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THE IMPACT OF FINANCING STRUCTURE AND LEARNING RATE ON THE FINANCIAL VIABILITY OF SMALL MODULAR REACTORS

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ABSTRACT[2]

Small modular reactors are expected to play an important role in the global energy transition, as their technological characteristics – including modular manufacturing, passive safety systems and the possibility of incremental capacity expansion – offer a novel approach to nuclear investment. At the same time, these investments face significant financial challenges arising in particular from technological novelty, regulatory uncertainties and the underdeveloped nature of financing structures. The aim of this study is to examine how cost reductions driven by serial production and learning feedback influence the financial returns of small modular reactor projects under different market conditions and capital structures, and to provide a methodological framework that renders their risk and return profiles interpretable from both banking and investor perspectives.

In the modelling, three components were examined, taking into account energy price volatility, the decrease in investment costs associated with learning, and the financial effects of different equity–debt ratios. The research is based on deterministic discounted cash flow modelling and Monte Carlo-based stochastic simulations. The model tested learning rates between 5% and 20%, representing cost reductions stemming from serial production and learning feedback. The Monte Carlo simulations indicate a high degree of dispersion and asymmetry in financial outcomes: net present values are concentrated predominantly in the negative range, internal rates of return rarely exceed 6%, and payback periods may extend to 35–40 years. Sensitivity analysis shows that higher learning rates considerably improve these indicators, confirming the economic relevance of learning curves for financial viability. The analysis demonstrates that at a price level of EUR 70/MWh and with a higher-equity financing structure, a payback period of 19–21 years may be achieved, whereas under a pessimistic price scenario the project remains unprofitable.

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Based on the results, it will be essential in the future to pursue standardisation, the development of modular manufacturing, and the acceleration of international reference projects, alongside the implementation of long-term guaranteed offtake prices, state loan guarantees, and adaptive financial models.

JEL codes: G24, G32, O33, Q40, Q48

Keywords: SMR, learning curve, Discounted Cash Flow, funding risk

1 INTRODUCTION

Amid the global energy transition and increasingly stringent climate targets, the financial sector plays a key role in determining which technologies can be realised and achieve economies of scale. The decarbonisation of electricity generation is not only environmentally imperative but also crucial for financial and societal stability; as a result, an increasing number of countries and developers view nuclear power as a reliable, low-emission source of baseload energy (Adorján–Rétfalvi, 2022). In terms of planning new investments, there is a notable shift towards small modular reactors (SMRs), which require both novel technology and innovative financing and business models. SMRs are nuclear generating units of smaller capacity (typically 50–300 MWe) that can be manufactured modularly and transported to sites for relatively rapid deployment. This approach fundamentally differs from the logic of traditional, site-built large power plants and opens new possibilities for decentralised, incremental electricity generation.

Their scalability is particularly important from a financial perspective, as it allows for gradual plant expansion, reducing the risk associated with single, large-scale investments. Because commissioning can occur incrementally, in multiple stages, it provides improved liquidity opportunities for operators and investors, which is especially advantageous in regions where capital market conditions do not allow the financing of a single, large nuclear unit. Furthermore, many SMR concepts rely on passive safety systems capable of maintaining core operational safety without human intervention, resulting in a lower risk profile compared with conventional plants (IAEA, 2020). Serial production and learning feedback continually reduce specific costs, giving learning curves particular economic relevance. Subsequent units are expected to benefit from significant reductions in capital expenditure (CAPEX), improving their return prospects. The initial deployments also establish regulatory practices, thereby simplifying procedures for later projects. Against this backdrop, a critical question is how initial risks can be mitigated and financial instruments structured to ensure long-term competitive yet safe return pathways (Locatelli et al., 2017).

International interest is evidenced by several projects already in advanced licensing phases worldwide. In Canada, Ontario Power Generation received approval from the Canadian Nuclear Safety Commission in April 2025 to construct the first BWRX-300 SMR at the Darlington site, marking the country's first such project (CNSC, 2025). The first unit is expected to be completed by 2028, with three additional units following by the mid-2030s. In the United States, TerraPower submitted its construction licence application for the Natrium reactor demonstration project in March 2024, currently under review by the Nuclear Regulatory Commission (TerraPower, 2024). This project plans a 345 MWe sodium-cooled fast reactor, anticipated to commence operation in 2030 (AP News, 2024). Oklo is also actively engaging with the NRC regarding licensing for the Aurora Powerhouse, a 15 MWe fast reactor to be built at the Idaho National Laboratory (Oklo, 2025). In Europe, the French company *new*cleo submitted its safety documentation to the French nuclear authority at the end of 2024, preparing to deploy a 30 MWe lead-cooled fast reactor, planned for operation by 2030 (World Nuclear News, 2024). These examples clearly demonstrate that SMR technology has moved beyond concept into active development and licensing, representing real investment opportunities.

Despite these plans, one of the greatest barriers to widespread adoption remains financing uncertainty arising from technological and regulatory uncertainty. Supply chains are not yet established, few reference projects have regulatory approval, and in many cases political support is ambiguous; as a result, private capital and commercial banks still perceive these investments as highly risky. However, this risk can be substantially mitigated through appropriate government guarantees, long-term offtake agreements, and new types of financial instruments (Ingersoll et al., 2020).

The aim of this study is to demonstrate the financial characteristics inherent to small modular reactor technology, how risk and return structures can be shaped to be interpretable from both banking and investor perspectives, and which financial innovations can facilitate successful market introduction. The study also highlights that the learning rate is not merely a technical or statistical parameter but a strategic financial factor capable of fundamentally influencing valuation outcomes.

2 METHODOLOGY

The deterministic and stochastic simulations were implemented in the MATLAB environment. The financial model is based on discounted cash flow (DCF) analysis, a widely accepted and broadly applied approach for investment evaluation (IAEA, 2021). The principle of DCF is to discount future cash flows to their present value using an appropriately chosen discount rate that reflects the cost of capital, the risk profile, and the time value of money. For large-scale energy investments, a commonly used reference discount rate is 6–9% under a conservative approach; in this study, an 8% rate was applied to reflect the typically long time horizons (INL, 2014). Operational expenditure (OPEX) were fixed at 3% of the capital expenditure, and various capital structure scenarios were modelled (20–80%, 50–50%, 80–20% equity–debt ratios) to assess their impact on project returns.

The payback period (PB) indicates the nominal time required to recover the investment's cash flows. In this study, the metric was applied in a static form, i.e., without accounting for the time value of money, based on the point at which cumulative cash flows reach zero. While this approach is not strictly part of the DCF methodology, it provides an illustrative measure of how quickly the project's cash flows turn positive nominally.

Different stakeholders in the investment have distinct objectives and return expectations. At the project level, return reflects the overall financial viability of the investment, expressed through the net present value (NPV), which indicates whether the project can recover the full cost of the invested capital over the evaluation period. From the perspective of a private investor, return is defined more narrowly: the key question is whether their own invested capital is recovered within the considered time frame at the given discount rate. In this interpretation, the payback reflects cash flows available after debt service and interest payments. In contrast, the perspective of a public financier is not purely financial. Public capital serves strategic objectives such as energy security, technological sovereignty, or the achievement of decarbonisation targets. Consequently, the implicit return expectation of the state is lower, as the social and economic benefits of the investment are decisive rather than direct financial profit; a private investor, by contrast, requires a market-based return.

The 8% discount rate used in the financial model, representing the cost of capital for private investors, approximates the estimated weighted average cost of capital (WACC) for the project. This metric is commonly used for long-lived, capital-intensive energy projects and determines the weighted cost of equity and debt according to their respective shares, expressed in the below general form:

$$WACC = \frac{E}{E+D} \times r_e + \frac{D}{E+D} \times r_d \times (1 - T) \quad (1)$$

where:

E = value of equity
D = value of debt
r_e = expected return on equity
r_d = cost of debt
T = tax rate

Since we are looking at project-level cash flows and the interest rate is nominal, the tax effect is negligible or zero, and the formula can be simplified:

$$WACC = \frac{E}{E+D} \times r_e + \frac{D}{E+D} \times r_d \quad (2)$$

The WACC combines the structural, market, regulatory, and technological risk components of financing and can be interpreted as a comprehensive discount rate representing the project's overall cost of capital. Naturally, changes in the proportions of the financing structure alter its value. Increasing the share of equity raises the WACC due to the greater weight of the more expensive source, whereas increasing the debt ratio lowers it by incorporating the relatively cheaper source. Higher indebtedness increases financial risk, while a higher equity proportion results in more stable but costlier financing. Accordingly, the discount rate reflects both the total cost of capital and the average risk profile of the project. In international practice, for nuclear investments in developed markets, WACC typically ranges between 5% and 7%, while the presence of new technologies or country- and political risks can justify values between 10% and 15%. The cost of capital is therefore not a static parameter but a dynamic metric that adjusts to the project's risk structure and financing proportions. The aim of this study is to illustrate the effect of different capital structures under identical cost-of-capital assumptions. As a simplifying assumption, the discount rate is held constant across all scenarios, serving as an average risk parameter that reflects the general risk profile of the investment regardless of the financing composition.

Assuming a financing structure of 70% public and 30% private equity, with a 5% cost of debt and a 10–12% expected return on private equity, the weighted cost of capital approximates 8%, consistent with the ranges reported in the international energy literature (Dobrowolski, 2022). This approach allows the effects of varying financing ratios to be demonstrated in terms of relative cash flow dynamics, while maintaining the WACC-based interpretation.

Basic research questions:

- *The evolution of capital and operating costs for first-of-a-kind (FOAK) and subsequent (Nth-of-a-Kind, NOAK) projects:* How do costs change as a result of the learning curve, and how does this affect financial viability?
- *The relationship between financing structures and risks:* How does altering the ratio of equity (private capital, state support) and debt influence the payback period and financial risks?
- *Changes in market electricity prices:* How do fluctuations in market prices affect financial indicators, and how can this uncertainty be managed?

2.1 First investments

The SMR technology is still emerging, and the first investments are expected to involve substantial technical and regulatory uncertainties. For this reason, state involvement is crucial – and indeed unavoidable – in the initial phase. The forms of support may include direct capital contributions, loan guarantees, tax incentives or research and development funding (Nyirkos, 2018).

The first few projects are likely to encounter difficulties similar to those observed during the construction of the Vogtle and Olkiluoto-3 units. The construction delays and schedule overruns demonstrated the types of financial challenges that can be expected, particularly when entering new markets. Private investors are generally only willing to participate to a limited extent at this early stage, as long payback periods and technological uncertainties imply a high risk. Various forms of risk-sharing, such as public–private partnership (PPP) arrangements, may alleviate these problems to some degree, yet full market-based financing remains rare in this phase due to limited experience and stringent regulatory requirements.

Table 1 presents the planned specific capital costs of the first-of-a-kind units of three manufacturers. The remarkably broad range is explained by differences in design characteristics, technologies, the maturity of licensing processes, and the level of development of manufacturing and supply chains.

Table 1
Planned investment amounts for models from different manufacturers

Manufacturer	Capacity	CAPEX (FOAK)
Nuscale	570MWe	4 600–6 200 USD/kW
Smart	100MWe	10 000 USD/kW
Rolls-Royce	470MWe	4 000–5 300USD/kW

Source: NEA. 2021.

2.2 Further investments

As the technology and regulatory environment mature and the initial difficulties are resolved, the way opens for greater private capital involvement. Repeated manufacturing, construction and operational experience enables substantial cost reductions in both time and labour requirements. This process mirrors developments observed in the renewable energy sector over the past decade, where capital and operating costs fell dramatically as the industry expanded. Subsequent units also face considerably lower licensing risks, since the technology has already been "proven" and regulatory authorities have gained experience through earlier approvals. In parallel, the supply chain strengthens, and mass production becomes progressively cheaper and faster. As a result, innovative financing models – previously considered too risky – may emerge, such as power purchase agreements (PPAs) and green bonds.

2.3 Learning Curve

The novelty of the analysis lies in the integration of the learning curve (LC) concept (3) into the traditional DCF framework, making it an integral part of the methodology. As more units of a given technology are deployed, optimisation, standardisation and accumulated operational know-how lead to decreasing CAPEX. It is reasonable to assume that each additional unit can be constructed at a somewhat lower cost, as prior experience, improvements in the supplier network and process optimisation reduce the per-unit expenditure. The objective was not only to quantify the relative advantages of different financing structures but also to provide an analytical framework that enables banks and institutional investors to make well-founded decisions.

The learning curve can be expressed as follows:

$$Cost(n) = Cost(1) * n^{\beta} \tag{3}$$

where

$Cost(n)$ is the unit cost of the n-th reactor
$Cost1$ is the unit cost of the first reactor (FOAK),
β is the parameter representing the slope of the learning curve, a negative value ($\beta < 0$ indicates that the per-unit cost decreases as n increases).

It can be incorporated into the formula as follows:

$$\beta = \frac{\ln(1-LR)}{\ln(2)} \tag{4}$$

where

LR is the value of the learning rate

Based on the above:

$$Cost(n) = Cost(1) * n^{\frac{\ln(1-LR)}{\ln(2)}} \tag{5}$$

The application of the learning rate (LR) to conventional nuclear power plants is not straightforward. Learning rates for large reactors exhibit considerable variation, with values around zero or even negative in some cases. In other words, instead of unit costs decreasing with accumulated experience, they sometimes increased. This phenomenon can be attributed to tightening regulations, complex licensing processes, and project management challenges. It is therefore common that the advantages of standardisation and series production are not fully realised (Rubin et al., 2015).

In the sensitivity analysis, the learning rate was examined across several ranges. Values between 10–15% are typically considered the average observed in the nuclear industry, while an upper value of 20% represents an optimistic but technologically justifiable scenario. The lower bound of 5% reflects the nuclear sector's particular developmental pace, constrained by regulatory limitations and a slow learning trajectory. This approach allows for a quantitative assessment of how the rate of cost reduction influences the financial viability of investments.

3 SIMULATION MODEL

The simulation consists of two clearly distinguishable phases. Both phases are based on examining the effects of reductions in capital and operating costs, taking into account the industry learning curve, advantages from economies of scale, and fluctuations in electricity prices. Since long-term financial stability is influenced not only by market price volatility, the study aimed to quantitatively identify the critical factors exerting the greatest impact on economic viability.

In the deterministic analysis, fixed parameters (CAPEX, OPEX, electricity price) were varied to generate different estimates of expected annual net cash flow, cumulative cash flow, and payback period. Through the different financial scenarios, the effects of the learning curve and financing structures could be analysed.

The analysis focuses on three key financial indicators:

- NPV, which reflects the project's value-creation capability as the difference between discounted cash flows and investment costs;
- IRR, the discount rate at which NPV equals zero;
- PB applied in a static form, which shows the point in time when cumulative cash flows nominally recover the initial investment.

Two main scenarios were applied:

- **Fixed financing ratio:** The payback period was analysed under fixed baseline assumptions (70% state investment – 30% external investors) for different electricity prices.
- **Varying levels of state participation:** FOAK and NOAK financial performance and payback periods were assessed under different equity (state participation) and debt ratios (20–80%, 50–50%, 80–20%).

These results provided an objective view of how different financing structures shape the financial dynamics of projects.

In the second phase, a Monte Carlo simulation with 10,000 runs was conducted to quantify uncertainties in the financial indicators. Input parameters (electricity price, CAPEX, financing conditions) were replaced with randomly generated values, allowing the statistical properties of the results to be analysed.

The project lifetime was assumed to be 40 years, with a construction period of 3 years. The baseline financial assumptions for the model were:

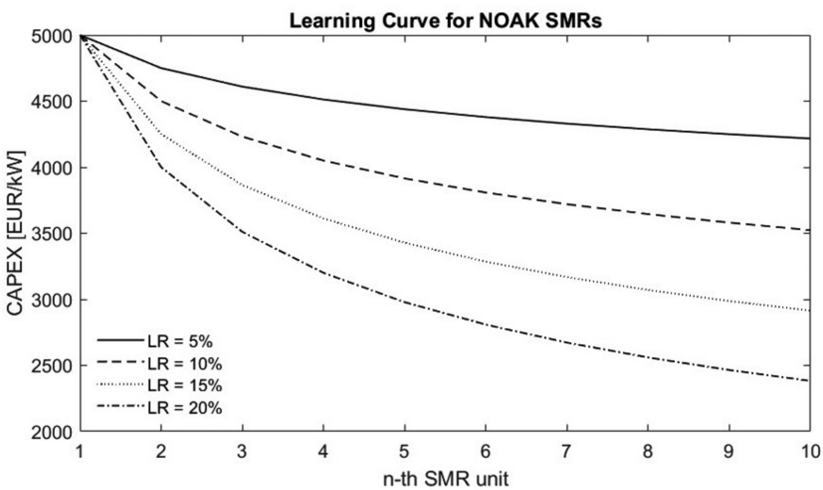
- Learning rate: 5–20% range
- Number of units: FOAK + 2 NOAK
- Unit capacity: 200 MWe per reactor, with 90% capacity factor

- FOAK CAPEX: 5,000 EUR/kW
- NOAK CAPEX: based on the learning curve (β = −0.15)
- OPEX: 3% of CAPEX
- Financing options: fixed (70–30%) and three variants of state participation (20–80, 50–50, 80–20)
- Debt parameters: 15-year term, 5% interest rate
- Discount rate (WACC): 8%; debt interest: 5%; expected equity return: 10–12%

3.1 SMR learning curve

Figure 1 illustrates how the unit cost of the technology is substantially reduced with each additional unit in the different LR cases. This is due to, among other things, standardised design and manufacturing enabling series production, and references from existing reactors, which make the licensing and manufacturing process simpler and faster, improving the prospects for return on investment. The model, of course, significantly simplifies the real process, as it does not take into account potential raw material price fluctuations, changes in regulatory expectations and other macroeconomic factors that can strongly influence the results.

Figure 1
NOAK learning curve



Source: author's compilation

It is important to note that cost reductions will only materialise if subsequent projects are actually implemented, but this requires the right political, economic and regulatory environment and a market that is able and willing to receive the energy generated (Mignacca–Locatelli, 2020).

3.2. Deterministic simulation

The model is designed to illustrate the financial impacts of different financing structures, and the calculations are based on two very different electricity price scenarios. The pessimistic scenario (EUR 30/MWh) is particularly relevant in light of Hungary's current purchase price for nuclear electricity. At present, the sales price of electricity generated by the Paks Nuclear Power Plant is approximately HUF 12/kWh, which corresponds to roughly EUR 30/MWh (Toldi, 2024). This price level represents a realistic lower reference point, as it reflects the favourable production costs arising from the economical operation of long-established nuclear capacities, and it is well suited for examining the financial challenges that future projects would face if implemented under market conditions similar to current prices.

The choice of the optimistic scenario (EUR 70/MWh) is linked to long-term market prospects and reflects a realistic price level applied as a long-term guaranteed purchase price in the international nuclear industry, which may be sufficient to cover the investment costs of new nuclear capacities. Based on international examples (the planned price levels of new nuclear plants in France), the EUR 60–80/MWh range may be considered a realistic benchmark (Zimmermann–Keles, 2023). Although the technical lifetime of nuclear facilities typically ranges from 40 to 60 years, in the case of commercial or mixed financing, investment loans generally have a shorter duration of 10–20 years to ensure the manageability of financial risks. A 15-year maturity allows the repayment of capital in the early phase of operation, when cash flow is at its strongest, while avoiding excessively long-term creditor obligations (IAEA, 2017).

3.2.1 Comparison of projects under two electricity price scenarios (EUR 30/MWh and EUR 70/MWh)

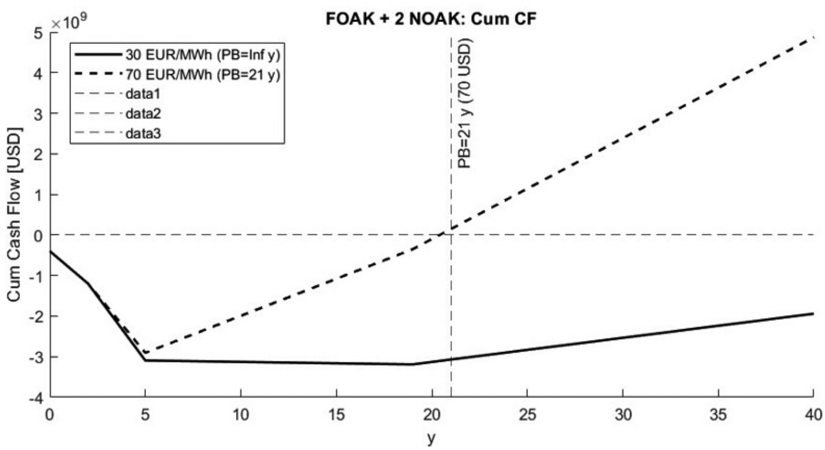
One of the key questions of the study was how the financial rate of return changes when not only a single first unit is built, but also immediately followed by further units. For this reason, we have already considered the construction of three units (one FOAK and two NOAK) in the initial simulation, because this allows us to effectively investigate the effect of the learning curve. If only a single unit were to be built, it would be possible to assess solely the investment costs of the FOAK unit and the higher financial risks arising from them. However, this would not provide an accurate picture of long-term economic viability, as one of the key economic advantages of the technology is precisely that, with the construction of additional units, the per-unit cost decreases substantially (IAEA, 2020). The CAPEX for the first unit is EUR 5,000/kW, and for the second and third units the learning curve is as follows:

$$CAPEX_2 = 1\ 000\ M\ EUR\ \times 2^{-0,15} \approx 900\ M\ EUR \tag{6}$$

$$CAPEX_3 = 1\ 000\ M\ EUR\ \times 3^{-0,15} \approx 846\ M\ EUR \tag{7}$$

As shown graphically in *Figure 2* and quantified in *Table 2*, the cumulative cash flow in both cases falls sharply in years 1-5 due to high initial investment and start-up costs. At EUR 30/MWh, there is no return on investment over a 40-year horizon. At EUR 70/MWh, however, the line crosses zero at around year 21 (PB=21 years), and the cumulative cash flow is expected to approach EUR 5×10^9 by the end of the fourth decade. The results confirm that financial performance is highly sensitive to the market electricity price.

Figure 2
Cumulative CF evolution at different electricity prices



Source: author's compilation

Table 2
Payback period at different electricity prices

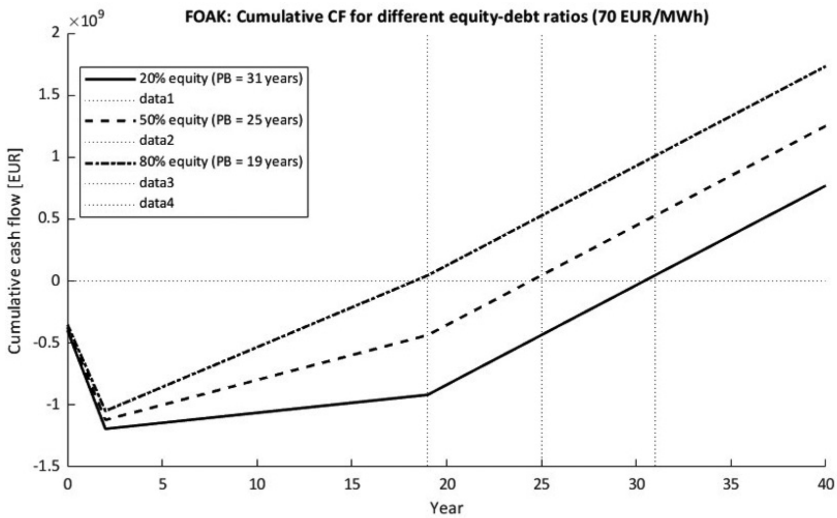
Scenario	Electricity price [EUR/MWh]	Cumulative CF after 40 years [M EUR]	Payback period [years]
FOAK + 2 NOAK	30	–2 000 (approx.)	no return
FOAK + 2 NOAK	70	+5 000 (approx.)	21

Source: author's compilation

3.2.2 Analysis of the FOAK project by financing structures (at EUR 70/MWh)

In the initial years, all three curves decline steeply due to high investment expenditures (FOAK investment phase), after which revenues gradually offset the costs over the following decades. A proportionally higher debt share (lower equity ratio) results in a longer repayment period, as shown in *Figure 3* and *Table 3*.

Figure 3
Evolution of cumulative CF under different financing structures



Source: author's compilation

Table 3
Payback period under different financing structures

FOAK unit financing	Cumulative CF after 40 years [M EUR]	Payback period [years]
20% equity, 80% debt	700 (approx.)	31
50% equity, 50% debt	1 300 (approx.)	25
80% equity, 20% debt	1 700 (approx.)	19

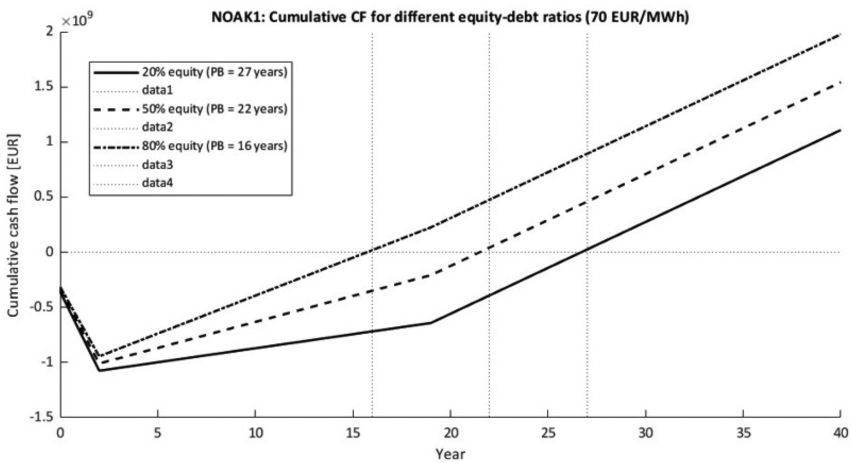
Source: author's compilation

The financing structure is a critical factor, at 20% equity, the initial investment relies heavily on debt and therefore carries higher interest charges. A higher equity ratio significantly reduces financial risks, gives a shorter payback period and more favourable financial results.

3.2.3 Analysis of the FOAK1 project by financing structures (at EUR 70/MWh)

The investment cost of NOAK1 unit (unit 2) is around €900 million (calculated according to the learning curve). The impact of the financing rates was examined for three different structures as shown in *Figure 4* and *Table 4.*

Figure 4
Evolution of cumulative CF under different financing structures (NOAK1)



Source: author's compilation

Table 4
Payback period under different financing structures (NOAK1)

NOAK1 unit financing	Cumulative CF after 40 years [M EUR]	Payback period [years]
20% equity, 80% debt	1 000 (approx.)	27
50% equity, 50% debt	1 500 (approx.)	22
80% equity, 20% debt	2 000 (approx.)	16

Source: author's compilation

For the NOAK1 unit, the payback period improves significantly already with an equity financing ratio of 20%, but an increase in the equity ratio gives even better results. By applying the learning curve, the investment costs of NOAK units can be significantly reduced, significantly improving economic viability and, in the long run, financial results.

3.2.4 Interpretation and statistical distribution of financial indicators

Deterministic analysis provides a simple and understandable picture of financial performance, but does not take into account real market and technological uncertainties. In reality, many parameters fluctuate in value. Monte Carlo simulations were used to quantify the uncertainties. The main financial parameters were randomly varied and the financial model was run through a large number of iterations. The results are summarised in *Table 5*.

In the model, I examined changes in two main parameters:

- *Electricity price:* Normal distribution with a mean (μ) of EUR 70/MWh and a standard deviation (σ) of EUR 10/MWh.
- *Investment costs* (FOAK specific CAPEX): EUR 5,000/kW with ±10% uncertainty, with normal distribution.

The payback period values in the model are calculated in an undiscounted (static) form, basically illustrating the liquidity rate of the investment. The effect of discounting is already incorporated in the NPV and IRR indicators, and in this study the assessment of financial viability is based on these indicators. The purpose of the PB is to illustratively convey the dynamics of the investment's cash flow.

Table 5
Main results of Monte Carlo simulation

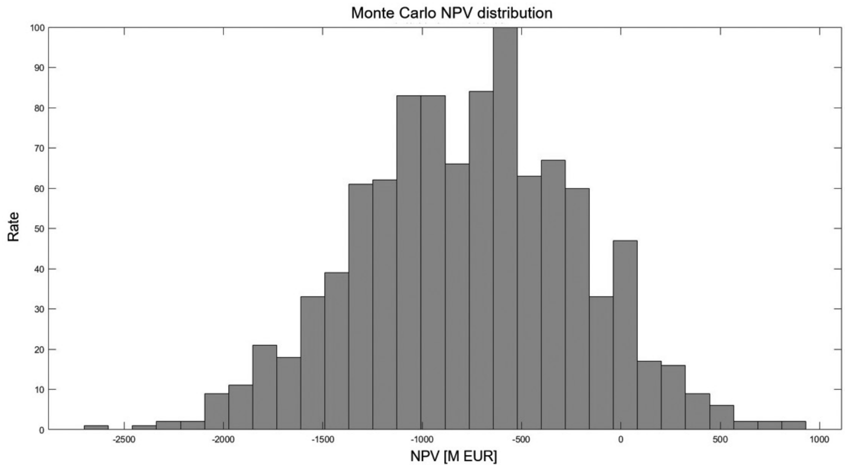
Financial indicator	Average value	Interpretation
NPV	~–764 M EUR	Significant negative value, showing the economic risks of the project
IRR	~5.34%	Average rate of return, the project is expected to be profitable, but not outstandingly
PB	~21,3 years	Assuming a 40-year horizon, it represents an acceptable and realistic payback period

Source: author's compilation

The histogram in *Figure 5* shows the Monte Carlo distribution of the net present value of the investment based on simulations of different uncertainty factors. In most scenarios, the NPV lies within the negative range, and the mode of the distribution also falls in this region. The long left tail extends down to –EUR 2,500 million, indicating the risk of unexpectedly poor outcomes (substantial losses). On the right, positive simulations occur up to +EUR 1,000 million, but their frequency is relatively low, so the probability of achieving a positive return is roughly on the order of 10–20%.

This result is unsurprising, as such asymmetric distributions are typical for projects with high capital costs and long payback periods. The probability of attaining a positive NPV was between 40% and 50%, meaning that the financial success of the investment depends roughly equally on favourable market and technological conditions. The median NPV is slightly negative in most runs, and the 25th–75th percentile range is relatively wide, reflecting the effects of learning rates and price uncertainty. Overall, this distribution exhibits a strong negative skew and asymmetry, indicating an unfavourable risk profile, and the statistical expected value is also negative, meaning that the investment's return is highly uncertain.

Figure 5
NPV distribution for FOAK + 2 NOAK

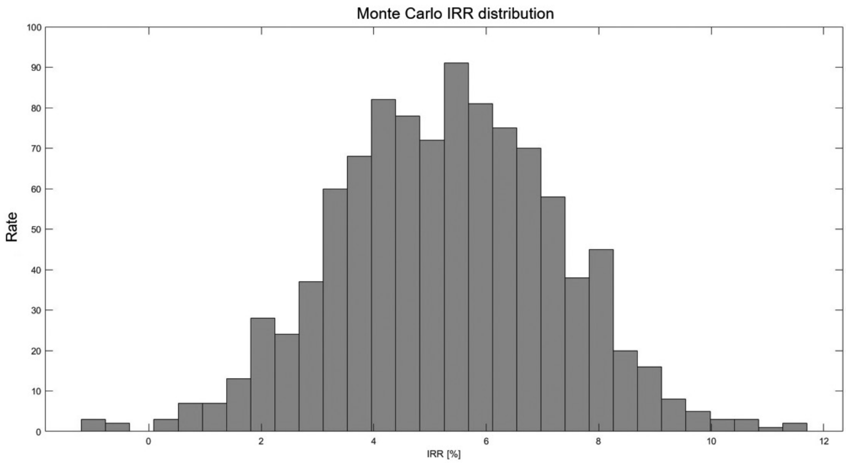


Source: author's compilation

Figure 6 shows the individual IRR values in percentage points and the frequency of occurrence. The distribution shows a density peak roughly between 2% and 8%, with a central value of around 5–6%, meaning that the return profile is largely concentrated around the 8% discount rate. The left tail extends down to –1%, indicating that certain unfavourable scenarios yield a negative internal rate of return, though these cases are relatively rare. The right tail reaches maxima around 10–12%, but IRR above 8% occurs only in a small fraction of cases (approximately 10–15%).

This implies that the project's financial viability hovers around the cost of capital, with only a moderate likelihood of exceptional profits. Consequently, even modest cost increases or revenue decreases could result in a negative NPV. At the same time, the IRR exhibits relatively low standard deviation, indicating that the returns are distributed stably but concentrated around a low average level.

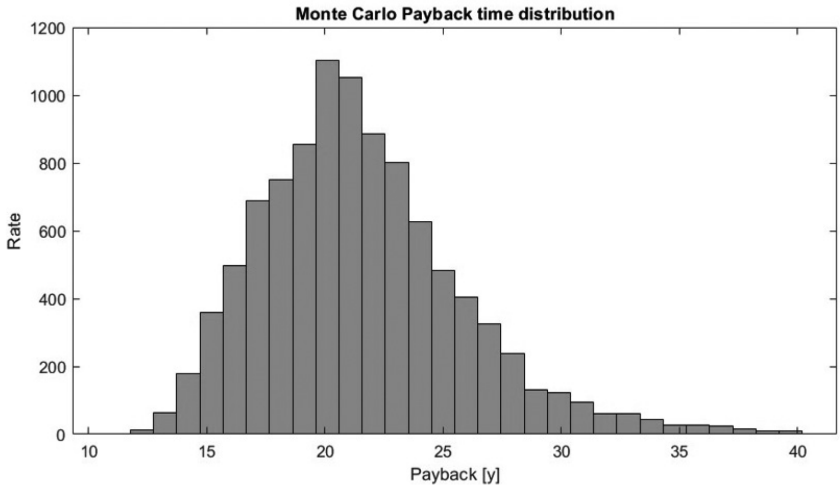
Figure 6
IRR distribution for FOAK + 2 NOAK



Source: author's compilation

Based on *Figure 7*, the static payback period ranged between 15 and 40 years, clearly illustrating the investment's liquidity exposure. Both the mean and median payback periods are 20 years, with the peak occurring approximately between 18 and 21 years, meaning that most scenarios fall within this interval. The 10th percentile is around 15–16 years, while the 90th percentile is approximately 26–28 years. The right-hand "tail," however, extends up to 35–40 years, indicating that in roughly 10–15% of simulations, the payback is considerably slower, often approaching – or even exceeding – the project's lifetime. This relatively wide, right-skewed distribution highlights that although the invested capital is typically recovered within 20 years on average, long payback scenarios carry significant financial risk.

Figure 7
PB distribution for FOAK + 2 NOAK



Source: author's compilation

The profitability of the investments is highly dependent on the sales price and capital structure and carries significant risk. According to the cumulative cash flow curves, at a price of EUR 30/MWh the project never achieves payback, whereas at EUR 70/MWh payback occurs around year 21, followed by a dynamic increase in profits. The wide distribution of static payback periods also highlights the project's liquidity risks, and based on NPV and IRR, the project can only become economically viable under favourable market and technological conditions.

Overall, although certain conditions (high price, high equity share) can yield attractive long-term returns, the projects face a substantial likelihood of negative NPV, moderate IRR, and potentially very slow payback.

3.2.5 The impact of the learning rate on financial indicators

The data in *Table 6* show that the impact of the learning process is mainly through a reduction in investment costs, coupled with improvements in production and licensing efficiency resulting from the experience of previous FOAK projects. According to Monte Carlo simulations, this resulted in an increase in NPV of 30-40% and an increase in IRR of 1-1.5 percentage points, while the payback period was reduced by an average of 2-3 years, which is particularly important for the speed of investment capital turnover and investor risk.

Table 6
Financial indicators at different learning rates

LR [%]	Average NPV [M EUR]	Median NPV [M EUR]	Average IRR [%]	Average return [years]
5	–179,58	–179,13	7,3099	17,258
10	–62,94	–65,358	7,7652	16,56
15	44,879	48,896	8,2009	16,002
20	180,68	172,81	8,7828	15,218

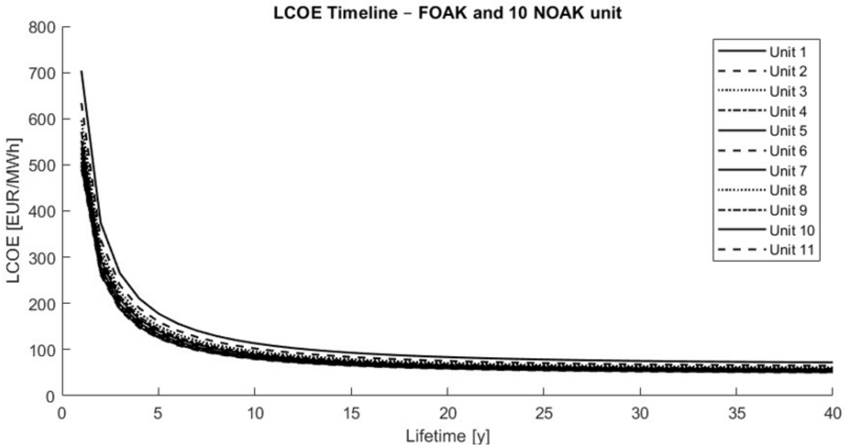
Source: author's compilation

3.2.6 Unit Energy Cost

The curves in *Figure 8* illustrate how the unit energy cost of the FOAK and the first NOAK unit evolves as a function of average operating lifetime. In both cases, values start very high because the capital cost of the investment is initially spread over a short period; as the lifetime increases, the cost declines rapidly and non-linearly. Between the second and fifth years, costs fall into the EUR 250–350/MWh range, around EUR 120–150/MWh at ten years, and drop below EUR 80–90/MWh between 20 and 30 years. The FOAK curve consistently runs slightly above the NOAK curve (reflecting the first-of-a-kind cost disadvantage), but as the investment is amortised, the difference gradually diminishes, stabilising at roughly EUR 65–75/MWh for both cases beyond 30–40 years.

These curves clearly demonstrate that the advantages from technological learning and series production are most pronounced for shorter-lived investments, whereas a long operating lifetime almost entirely offsets the impact of capital costs over the lifespan, meaning that both units achieve competitive unit costs only after 20 years.

Figure 8
Unit Energy Cost (LCOE) for FOAK and NOAK



Source: author's compilation

4. SUMMARY AND RECOMMENDATIONS

Dynamic analyses show that the real payback trajectory of SMR projects is determined not only by unit costs and market prices, but also by the financing arrangements, the degree of the learning curve and the initial risks of the project cycle. Based on the deterministic simulations, at an electricity price of EUR 70/ MWh and a favourable equity ratio, the static payback period is between 20-25 years, which is a realistic target based on the nominal cash flows of the investment. The results of the Monte Carlo analyses, however, indicate that the NPV distribution has a long left tail, and the wide variation in payback periods between 15 and 40 years can significantly affect the project's financial stability, with the probability of a positive NPV around 40–50%. Thus, profit realisation, if it occurs at all, may vary by decades when accounting for the time value of money. The median of the IRR distribution slightly exceeds 6%, but a standard deviation of around ±2% and the presence of negative outcomes highlight that investors will require comprehensive risk management strategies, financial buffers, and flexible rescheduling of the project lifetime beyond conventional price–cost models. The analysis confirmed that the learning curve parameters have a decisive impact on the projects' economic indicators. At a 15–20% learning rate, NPV and IRR values approach the threshold of commercial viability, whereas at lower rates (5–10%), projects typically remain sustainable only in a subsidised environment.

Accordingly, it is essential for both policymakers and investors to compensate for market and technological uncertainties through targeted measures. First, long-term PPA contracts of at least 20–25 years should be established, with rates fully covering the cash flow requirements justified by the investment. In addition, state loan guarantees, investment tax incentives, and risk capital injections – potentially in the form of repayable, partially incentivised grants – are fundamental to ensuring that private capital can be proactively engaged during the FOAK phase. For subsequent units, the learning curve can be deliberately maximised through standardised modular manufacturing and the consolidation of the supply chain, while standardised construction and commissioning schedules can minimise the financial burden of delays.

As an additional recommendation, it is advisable to implement a financial stress-test protocol that regularly examines extreme fluctuations in key parameters – development and operational costs, interest rates, and market prices – and enables the adaptation of best practices. Engaging the insurance market, specialised credit and contract-disruption (delay-risk) insurances should be established to provide coverage even under the highest construction and licensing risks. Communication campaigns and local partnership models that build social acceptance are also important, as they can reduce hostile local pressure and strengthen medium- and long-term operational stability.

In the energy transition, SMR technology can play a sustained role only if operational, maintenance, and fuel-cycle costs continue to improve. Establishing a joint industry–research consortium is recommended. This would ensure the collection of empirical data from actual NOAK projects, continuous updating of learning-curve parameters, and the development of new business models, such as Energy-as-a-Service. In this way, financing models would function not as static instruments but as adaptive tools, ensuring long-term competitiveness even in more complex market and technological environments.

Limitations and future research directions

The models presented, together with the associated financial risk analysis, enhance the transparency of the technology's investment conditions; however, future research should prioritise the integration of innovative financing mechanisms – such as green bonds and ESG-based financial instruments – and their extension to capture changes in the geopolitical and regulatory environment. The discount rate applied by us in all scenarios was a fixed 8%. Although the WACC would in reality vary depending on the financing structure, using a fixed rate enabled a consistent comparison of the effects of different capital structures. The empirical validation of the technological learning curve based on actual investment data is likewise necessary, and further development of the electricity price modelling through dynamic, time-dependent market analyses could reveal the implications of alternative future energy market scenarios.

In the model, the PB is based on non-discounted cash flows and therefore appears as a nominal value. This approach illustrates the investment's liquidity profile but does not substitute for discounted indicators such as NPV or IRR. Calculating a discounted PB may offer a useful direction for future research. The model focuses explicitly on financial indicators and does not account for social, environmental, or security-of-supply considerations.

Given the complexity of such investments, future research would benefit from developing a dynamic version of the model that incorporates the temporal evolution of the learning rate, the adaptive changes in financing parameters, and the cyclical movement of energy prices. Integrating these factors could expand the analysis towards comprehensive decision-support applications.

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