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ASSESSMENT OF COST AND SCHEDULE PERFORMANCE IN CONSTRUCTION OF KEY NUCLEAR REACTORS

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Abstract: The nuclear industry is a unique sector that is especially vulnerable to delays. A multitude of impactful factors such as the complexity of design, tight on-site schedules, and a logistically sophisticated end-to-end supply chain, to name just a few, make the entire project highly prone to complications. In 2017, it was estimated that nearly two-thirds of the 55 nuclear plants under construction at that time were behind schedule.

Furthermore, since 2010, delays of this nature have been believed to have contributed to an almost 20% increase in the final costs of the projects. This work analyzed recent construction performance of Generation III/III+ nuclear reactor projects, specifically examining AP1000, EPR, and APR1400 technologies. Key performance indicators evaluated included planned versus actual construction times, costs, and capacity construction rates, revealing significant deviations across the analyzed projects. Each nuclear project's performance was quantitatively assessed using the schedule performance ratio, cost performance ratio, and an integrated performance coefficient to comprehensively compare efficiencies across different reactor technologies. Analysis further identified key reasons behind these deviations, such as evolving regulatory environments, safety requirements, project management inefficiencies, supply chain immaturity, and limited skilled workforce availability, which contributed to persistent first of a kind (FOAK) challenges and obscured the anticipated nth of a kind (NOAK) improvements. Based on these findings, recommendations are provided for future research, emphasizing the necessity to apply insights gained from large reactor deployment challenges to the emerging Small Modular Reactor (SMR) technologies.

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Keywords: NOAK; FOAK; learning curve; nuclear power plant cost; nuclear power plan construction schedule.

INTRODUCTION

The persistent occurrence of delays and cost overruns in nuclear power plant projects re mains a significant challenge within the nuclear energy sector. Identifying the primary fac torscontributing to these issues, as well as determining whether they can be effectively mitigated or entirely prevented, is critical to the successful deployment of current and future nuclear reactors [1,2]. Despite extensive research, these questions continue to be inadequately addressed, underscoring their relevance and urgency. This article addresses these concerns through detailed case studies of recent reactor projects, specifically the European Pressurized Reactor (EPR), the AP1000, and the Advanced Power Reactor 1400 (APR1400). The analysis presented herein compares time-to-market outcomes, examining notable distinctions between first of a kind (FOAK) and n^{th} of a time (NOAK) reactor deployments with respect to scheduling, budget adherence, and overall project efficiency. Furthermore, the paper explores innovative construction methodologies and project management strategies aimed at optimizing schedules, controlling costs, and effectively managing risks in future nuclear power plant initiatives.

It is widely acknowledged that FOAK nuclear projects inherently require increased attention and intensified effort throughout their duration, rendering them particularly susceptible to numerous risks compared to NOAK deployments. The initial construction phase of FOAK projects represents an essential opportunity to acquire practical insights and experiential knowledge [3]. Deconstructing each project process into more manageable segments allows for critical analyses and informed conclusions, thus facilitating more effective management strategies for future implementations.

Empirical evidence consistently underscores the significance of delivery stream-related factors in determining overall project success. Specifically, supply chains must exhibit adaptability to the dynamic operational environment and unique challenges characteristic of FOAK initiatives. Notably, the frequent necessity for design modifications at this preliminary stage often jeopardizes timely and budget-compliant project completion. Additionally, the accurate selection of certified component suppliers emerges as a critical hurdle, compounded by the intricacies of specialized logistics and site transportation, which frequently involve complex coordination of heavy equipment and the careful navigation of routes adhering to stringent safety and environmental standards [4].

NOAK projects are typically characterized by enhanced viability, manifesting through shortened timelines, reduced costs, and lower risk levels. Subsequent implementations rely on fully validated and standardized designs, supported by refined and streamlined construction methodologies and managerial frameworks. Two pivotal concepts, namely the learning curve and economies-of-scale effects associated with serial production, significantly influence NOAK deployments. The learning curve predominantly benefits on-site operational efficiency, while economies of scale bolster essential aspects of the supply chain. Collectively, these concepts encapsulate the cumulative advantages derived from iterative experience, translating into improved overall project performance. The resulting improvements encompass smoother scheduling, enhanced predictability in workflow execution, and heightened anticipation of potential project disruptions, thereby empowering stakeholders to effectively mitigate risks and to establish a synergistic, optimized strategy for construction and logistics, substantially reducing susceptibility to unforeseen disturbances.

The learning curve describes the relationship between accumulated experience and increased competence, illustrating how the effort required to achieve specific outcomes diminishes as experience accumulates, shown in Fig.1. Enhanced workforce proficiency, streamlined operational procedures, and reduced error rates significantly contribute to lowering construction costs and durations in subsequent project implementations.

Nevertheless, once the learning curve approaches its limit, sustaining efficiency improvements necessitates innovative methods.

During the initial phases of nuclear power plant construction, costs escalate rapidly due to continual design revisions, prolonged licensing procedures, and the complexities of synchronizing workflows. These phases require meticulous adjustments within the delivery stream and careful yet time-intensive coordination among project activities. Upon concluding this developmental stage, project expenditures and time investments per unit typically reach their highest level, marking the completion of the FOAK milestone a crucial benchmark within the project's lifecycle.

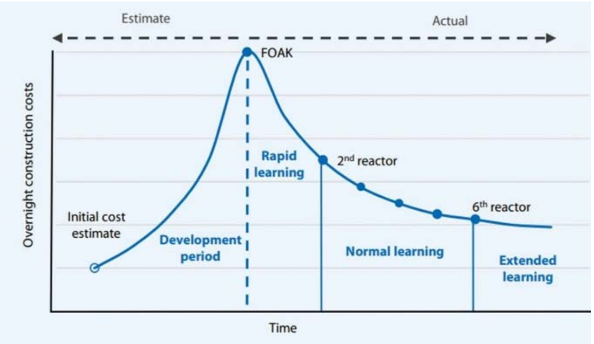

Fig. 1. Typical Learning Curve for Nuclear Reactors [5]
Рис.1. Типова крива навчання для ядерних реакторів [5]

The expertise gained during the initial unit's implementation yields rapid benefits, significantly facilitating subsequent unit commissioning. Critical issues encountered in early stages are addressed, and essential processes undergo substantial improvements. According to existing research, potential time and cost reductions between FOAK and NOAK reactor deployments may reach up to 30%, highlighting a substantial efficiency gain. However, as skills continue to develop, the pace of improvement progressively decelerates, aligning with the diminishing returns characteristic of the learning curve. Over time, the rate of enhancement stabilizes due to limited incremental gains from additional experience. At this juncture, processes become fully optimized, workflows are highly structured, and operational efficiencies are maximized. Beyond this point, significant further reductions in cost and construction duration become minimal, indicating that the learning curve has plateaued.

Economies of scale have recently attracted significant attention, particularly concerning the deployment of Small Modular Reactors (SMRs); however, the concept applies equally to larger reactor units. It refers to the reduction in unit costs as production scales increase. Consequently, beyond a specific threshold, constructing multiple smaller reactors could potentially become more economically feasible than establishing a fleet of large-scale reactors (LSRs) achieving the same total capacity. Conversely, economies of multiples emphasize cost and schedule efficiencies achieved through cumulative learning from constructing and operating successive reactor units, presents in equation (1). Unlike economies of scale, which depend primarily on production scale, economies of multiples rely heavily on accumulated expertise gained from previous deployments [6].

$$C_{NOAK} = C_{FOAK} \cdot (1 - LR)^{\log_2 N}. \qquad (1)$$

Where C_{NOAK} and C_{FOAK} represent the cost of NOAK and FOAK, respectively; LR is the learning rate, showing cost reduction per deployment; and N is the number of units.

A crucial consideration is understanding how these two concepts interact and identifying the crossover point at which one becomes more advantageous than the other. Typically, the learning curve, beginning with a FOAK reactor deployment, follows a logarithmic progression. To illustrate this interplay more clearly, a simplified analytical scenario is presented based on equation (1).

The typical learning rate for large-scale reactors varies between 5 and 10%, compared to a value for SMRs ranging from 10 to 20% [7]. For this example, let the learning rates be 8% for a LSR capacity of 1200 MW_e and 10% for a SMR capacity of 400 MW_e, respectively. Assuming that initial cost for 1200 MW_e plant for SMR FOAK project is 25% higher than an identical LSR FOAK project, the projection of the levelized cost is presented in Fig.2. It can be determined that economies-of-multiple offer a cost advantage over economies-of scale for the cases considered, up to the crossover point of approx. 7 GW_e power plant capacity.

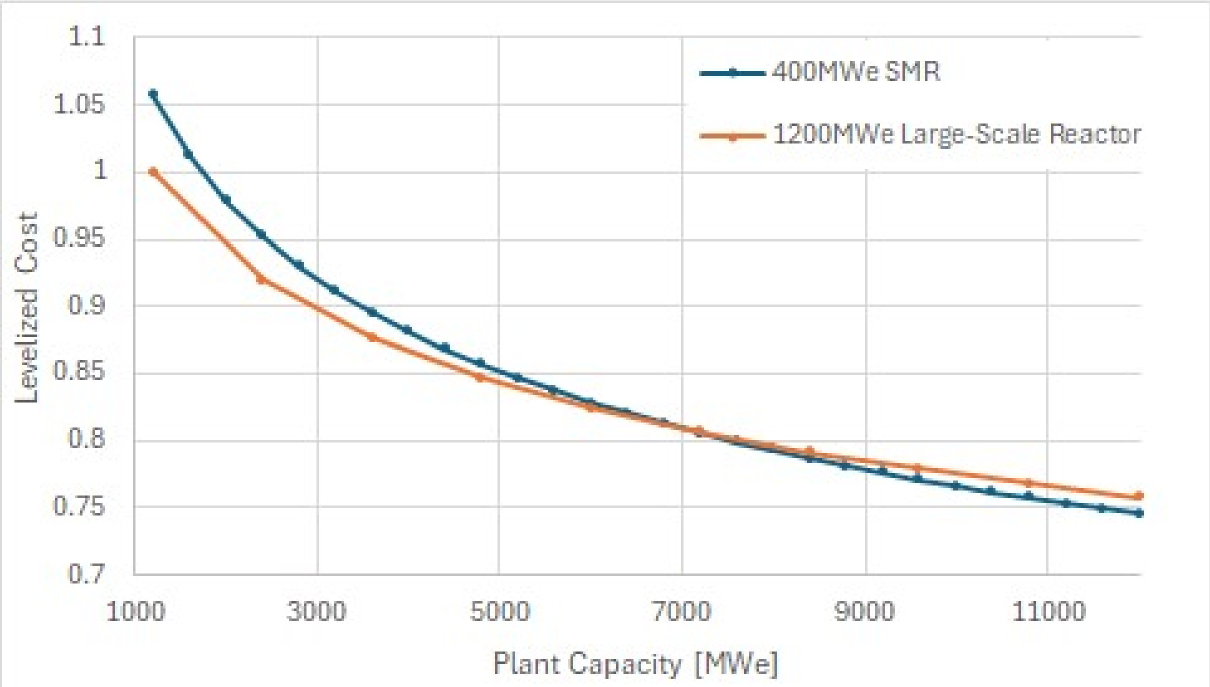

Fig.2. Levelized costs for 400 MW_e SMR and 1200 *MWe* LSR by plant capacity

Рис.2. Приведена собівартість електроенергії для SMR (400 МВт(е)) та *MWe* LSR (1200 МВт(е)) реакторів у залежності від потужності енергоблоку

KEY NUCLEAR REACTORS

The AP1000 is a pressurized water reactor that has been built in China and the United States. It yields a maximum thermal power output of 3,415 *MWth* and a net electrical output of 1,115 *MWe*, presented in Fig. 3.

Westinghouse designed the reactor with the primary goal of reducing costs and improving safety by minimizing the use of expensive components, extensive piping, and complex cabling. Westinghouse achieves these by implementing passive safety systems, which eliminate the need for active cooling pumps in safety functions. In comparison to previous designs, the AP1000 offers 50% fewer safety-related valves, 35% fewer pumps, 80% less safety-related piping, 85% less control cabling, and 45% less seismic building volume [8]. These advancements contribute to both increased safety and improved economic performance. The construction of plant additionally utilizes a modular approach, with large components prefabricated at centralized facilities and transported to the site for assembly, significantly speeding up the construction process. The AP1000 design incorporates two steam generators and canned rotor main coolant pumps, thereby preventing seal leakage issues. In the event of a coolant loss, the containment structure is passively cooled. Emergency core cooling water is stored at a high elevation within the containment, allowing gravity to flow into both the reactor vessel and the surrounding cavity. The plant includes two separate safety systems: one for core cooling in the event of a major pipe break, and another for containment cooling. The in-containment refueling water storage tank (IRWST) is a vital part of this passive mechanism, since it discharges water into the core by gravity after potential reactor depressurization. The tank contains enough water to fully cover the reactor fuel and fill the cavity above the fuel assemblies [9]. Technical parameters are presented in Table 1.

Table 1. Parameters of the AP1000 Reactor [10, 11]
Табл. 1. Параметри реактора AP1000 [10, 11].

Parameter	Value
1	2
Reactor Thermal Power	3,415 MWth
Reactor Electrical Power	1,115 MWe
Containment	Single
Core Inlet/Outlet Temperature	280.7°C / 321.1°C
Number of Fuel Assemblies	157
Fuel Assembly Length	14 ft.
Core Damage Frequency	2.4×10^{-7}
Emergency Safeguards	Passive In-Vessel Retention System
Number of Steam Generators	2
Main Coolant Pumps	4 Canned Rotor
Refueling Interval	18 Months
Construction Period	3 Years
Concrete	<100000 m^3
Steel Used	<12000 MT

Several full-scale AP1000 reactor projects have been completed, demonstrating the design's viability in commercial applications. In China, four AP1000 units are operational two at the Sanmen Nuclear Power Plant in Zhejiang Province and two at the Haiyang Nuclear Power Plant in Shandong Province marking the design's first commercial use. In the United States, two AP1000 units have been built at the Vogtle Electric Generating Plant in Georgia and two another units in VC Summer has been cancelled during a construction phase. While the Chinese units were completed and brought online in the late 2010s, the US projects were delayed and over budget, with Vogtle Unit 3 going commercial in 2023 and Unit 4 in 2024.

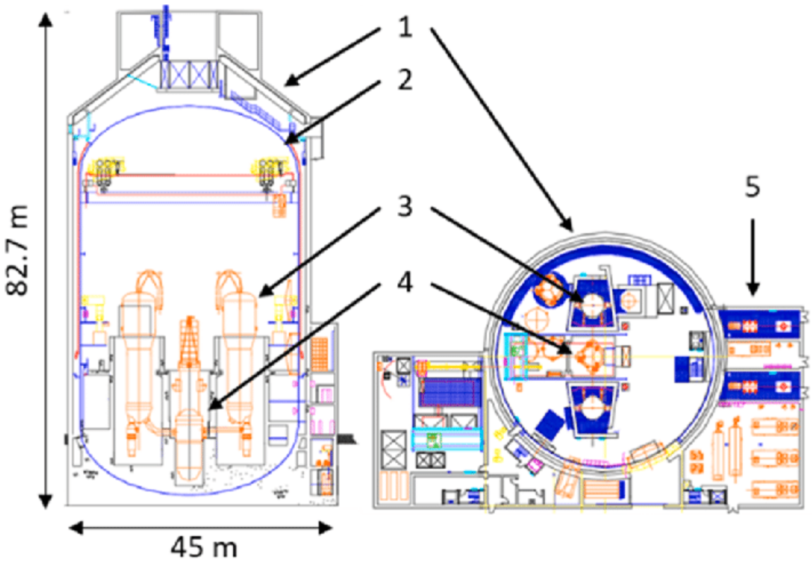

Fig.3. The reactor and auxiliary buildings for the Westinghouse AP1000:
1. shield building, 2. containment building, 3. steam generator, 4. reactor pressure vessel, 5. auxiliary building [12]

Рис. 3. Реактор та допоміжні споруди Westinghouse AP1000:
1. захисна оболонка (shield building), 2.герметична оболонка (containment building),
3. парогенератор (steam generator), 4. корпус реактора (reactor pressure vessel),
5. допоміжний корпус (auxiliary building) [12].

The EPR is a pressurized water reactor with a thermal output of 4,500 *MWth*, yielding 1,660 *MWe*, shown in Fig. 4. Four EPRs have already been constructed worldwide: one in Finland (Olkiluoto), one in France (Flamanville), and two in China (Taishan Units 1 and 2). The EPR was developed through a collaboration between Areva, EDF and Siemens to enhance safety using a more traditional, yet robust reactor design. Compared to previous French and German designs, the plant's size was increased to benefit from economies of scale and improve overall competitiveness. Technical parameters are presented in Table 2.

The first EPR to begin construction was at Olkiluoto in Finland. Although initially scheduled for completion in 2009, the project last more than a decade late and significantly over budget in 2022. Taishan Units 1 and 2, completed in 2018 and 2019 respectively, were the first EPRs to begin commercial operations, owing to efficient project execution and regulatory processes. Flamanville 3, which construction was launched in 2007 faced similar setbacks and rising costs, and as a result, was completed only in 2024.

Table 2. Parameters of the EPR Reactor [10]
Табл.2. Параметри реактора EPR [10]

Parameter	Specification
Reactor Thermal Power	4,500 MWth
Reactor Electrical Power	1,660 MWe
System Pressure	2,250 PSIA
Core Inlet/Outlet Temperature	295.6°C / 329.8°C
Number of Fuel Assemblies	241
Fuel Assembly Length	480 cm
Core Damage Frequency	5×10^{-7}
Emergency Safeguards	Active (4 Independent Trains)
Steam Generators	4
Main Coolant Pumps	4
Containment	Double
Refueling Interval	18 Months
Construction Period	5 Years
Concrete	204498 m^3
Steel Used	70903 MT

The design incorporates multiple independent and redundant safety systems, along with a core catcher to manage potential fuel melt accidents in the event of system failure. However, these added features increased both the complexity and cost of construction. The Olkiluoto and Flamanville projects, in particular, experienced major delays and cost overruns due to challenges associated with FOAK construction [13].

The APR1400 (Advanced Power Reactor 1400) is a Generation III pressurized water reactor designed by Korea Electric Power Corporation (KEPCO) and Korea Hydro & Nuclear Power (KHNP), shown in Fig. 5. It is an evolutionary design that builds on the proven OPR1000, with significant improvements in safety, performance, and operational efficiency.

The APR1400 provides a thermal power output of 4,000 MWth and a net electrical output of around 1,400 MWe. Technical parameters are presented in Table 3.

The design places a strong emphasis on enhanced safety systems, digital instrumentation and control, and standardization to reduce construction and operational costs. Unlike passive designs like the AP1000, the APR1400 utilizes active safety systems with strong redundancy, such as four safety injection pumps, two independent trains of emergency core cooling systems (ECCS), and a safety depressurization system [15].

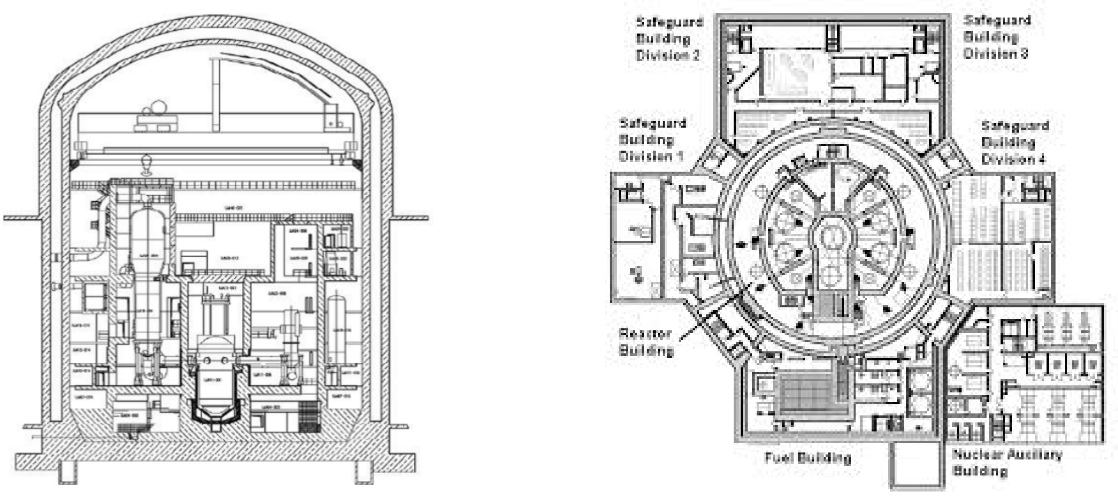

Fig.4. The EPR Reactor Section and Plan [14]
Рис.4. Переріз та план реактора EPR [14]

These systems are intended to address both large-break and small-break loss of coolant incidents. The containment structure is double-walled and is capable of withstanding both external events and internal pressure surges.

The reactor core consists of 241 fuel assemblies, and the plant is designed for refueling every 18 to 24 months [16].

Table 3. Parameters of APR1400 Reactor [10]
Табл. 3. Параметри реактора APR1400 [10]

Parameter	Specification
Reactor Thermal Power	4,000 MWth
Reactor Electrical Power	1,400 MWe
System Pressure	2,250 PSIA
Core Inlet/Outlet Temperature	290°C / 323°C
Number of Fuel Assemblies	241
Fuel Assembly Length	365.8 cm
Core Damage Frequency	~1×10^{-5} / reactor-year
Emergency Safeguards	Active (2 × 100% Redundant Trains)
Steam Generators	2 (U-tube type)
Main Coolant Pumps	4
Containment	Single
Refueling Interval	18–24 Months
Construction Period	~5 Years
Concrete	unknown
Steel Used	unknown

The APR1400 reactor design has been successfully deployed in several projects, both domestically in South Korea and internationally. In South Korea, Shin-Kori Units 3 and 4 have been commissioned and are operational since 2016 and 2019, respectively. On the international front, the Barakah Nuclear Power Plant in the United Arab Emirates hosts four APR1400 reactors. Unit 1 became operational in 2021, followed by Unit 2 in 2022, Unit 3 in 2023, and Unit 4 in 2024. South Korea is also expanding its nuclear energy capacity with the construction of Shin-Hanul Units 1 and 2, scheduled for initial completion by 2026, as well as two more reactors at the Shin-Kori site, which are in the advanced stages of construction.

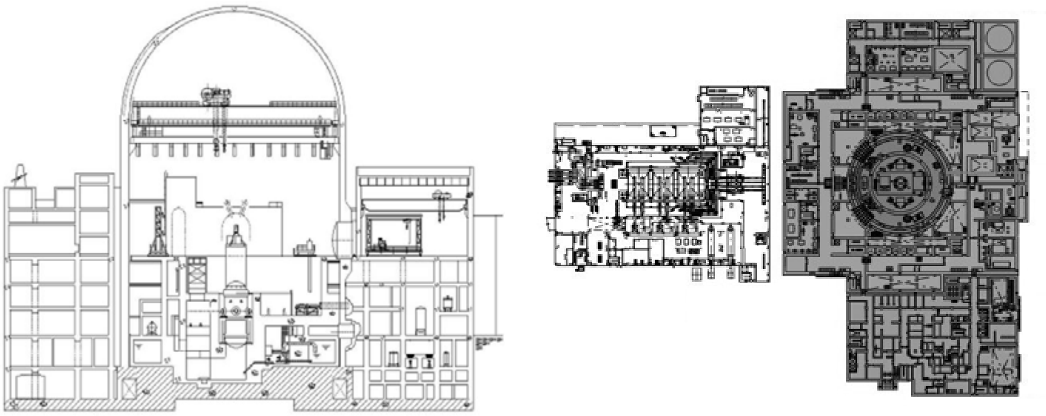

Fig.5. Cross-section and plan of the APR1400 reactor [17]
Рис.5. Поперечний переріз та план реактора APR1400 [17]

PURPOSE AND METHODS

The primary objective of assessing nuclear power plant projects in terms of time and cost performance is to quantify and analyze the distinct impacts associated with FOAK and NOAK deployments. Understanding these effects is crucial for improving project management strategies, forecasting future outcomes, and enhancing overall efficiency in nuclear power plant construction. While Earned Value Management (EVM) [18] is a comprehensive method traditionally employed during project execution for continuous monitoring [19], controlling costs, and providing accurate forecasts [20], the present analysis applies a simplified approach tailored specifically for post-project evaluations [21].

This simplified evaluation methodology centers around four critical post-completion metrics:

Planned Time of Construction (T_p), Final Time of Construction (T_f), Planned Costs of Construction (C_p), and Final Costs of Construction (C_f). Utilizing these metrics, two key performance indicators are defined: the Schedule Performance ratio (SP) and the Cost Performance ratio (CP), computed as equation (2) and (3):

$$SP = T_p/T_f \ , \qquad (2)$$

$$CP = C_p/C_f \ . \qquad (3)$$

These ratios provide intuitive and straightforward insights into project schedule adherence and budget management.

To derive a comprehensive performance indicator that simultaneously captures both time and cost dimensions, the aggregated Performance Coefficient (PC) is introduced, defined as equation (4):

$$PC = SP \cdot CP = \frac{T_p}{T_f} \cdot \frac{C_p}{C_f}. \qquad (4)$$

This consolidated coefficient serves as an effective tool for objectively evaluating overall project efficiency [22]. All projects included in the study are assessed using this unified metric, allowing for clear, comparative analysis across multiple nuclear plant projects. Finally, the resulting data are visualized using graphical techniques to facilitate a clear understanding of performance trends, enabling the identification of best practices, common pitfalls, and practical insights that contribute to more effective planning and execution strategies in future nuclear reactor projects.

RESULTS AND EXPLANATIONS

The main conclusion drawn from the table 4 is that all analyzed nuclear reactor projects experienced significant delays and considerable cost overruns compared to their initial plans. Specifically, reactors deploying AP1000 and EPR technologies demonstrated substantial deviations in both construction time and final budget, exemplified by the Vogtle and

Olkiluoto projects, respectively. The Vogtle 3 AP1000 unit took 125 months to complete compared to a planned duration of 40 months, with costs increasing from an estimated 14.3 billion USD to a final 36.8 billion USD. Similarly, the EPR reactors, such as Olkiluoto 3 and Flamanville 3, showed extreme extensions of timelines, from planned construction periods around 4-5 years to actual completion taking over 17 years, coupled with budget escalations by a factor of approximately three to four. Projects involving APR1400 technology, such as ShinKori and Barakah, also experienced delays and budget increases, albeit relatively smaller. The main outcome from

Table 5 is that nuclear reactor construction projects experienced significant reductions in capacity construction rates *(MW/month)* and considerable increases in unit costs per *MW (kUSD/MW)* compared to their planned estimates.

Table 6 presents the Performance Coefficient (PC), which integrates both schedule (SP) and cost (CP) performance ratios, clearly indicates significant challenges across all nuclear technologies and projects. Projects closer to a PC value of 1 represent better performance, yet none of the examined projects achieved this ideal. APR1400 projects generally performed better than AP1000 and EPR projects, with ShinKori 5 and 6 attaining the highest PC of 0.66 due to relatively better control of time (SP = 0.76) and cost (CP = 0.86). In contrast, the EPR reactors had notably low PC values, particularly Olkiluoto 3 (PC = 0.07) and Flamanville 3 (PC = 0.09), driven by severe deviations in both schedule and cost management. AP1000 projects also struggled significantly, especially Vogtle units (PC = 0.13), underscoring substantial inefficiencies.

Overall, the results demonstrate systemic weaknesses in the planning and execution of nuclear construction projects, with clear room for improvement, especially in managing schedules and controlling costs effectively.

The fig.6 illustrate comparative analyses of construction time and cost performance, capacity rates, and specific capital costs for nuclear reactors based on AP1000, EPR, and APR1400 technologies.

Table 4. The results of comparison planned and final costruction time and cost for nuclear reactors [23]
Табл.4. Порівняльний аналіз планових і фактичних показників тривалості будівництва та вартості ядерних реакторів [23]

<table>
<tr><th>Technology</th><th>Unit</th><th>Net capacity [MW]</th><th>Planned Construction Time [Months]</th><th>Final Construction Time [Months]</th><th>Planned Cost [bln USD]</th><th>Final Cost [bln USD]</th></tr>
<tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td></tr>
<tr><td>AP1000</td><td>Vogtle 3</td><td>1117</td><td>40</td><td>125</td><td rowspan="2">14,30</td><td rowspan="2">36,80</td></tr>
<tr><td>AP1000</td><td>Vogtle 4</td><td>1117</td><td>44</td><td>125</td></tr>
<tr><td>AP1000</td><td>Sanmen 1</td><td>1157</td><td>52</td><td>107</td><td rowspan="2">5,84</td><td rowspan="2">7,30</td></tr>
<tr><td>AP1000</td><td>Sanmen 2</td><td>1157</td><td>56</td><td>103</td></tr>
<tr><td>AP1000</td><td>Haiyang 1</td><td>1170</td><td>55</td><td>113</td><td rowspan="2">6,00</td><td rowspan="2">≈ 9,00</td></tr>
<tr><td>AP1000</td><td>Haiyang 2</td><td>1170</td><td>57</td><td>109</td></tr>
<tr><td>EPR</td><td>Olkiluoto 3</td><td>1600</td><td>47</td><td>212</td><td>3,55</td><td>12</td></tr>
<tr><td>EPR</td><td>Flamanville 3</td><td>1600</td><td>67</td><td>205</td><td>3,6</td><td>13,6</td></tr>
<tr><td>EPR</td><td>Taishan 1</td><td>1660</td><td>44</td><td>109</td><td rowspan="2">7,5</td><td rowspan="2">14,3</td></tr>
<tr><td>EPR</td><td>Taishan 2</td><td>1660</td><td>63</td><td>113</td></tr>
</table>

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Table 4 (continuation)
Продовження Табл.4

1	2	3	4	5	6	7
APR1400	ShinKori3	1416	60	97	4,89	6,46
APR1400	ShinKori4	1418	60	121		
APR1400	ShinKori5	1340	71	95	7,58	8,80
APR1400	ShinKori6	1340	69	89		
APR1400	ShinHanul1	1340	57	125	6,26	7,60
APR1400	ShinHanul2	1340	56	130		
APR1400	Barakah1	1345	72	105	24,40	32,00
APR1400	Barakah2	1345	75	100		
APR1400	Barakah3	1345	58	93		
APR1400	Barakah4	1345	59	102		

Table 5. The results of determining planned and final capacity construction costs and rates for nuclear reactors
Табл.5. Результати визначення запланованих та фактичних витрат на будівництво та темпи будівництва ядерних реакторів

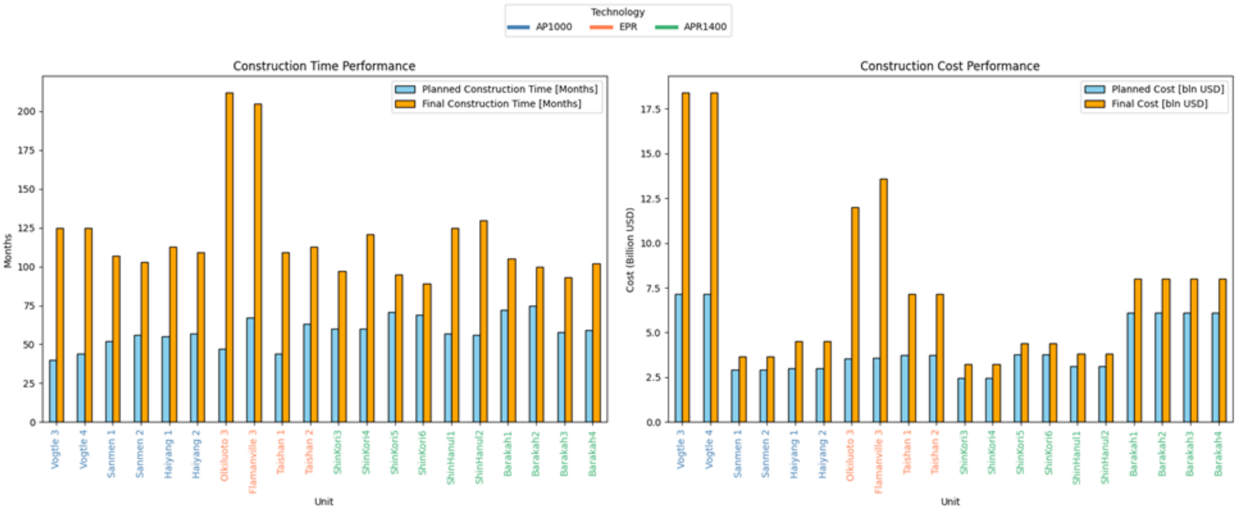
Technology	Unit	Net capacity [MW]	Planned Capacity Construction Rate [MW/month]	Final Capacity Construction Rate [MW/month]	Planned Cost per MW [kUSD/MW]	Final Cost per MW [kUSD/MW]
AP1000	Vogtle 3	1117	27,93	8,94	6401,07	16472,69
AP1000	Vogtle 4	1117	25,39	8,94		
AP1000	Sanmen 1	1157	22,25	10,81	2523,77	3154,71
AP1000	Sanmen 2	1157	20,66	11,23		
AP1000	Haiyang 1	1170	21,27	10,35	2564,10	3846,15
AP1000	Haiyang 2	1170	20,53	10,73		
EPR	Olkiluoto 3	1600	34,04	7,55	2218,75	7500,00
EPR	Flamanville 3	1600	23,88	7,80	2250,00	8500,00
EPR	Taishan 1	1660	37,73	15,23	2259,04	4307,23
EPR	Taishan 2	1660	26,35	14,69		
APR1400	ShinKori3	1416	23,60	14,60	1725,48	2279,46
APR1400	ShinKori4	1418	23,63	11,72		
APR1400	ShinKori5	1340	18,87	14,11	2828,36	3283,58
APR1400	ShinKori6	1340	19,42	15,06		
APR1400	ShinHanul1	1340	23,51	10,72	2335,82	2835,82
APR1400	ShinHanul2	1340	23,93	10,31		
APR1400	Barakah1	1345	18,68	12,81	4535,32	5947,96
APR1400	Barakah2	1345	17,93	13,45		
APR1400	Barakah3	1345	23,19	14,46		
APR1400	Barakah4	1345	22,80	13,19		

Table 6. The results of determining the final rates of nuclear projects performance
Табл.6. Результати визначення фінальних показників ефективності ядерних проектів

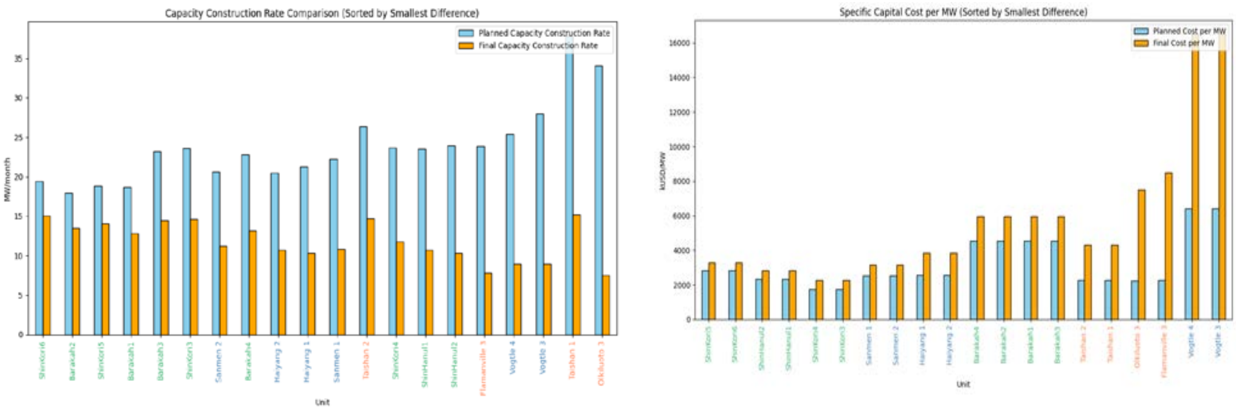
Technology	Unit	Average Planned Construction Time per Unit [Months]	Average Planned Cost per Unit [bln USD]	Average Final Construction Time per Unit [Months]	Average Final Cost per Unit [bln USD]	SP	CP	PC
AP1000	Vogtle (3,4)	42	7,15	125	18,4	0,34	0,39	0,13
AP1000	Sanmen (1,2)	54	2,92	105	3,65	0,51	0,80	0,28
AP1000	Haiyang (1,2)	56	3	111	4,5	0,50	0,67	0,34
EPR	Olkiluoto 3	47	3,55	212	12	0,22	0,30	0,07
EPR	Flamanville 3	67	3,6	205	13,6	0,33	0,26	0,09
EPR	Taishan (1,2)	53,5	3,75	111	7,15	0,48	0,52	0,25
APR1400	ShinKori 3,4	60	2,445	109	3,23	0,55	0,76	0,42
APR1400	ShinKori 5,6	70	3,79	92	4,4	0,76	0,86	0,66
APR1400	ShinHanul 1,2	56,5	3,13	127,5	3,8	0,44	0,82	0,37
APR1400	Barakah (1,2,3,4)	66	6,1	100	8	0,66	0,76	0,50

Figure 6(a) compares planned and final construction durations, highlighting significant schedule overruns. The EPR (Olkiluoto, Flamanville) projects exhibit the largest discrepancies between planned and final times. Figure 6(b) contrasts planned and final construction costs. The AP1000 (Vogtle) and EPR reactors (Olkiluoto and Flamanville) show severe cost escalations. Figure 6(c) presents capacity construction rate (MW/month), revealing that the APR1400 units generally maintained closer consistency between planned and achieved construction rates compared to AP1000 and EPR reactors, with AP1000 and EPR experiencing significant reductions in efficiency. Figure 6(d) illustrates the specific capital cost per MW, showing substantial deviations between planned and final costs, particularly for AP1000 (Vogtle) and EPR (Olkiluoto, Flamanville) reactors, indicating severe underestimation of initial budgets. APR1400 reactors experienced less drastic increases.

Figure 7 provides a direct comparison between planned and final construction times and costs for nuclear reactor projects based on AP1000, EPR, and APR1400 technologies. Each arrow in the chart connects the planned (starting point) and final (ending point) scenarios, clearly visualizing the extent of deviations. AP1000 reactors (Vogtle) exhibit extremely large increases both in construction time and cost, with final values significantly higher than planned, emphasizing severe underestimation and project management challenges. But (Sanmen and Haiyang) projects present better performance results comperable to APR1400. EPR reactors (Olkiluoto 3, Flamanville 3) also demonstrate substantial deviations, comparable to AP1000, but slightly lower, illustrating extensive schedule delays and cost overruns. APR1400 reactors (ShinKori, ShinHanul, and Barakah units) show notably smaller discrepancies between planned and actual outcomes, indicating more realistic forecasting, better project control, and improved management practices. Figure 8 illustrates a clear performance evaluation of nuclear reactor projects, comparing the Schedule Performance Ratio (SP) against the Cost Performance Ratio (CP), combined into a Performance Coefficient (PC), visualized by circle sizes. The best-performing project is the APR1400 (ShinKori 5,6), indicated by the largest circle and its position closest to the ideal (top-right corner), highlighting balanced efficiency in both cost and schedule control. In contrast, the EPR (Olkiluoto) project exhibits the poorest performance, positioned at the bottom-left corner with the smallest circle, underscoring significant issues with cost overruns and extensive delays. Overall, APR1400 projects consistently outperform AP1000 and EPR reactors in managing construction schedules and costs effectively. The figure 9 does not show a clear learning trend or progressive improvement across subsequent projects. Instead, fluctuations in both construction time and cost are observed for all technologies, with notable inconsistencies.



а *б*



c *d*

Fig.6. (a) Construction Time Performance, (b) Construction Cost Performance, (c) Capacity Rate Comparison, (d) Specific Capital Cost per MW

Рис.6 (а) Виконання термінів будівництва, (б) Виконання кошторису будівництва, (в) Порівняння показників потужності, (г) Питомі капітальні витрати на 1 МВт

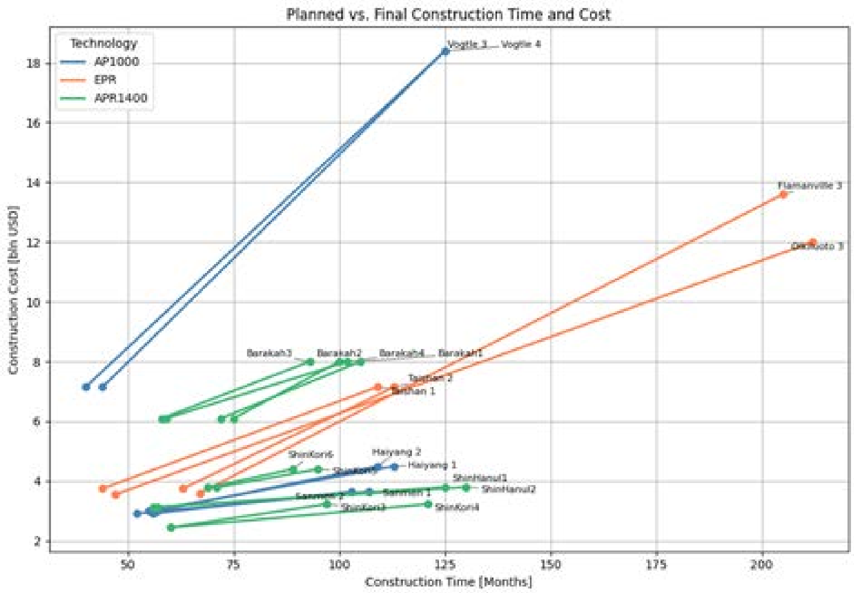


Fig.7. Comaparison of planned and final construction time and cost
Рис.7. Порівняння запланованих та фактичних показників термінів будівництва та вартості

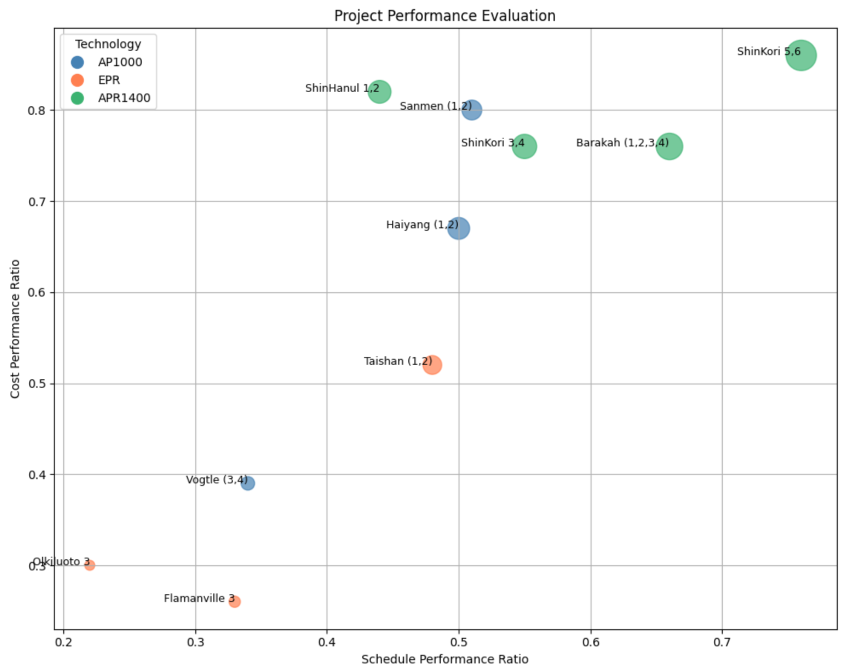


Fig.8. Project Performance Evaluation
Рис. 8. Оцінка ефективності проекту

The APR1400 curves demonstrate variability with initially high values decreasing in some projects but not consistently downward. The EPR exhibit minimal evidence of a learning or improvement trend. The AP1000 curves displays significant increases, especially in cost for the Vogtle units, reflecting deteriorating rather than improving performance.

CONCLUSIONS AND RECOMMENDATIONS

Analysis of recent Generation III/III+ nuclear reactor projects reveals substantial delays and significant cost overruns, indicating persistent FOAK challenges and limited visibility of the anticipated NOAK effect, which usually provides improved efficiency in subsequent builds.

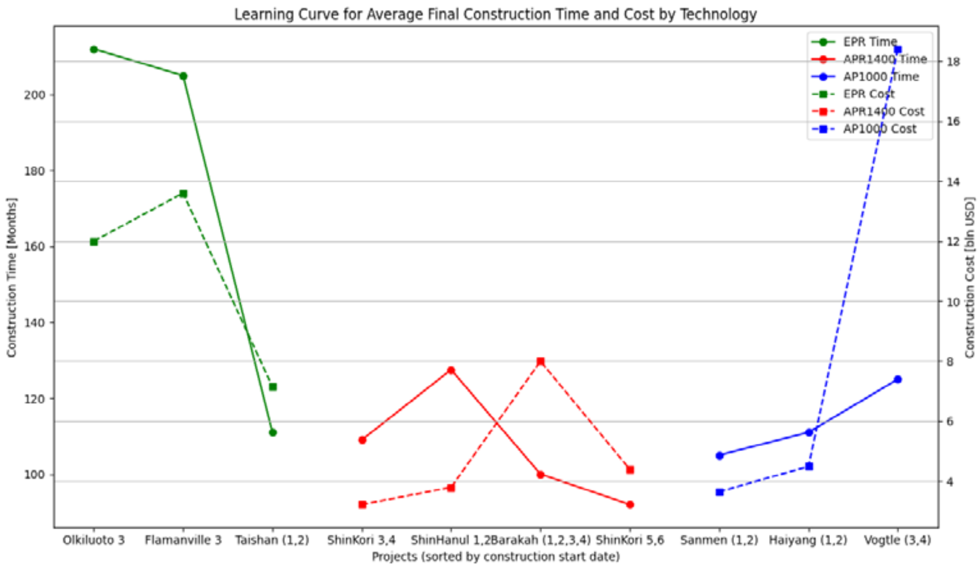


Fig. 9. Learning curve for average projects time and cost by technology
Рис. 9. Дослідна крива для середніх показників часу та вартості проєктів за технологіями

Factors contributing to these delays and cost escalations include evolving regulatory frameworks, particularly heightened safety requirements following events such as the inadequate project management, design modifications occurring mid-construction, supply chain immaturity, and insufficient skilled workforce. Projects frequently began construction prior to finalizing design details, leading to significant rework and productivity losses. Moreover, issues such as quality control scandals and a high workforce turnover rate further inhibited the transfer and retention of experience.

Collectively, these challenges diminished potential efficiencies typically gained in repeated construction, demonstrating that each project essentially encountered renewed complexities characteristic of FOAK implementations. Currently, there are 65 nuclear reactors under construction globally, with an additional 90 reactors planned [24], underscoring continuing investment in nuclear energy. Simultaneously, there is significant and growing interest in developing Small Modular Reactor (SMR) technologies [25], intended for diverse applications including remote regions, industrial processes, and flexible grid integration. Given the challenges highlighted by recent reactor construction projects, future research is recommended to specifically focus on analyzing FOAK and NOAK effects associated with large scale reactors and try to rescale it to SMRs to better understand and mitigate potential cost overruns and schedule delays inherent in deploying this emerging technology.

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ОЦІНКА ВАРТОСТІ ТА ВИКОНАННЯ ГРАФІКІВ БУДІВНИЦТВА КЛЮЧОВИХ ЯДЕРНИХ РЕАКТОРІВ

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Анотація. Атомна промисловість є унікальним сектором, який особливо вразливий до затримок. Велика кількість впливових факторів, таких як складність проєктування, стислі терміни виконання робіт на майданчику та логістично складний наскрізний ланцюжок поставок, і це лише деякі з них, роблять весь проєкт дуже схильним до ускладнень. У 2017 році оцінено, що майже дві третини з 55 атомних електростанцій, які будувалися на той час, відставали від графіка.

Крім того, вважається, що з 2010 року такі затримки призвели до збільшення кінцевої вартості проєктів майже на 20%. У цій роботі проаналізовано останні результати будівництва проєктів ядерних реакторів покоління III/III+, зокрема, досліджено технології AP1000, EPR і APR1400. Ключові показники ефективності які було оцінено, включали порівняння запланованих і фактичних термінів будівництва, витрати і темпи спорудження потужностей, які виявили значні відхилення між проаналізованими проєктами. Ефективність кожного ядерного проєкту була кількісно оцінена за допомогою коефіцієнта продуктивності графіка, коефіцієнта ефективності вартості та інтегрованого коефіцієнта ефективності для повного порівняння ефективності різних реакторних технологій. Аналіз також визначив ключові причини цих відхилень, такі як мінливе нормативне середовище, вимоги до безпеки, неефективність управління проєктами, незрілість ланцюжка постачання і обмежена доступність кваліфікованої робочої сили, які сприяли постійним проблемам, пов'язаних з першими у своєму роді реакторами (FOAK), і затьмарювали очікувані поліпшення, пов'язані з n-ми у своєму роді реакторами (NOAK). На основі цих висновків надано рекомендації для майбутніх досліджень, наголошуючи на необхідності застосувати знання, отримані під час розгортання великих реакторів, до нових технологій малих модульних реакторів (ММР).

Ключові слова: NOAK; FOAK; час виходу на ринок; будівництво АЕС; вартість; графік робіт

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