summer-3	AP1000	06.11.2013	01.07.2018	31.07.2017***	3.7****	4.7	ND
9	Korea	Shin-Kori-3	APR1400	16.11.2008	01.12.2013	20.12.2016	8.1	5.0	3.1
10	Korea	Shin-Kori-4	APR1400	19.08.2009	01.09.2014	29.08.2019	10.0	5.0	5.0
11	Korea	Shin-Kori-5	APR1400	01.04.2017	01.03.2022	01.03.2023*	5.9**	4.9	1.0
12	Korea	Shin-Kori-6	APR1400	20.09.2018	01.03.2023	01.06.2024*	5.7**	4.4	1.3
13	Korea	Shin-Hanul-1	APR1400	10.07.2012	01.04.2017	01.12.2022*	10.4**	4.7	5.7
14	Korea	Shin-Hanul-2	APR1400	19.06.2013	01.02.2018	01.12.2023*	10.5**	4.6	5.8
15	UAE	Barakah-1	APR1400	19.07.2012	01.07.2018	06.02.2021	8.6	6.0	2.6
16	UAE	Barakah-2	APR1400	16.04.2013	01.07.2019	01.12.2021*	8.6**	6.2	2.4
17	UAE	Barakah-3	APR1400	24.09.2014	01.07.2019	01.07.2022*	7.8**	4.8	3.0
18	UAE	Barakah-4	APR1400	30.07.2015	01.07.2020	01.07.2022*	6.9**	4.9	2.0
19	Finland	Olkiluoto-3	EPR	12.08.2005	01.07.2009	01.02.2022*	16.5**	3.9	12.6
20	France	Flamanvile-3	EPR	03.12.2007	01.07.2013	01.07.2023*	15.6**	5.6	10
21	China	Taishan-1	EPR	18.11.2009	01.07.2013	13.12.2018	9.1	3.6	5.5
22	China	Taishan-2	EPR	15.04.2010	01.07.2015	07.09.2019	9.4	5.2	4.2
23	UK	Hinkley Point C-1	EPR	11.12.2018	01.12.2025	01.06.2026*	7.5**	7.0	0.5
24	UK	Hinkley Point C-2	EPR	12.12.2019	01.07.2026	01.06.2027*	7.5**	6.6	0.9

Table 2. Timeline for construction of reactors of a given type (*Commercial operation date currently expected; **Current construction time expected; ***Date of construction interruption; ****Construction time to interruption).

US

Westinghouse, an American company offering the AP1000 reactor in Poland with a net capacity of between 1117-1170 $MW_{el,net}$, has successfully completed construction of four nuclear units at China's Sanmen (two units) and Haiyang (two units) power plants. In the United States, it is building two units of the Vogtle plant, and construction of two more units at the Summer plant has been abandoned for the time being.

The average delay of Westinghouse projects in China was about 4.5 years, with an increase in costs of about 25%, compared to the costs initially planned. The construction cost of the Haiyang plant is not known, but it is believed to be comparable to that of the Sanmen plant because of its twin nature. The construction schedule for the AP1000 units in China shows that the delay in placing a unit into commercial service decreases in proportion to the number of units that are connected in sequence. This suggests that lessons learned from previous construction are being applied to subsequent units.

Construction of the two nuclear units at the Vogtle site in the United States is currently behind schedule by about 6 years and has cost about 82 percent more. Interestingly, the original construction time for the two units was expected to be 3.5 years, which under previous and current market conditions seems highly optimistic. This short construction time assumed may have been due to delays in obtaining the final construction permit, which was delayed as new safety standards were defined after the Fukushima accident in Japan. On the other hand, the planned construction time for the other AP1000 units was a little more (about 4.5 years), which also seems an unrealistic, unattainable deadline.

The construction of two nuclear units at the Summer plant in South Carolina is also worth mentioning here. The development was abandoned by the investor after 4.5 years and a projected 2.5-fold increase in total investment costs. As of 2017, the plant was about 40 percent complete, with construction costs of about $9 billion, close to the total planned investment cost. The Summer project fiasco led Westinghouse into numerous financial problems, ultimately resulting in a forced restructuring of the company.

South Korea

Korea's KEPCO is the technology provider for the APR1400 reactor with a net capacity of 1340-1418 $MW_{el,net}$. Currently, three APR1400 units have been commissioned - two at the Shin-Kori power plant in Korea and one at the Barakah power plant in the United Arab Emirates. In South Korea, a further four units are under construction - two at the Shin-Kori power plant and two at the Shin-Hanul's. In the United Arab Emirates the construction of the remaining three units of the Barakah power plant continues.

The commissioning of the first two commercial APR1400 reactors at Shin-Kori (units 3 and 4) was delayed by 3 and 5 years respectively and the cost increase was eventually about 30 percent. Further expansion of the plant with units 5 and 6 shows about a one-year delay and a 16 percent cost increase. As for the construction of two new units at the Shin-Hanul power plant, it is delayed by about 6 years and has a cost increase of 20 percent. The reason for the construction delay is related to the Korean government's announcement in 2017 to reduce nuclear capacity and thus physically stop the construction of the plant, the completion of which is still uncertain at the moment. It should be noted, however, that the construction of the first commercial reactor APR1400 (Shin-Kori 3) had the least delay, but the largest increase in construction costs. It is also worth noting that the construction of Shin-Kori units 5 and 6 has so far had the smallest increase in cost and the fewest delays, but these units are still under construction and eventually the numbers may change.

Korean KEPCO's flagship and only export project is the construction of four nuclear units at the Barakah power plant in the United Arab Emirates. The first unit of this power plant was put into commercial operation in April 2021. Its construction was delayed by about 2.5 years, but in the end no increase in the cost of construction of the plant was reported. Most likely, this is due to the correct estimation of the power plant construction costs still at the preliminary design stage. It is worth noting that planned construction costs in the United Arab Emirates are about two times greater than planned construction costs for similar plants in Korea, which explains the lack of change in costs shown. The next three units of the Barakah power plant are to be successively put into operation by the end of 2022. If both the cost and schedule of the development remain unchanged, the Barakah project will demonstrate the full maturity of the Korean industry to export nuclear technology.

France

French company EDF is the bidder for EPR reactor technology with a net capacity of 1600-1650 $MW_{el,net}$. Two nuclear units with EPR reactors have already been commissioned in China's Taishan power plant. Other units are under construction in Finland - one unit at the Olkiluoto power plant, in France - one unit at the Flamanvile power plant and in the UK - two units at the Hinkley Point C power plant.

Construction of the first EPR unit began in 2006 at the Olkiluoto power plant in Finland. After almost 15 years of construction, the unit, originally planned for only four years, is still not complete and its costs have already risen to about 250 percent. If the unit's projected start-up date is met (2022), the delay in its commissioning will still be nearly 13 years. The construction problems with the plant are mainly due to the lack of experience of the French company, Areva, which was responsible for the construction at the time, with such large infrastructure projects. In addition, the Olkiluoto EPR reactor was the first of its kind and so its construction technology had not yet been fully developed and tested. Another reason for the delay was the insufficient quality of plant components made by various sub-suppliers. It should be noted that the Finnish Nuclear Safety Authority, STUK, which is regarded as one of the most stringent nuclear safety authorities in the world, has played a key role in detecting inaccuracies in both the design and construction of the plant.

Construction of the next EPR, this time at the Flamenvile site in France, began in 2007. With its currently assumed commissioning date (2023), it will be delayed by about 10 years with construction costs almost 4 times the original estimate. The delays and escalation in costs are due to similar problems to those with the Olikiluoto plant in Finland.

Another two EPR reactors are currently under construction in the UK at the Hinkley Point C plant. Construction started in 2018 and is now showing a delay of less than a year and a 2% increase in costs, which is explained by dynamically changing sanitary requirements related to the COVID-19 pandemic. It seems interesting to indicate a planned completion date of about 7 years from the start of construction of the plant, which is about 2 years longer compared to the planned completion dates for the first EPR reactors built with this technology, but also a more realistic date.

In addition, France's EDF has placed two EPR reactors at China's Taishan plant into commercial operation. The increase in cost of the Chinese investment is estimated to be about 20% and the delays were about 5.5 years for unit one and 4.5 years for unit two.

Implications for the Polish nuclear program

According to the politicians' announcements, the cost of the Polish nuclear program is estimated at 80-150 billion zlotys (about 21-40 billion USD). Six nuclear reactors are to be built with a net capacity of between 6-9 $GW_{el,net}$. According to the Polish Nuclear Power Program, optimum net installed capacity is to be 7.7 $GW_{el,net}$ in 2045 and 10 $GW_{el,net}$ in 2050. Construction of the first nuclear power plant unit is to begin in 2026, with commissioning to begin in 2033. Subsequent units are to be commissioned every 2-3 years. The planned construction time for one unit has been estimated for 7 years.

When considering the compatibility of the construction criteria for the six nuclear units, the closest option to achieving the optimum installed capacity of 7.7 GWel,net in 2045 is to build AP1000 or APR1400 reactors. The first option is associated with a power shortfall of about 680 $MW_{el,net}$ and the second with a surplus of about 810 $MW_{el,net}$. Construction of six EPR units would be associated with a surplus of about 2,200 $MW_{el,net}$, although this is the option that is consistent with the planned optimum installed capacity by 2050 of about 10 $GW_{el,net}$, respectively.

The cost analysis takes into account the minimum and maximum planned and actual construction costs per $MW_{el,net}$ estimated for existing nuclear units of the type. Using these costs, the total investment to build six nuclear units of maximum net capacity, as detailed in the reactor specifications, was calculated in US$ billion, as shown in Table 3. Overall analysis therefore shows that, so far, the APR-1400 units have been the most economical to build and the EPR series the most expensive. For the APR1400 reactor from KEPCO, the amount planned by Poland is sufficient to build all the planned nuclear units. For the US AP1000, the planned amount may not be sufficient because actual construction costs are likely to increase substantially. Looking at the minimum planned and minimum actual construction costs, the amount provided by Polish politicians is sufficient to implement all the technologies discussed above. Looking at the maximum planned and maximum actual construction cost, the only vendor within this amount is Korea's KEPCO. It should be noted, however, that the cost ranges shown are for projects in countries with widely differing construction costs, such as China and the United Kingdom. This suggests that bids to build reactors in Poland will fall between the minimum and maximum construction estimates shown.

When reviewing the construction dates of nuclear units already under construction by all vendors, the lowest average delay is for the APR1400 (3.6 years), the AP1000 (4.5 years), and the EPR (4.8 years). Interestingly, the construction time per reactor, irrespective of the technology used, is about 9 years, which is 2 years longer than forecast in the Polish Nuclear Power Program.

Reactor type	Total installed power [$MW_{el,net}$]	Unit	Planned costs		Actual costs	
			Minimum	Maximum	Minimum	Maximum
AP1000	7020	[M USD/$MW_{el,net}$]	2.52	6.40	3.15	11.64*
		[B USD]	17.69	44.93	22.11	81.71
APR1400	8508	[M USD/$MW_{el,net}$]	1.73	4.54	2.28	4.54*
		[B USD]	14.72	38.63	19.40	38.63
EPR	9900	[M USD/$MW_{el,net}$]	2.21	9.39	2.74	9.60*
		[B USD]	21.88	92.96	27.13	95.04

Table 3. Estimated construction costs for six reactors of a given type (*actual costs currently projected for units under construction).

Conclusions and recommendations

1. All nuclear projects, whether under construction or completed, are running several years behind schedule, indicating that the completion dates quoted by vendors were too short.

2. The AP1400 built by Korea's KEPCO in the United Arab Emirates was the least delayed (2.6 years) of the nuclear units so far in operation and the EPR unit built by France's EDF at China's Taishan-1 plant was the most delayed (5.5 years).

3 The costs of all the nuclear projects under consideration, with the exception of the KEPCO project in the United Arab Emirates, have been exceeded. Therefore, potential investors should reflect the potential risk of cost overruns in their construction cost estimates.

4. The largest cost increases for new nuclear units were those for two French-built EPR at Olkiluoto in Finland (almost three-fold increase) and Flamanvile in France (almost four-fold increase), and two US-built AP1000 units at Vogtle in the US (almost two-fold increase).

5. The US and French technology suppliers have so far failed to complete nuclear reactor projects in their home countries because of a series of logistical problems, underestimation of construction costs, and serious supply chain disruptions. Both suppliers have completed nuclear power plants in China, where project logistics are facilitated. Korean vendor KEPCO is the only one to have commissioned two new units at its home plant, Shin-Kori.

6. In terms of construction cost, schedule, and optimal installed capacity, the Korean KEPCO offer appears to be the most advantageous for Poland. It should also be noted that the construction of more nuclear reactors in Korea has been restricted by the Korean government's decision, which further affects the Korean desire to participate in the Polish nuclear program. As they are currently looking for new markets for their technology, the construction of six nuclear units in Poland may be treated as a priority by both KEPCO and the South Korean government.

7. The US Westinghouse, is not far behind the Koreans in terms of schedule, although the actual costs of building the reactors may be much higher than those planned for the Polish nuclear program. The Americans are also looking for new markets for their technology, so the construction of nuclear reactors by an American company in Europe may provide a strong argument for the administration of President Joe Biden to revive nuclear power and the nuclear industry in the USA. Westinghouse's commitment is also evident in the opening of an office in Warsaw and a new service center in Krakow, Poland, which indicates a serious approach to a potential nuclear project in Poland.

8. The French EPR is the most expensive nuclear system potentially under consideration in Poland. Moreover, the signing of a preliminary agreement by EDF with India to build six EPR units, and a possible decision by the French government to build a further six EPR units in France, could have a negative impact on the potential construction in Poland. If both projects go ahead, there is a risk that the Polish investment will not be given the right priority. Whether EDF can logistically accommodate such a large number of nuclear projects at the same time is another open question.

9. It is recommended that construction progress on the next AP1000, APR1400, and EPR reactors be monitored, particularly at Vogtle, Barakah, and Hinkley Point C. Tracing construction advances at these sites will provide a better estimate of the performance of technology providers in countries other than China.

10. It is also recommended that the technology and construction processes for reactors of the same type as those offered in Poland be compared with reactors already under construction in other countries to identify potential sources of cost and schedule increases. Examples of such potential problems could include different safety standards, quality control of the construction process, and the process of certifying such a facility by the appropriate authorities. In addition, the supplier of the technology under consideration should be required to identify the cause of delays and cost increases for other nuclear projects that have been carried out previously. An indication of planned mitigation measures, if any, should also be included in the vendor's final proposals to avoid the cost overruns and time delays discussed in the above analysis..

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