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Future nuclear fission reactors – uncertainties, the effect of parameter choice and an application to small modular reactor concepts

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Future Nuclear Fission Reactors – Uncertainties, the Effect of Parameter Choice, and an Application to SMR Concepts

Abstract

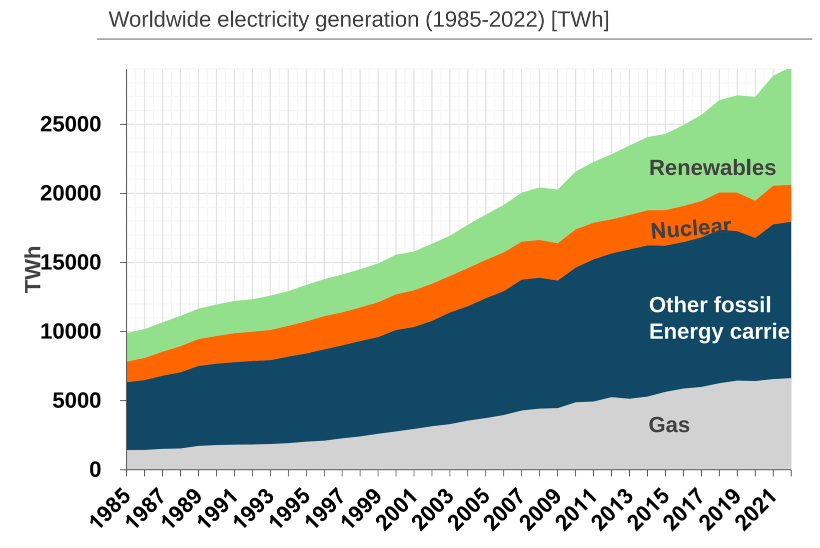
- Declining generation costs of renewable energy systems driving a paradigm shift in energy systems across the world. On the other hand, OECD countries still spend about 21% of total research and development expenditures on nuclear developments alongside the current discussion in recent literature about the role of new nuclear developments in combating the recent energy crisis and climate change.
- In this paper, we introduce the current state of knowledge about cost developments for high- and low-capacity reactors with an application of SMR concepts to draw a picture of the current understanding of the costs of future nuclear energy developments.
- In the case of SMR concepts we follow *Steigerwald et al. (2023)* and introduce two different approaches in comparison of current manufacturer advertised costs for 15 concepts with sufficient available data. Finally, we apply the Monte Carlo method to benchmark the cost projections assumed by the manufacturers by varying production parameters in simulations of the net present value (NPV) and the levelized cost of electricity (LCOE).
- We conclude that any technology foresight has to take the case specifics into account as much as possible, including technological and institutional specifics; this also holds for SMR concepts. It seems to be that future nuclear technologies are not able to compete with renewable energy technologies.

Contribution

- Classification of nuclear energy in the current energy system
- Overview of current cost developments for high-capacity future reactor technologies and low-capacity so-called SMR concepts
- Introduction of different functional forms applied in literature and a large data set consisting of both producers' and other publicly available data
- Large-scale Monte Carlo analysis of potential net present values (NPV) and levelized costs of electricity (LCOE)
- Application of a variance-based sensitivity analysis for the Monte Carlo simulation

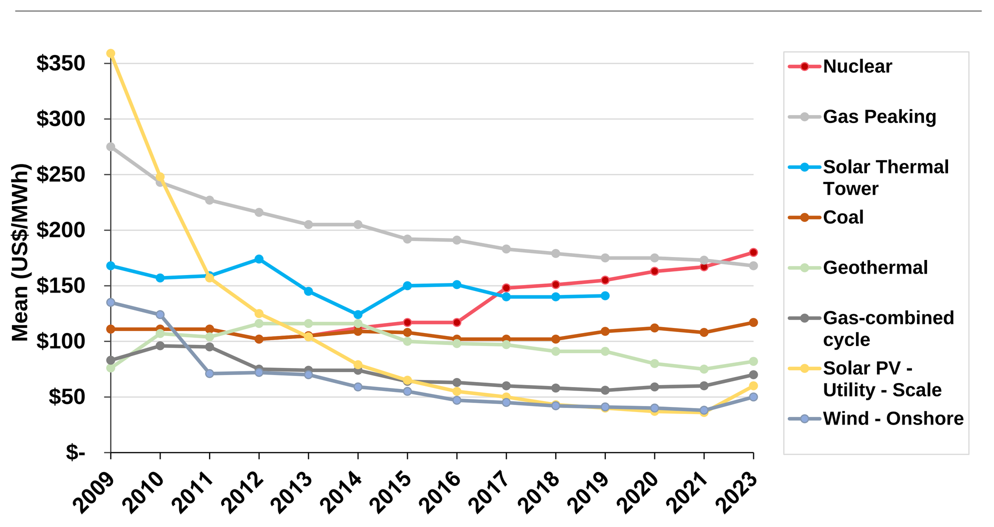
Nuclear Technologies – Status

Worldwide electricity generation (1985-2022) [TWh]



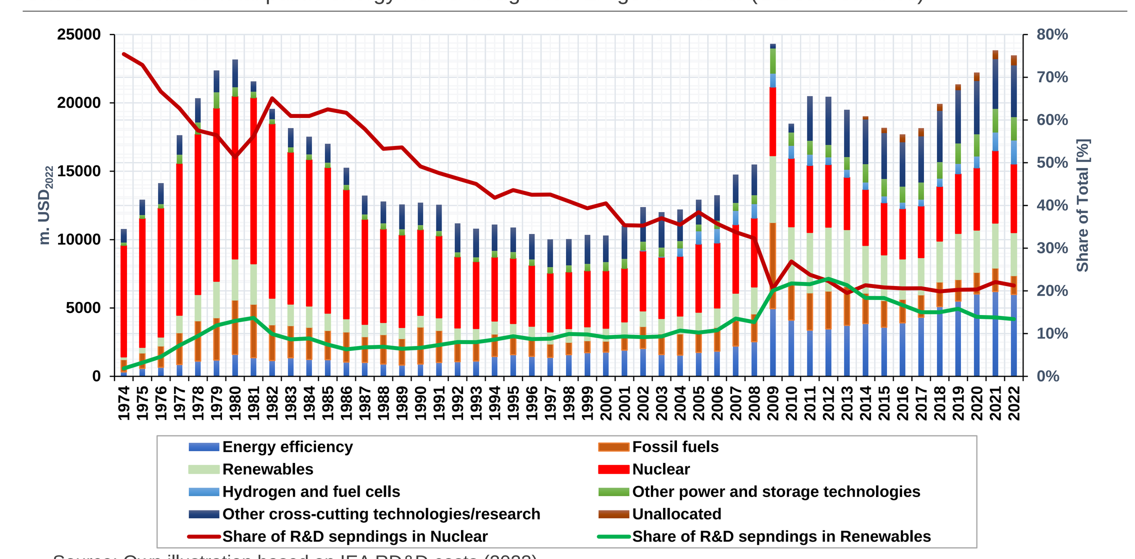
Source: Own illustration based on Energy Institute, Statistical Review of World Energy (2023)

Selected historical mean unsubsidized LCOE values



Source: Own illustration based on LAZARD LCOE Analysis (2023)

Share of estimated total public energy RD&D budget for IEA governments (OECD countries)



Source: Own illustration based on IEA RD&D costs (2023)

Cost Assumptions for Future Technologies

High-capacity Reactors

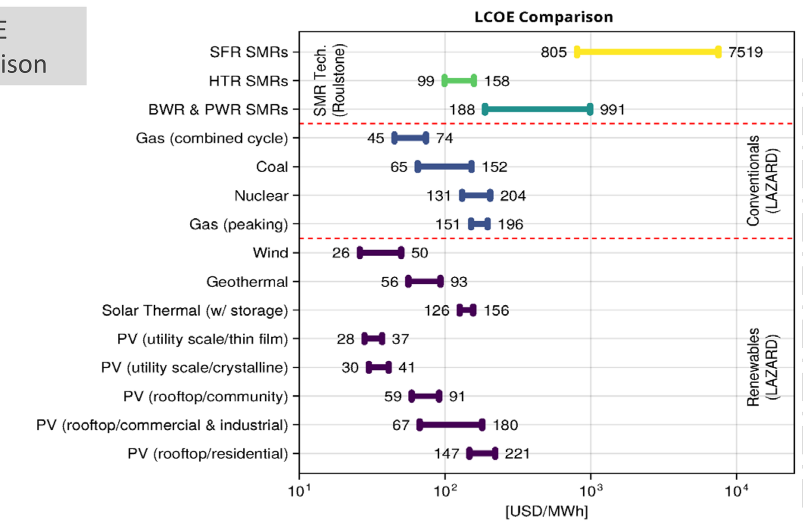
Water-cooled Reactors	• Issues through long construction times and increasing costs of current projects
Sodium Fast Reactors (SFR)	• Capital costs typically higher than current LWR, operation costs with a disadvantage due to the need of fuel reprocessing and higher cost of MOX fuel fabrication compared to current LWRs. • Operation continues to point to high investment risk, since even simple event sequences can trigger longer-term plant shutdowns or even premature decommissioning. • All in all, it can be assumed that SFRs have an intrinsic disadvantage compared to LWRs in terms of economic efficiency.
Lead-cooled Fast Reactors (LFR)	• No detailed cost estimates known for construction and operation of LFR, high risks for capital providers. • Cost advantages over SFRs are possible through simpler design and by not using an intercooler loop. Using a more compact and simpler design, LFRs would have a potential cost advantage over LWRs, using an open fuel cycle. • Overall, a significant advantage or disadvantage of LFRs over LWRs is not expected.
Gas-cooled Fast Reactors (GFR)	• Developers point to improved economy due to a possible higher efficiency as a major advantage, especially through the usability for high-temperature applications (e.g., process heat) - the feasibility of this is still largely open at present. • Reliable information about investment requirements, construction times, operating costs, design life, and utilization are missing - there is no comparable experience to date.
Molten Salt Reactors (MSR)	• Reliable statements about investment requirements, construction time, operating costs, design life, and capacity utilization are missing - there is no comparable experience to date.
Very High Temperature Reactors (VHTR)	• Potential advantage through its possibility for cogeneration and process heat production depending on the temperature, compared to LWR. • Since the investment costs for LWR are highly dependent on the manufacturer and the country of construction, and at the same time the costs of VHTR are highly dependent on the possibility of using the process heat, ultimately, no final evaluation can be made at the technology line level.
Supercritical Water Reactors (SCWR)	• Higher efficiency of the reactor system in the range of 45% compared to today's LWRs in the range of approx. 35% and possible savings in investment costs estimated at approx. 20% will result in cost advantages compared to today's LWRs if the open material problems can be solved at moderate costs. • Cost effects due to the more complex fuel assembly design cannot be estimated at the technology line level, but it can be assumed that these do not outweigh the advantages mentioned.
Accelerator-driven Supercritical Systems (ADS)	• Possible power regulation without the criticality condition, advantages exist over LWR and the other technology lines in the integration with other fluctuating energy sources. • Additional costs for the construction of the accelerator and the spallation neutron source and their operation. A part of the generated electricity is used for the operation of the facility. This leads to higher costs compared with LFR and additional risks through missing experience so far.

Source: Pistner et.al. (2023): Analyse und Bewertung des Entwicklungsstands, der Sicherheit und des regulatorischen Rahmens für sogenannte neuartige Reaktorkonzepte

Low-capacity Reactors

Current Status	• 6 demo projects in China and Russia seem to be Online • Cost increases seem to be typical for demo facilities and planned projects
Data	• A unique dataset of 19 SMR concepts together with fuel and O&M cost assumptions is available
Theory	• Recomputation of current concept data delivers a difference between cost assumption and manufacturer costs • The parameter choice seems to make a difference
Investment Decision	• Introduction of two comparative metrics: Net Present Value and Levelized cost of Electricity • Simulation of a possible project lifetime with the help of Monte Carlo simulation
LCOE Comparison	

LCOE Comparison



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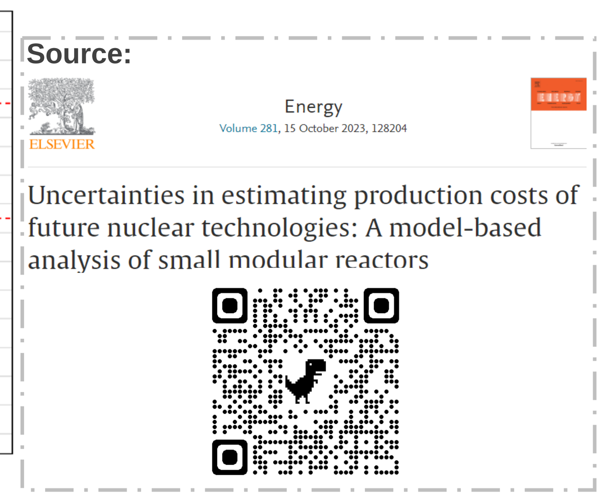


Source: Steigerwald et.al. (2023): Uncertainties in estimating production costs of future nuclear technologies: A model-based analysis of small modular reactors

Application of SMR Concepts

Two approaches to estimate production costs with respect to influencing cost-decreasing effects

Introduction of two approaches from literature to describe basic production theoretical effects

Roulstone et al. propose a simple model with c for costs, a constant scaling parameter β, a learning rate x, a factor $d(n) = \log(n)/\log(2)$ that considers the doubling in production with $n \in \mathbb{N}$ being the number of units produced and p for the plant's power output:

(1) $c_{smr} = c_{lr} * \left(\frac{p_{Smr}}{P_{lr}}\right)^{\beta}$ and $c_{smr,n} = c_{lr} * \left(\frac{p_{Smr}}{P_{lr}}\right)^{\beta} * (1-x)^{d(n)}$.

Rothwell suggests attaching specific, size-dependent weights to the scaling parameter γ (all other variable definitions as in Eq. (1)):

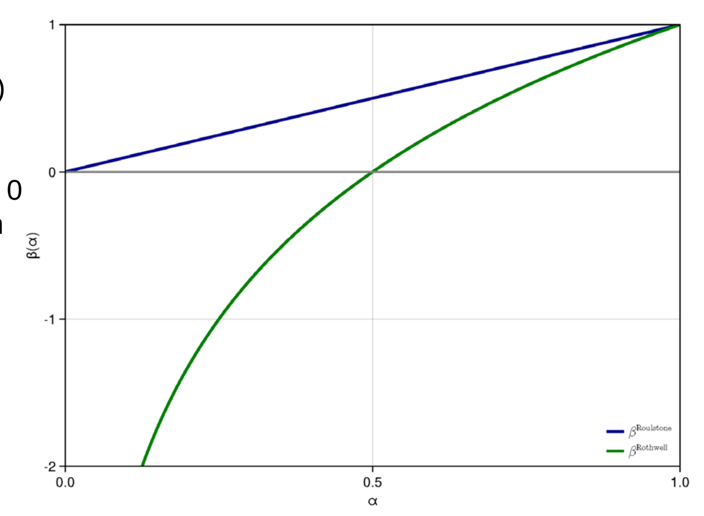
(2) $c_{smr} = c_{Lr} * \left(\frac{p_{smr}}{p_{lr}}\right) * \gamma^{(\ln p_{Smr} - \ln p_{lr})/\ln 2}$ and

$c_{smr} = c_{Lr} * \left(\frac{p_{smr}}{p_{lr}}\right) * \gamma^{(\ln p_{Smr} - \ln p_{lr})/\ln 2} * (1-x)^{d(n)}$

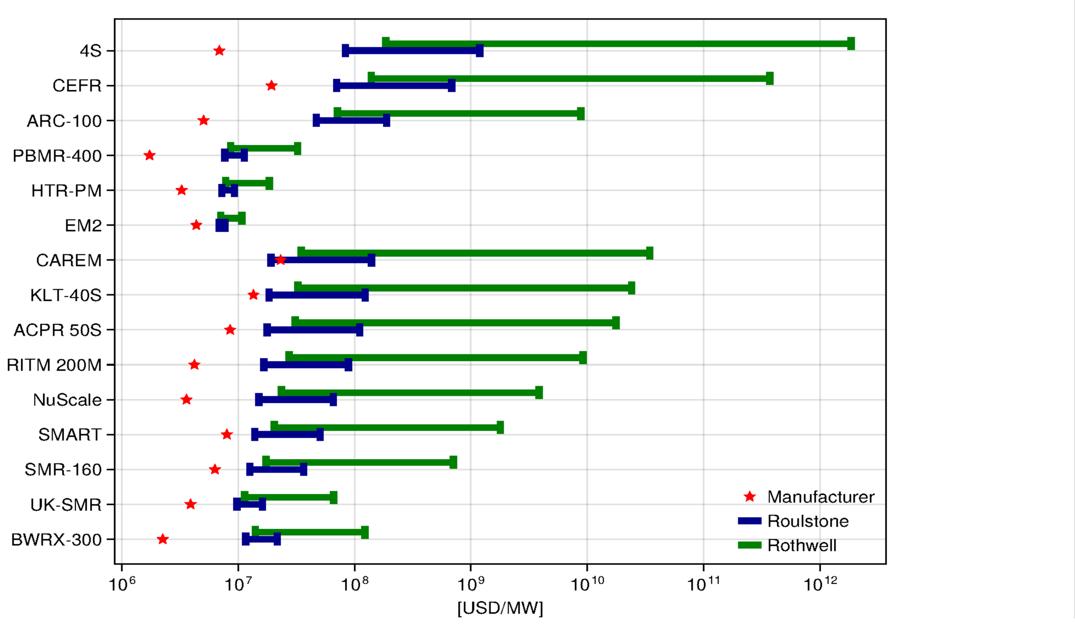
Comparison of both in respect to the scaling factor

Observations:

For $\beta = 0$ (corresponding to $\gamma = 0.5$) the construction costs, derived from Eq. (1) coincide with the cost c_{lr}, whereas in the limit when γ tends to 0 the construction costs obtained from Eq. (2) diverge. In particular, for sufficiently small values of $\gamma > 0$ the construction costs, c_{smr}, may even become larger than the cost of the reference reactor, c_{lr}, which would render the investment fully uneconomical compared to the reference reactor



Comparison of estimated costs and manufacturer advertised costs delivers a gap

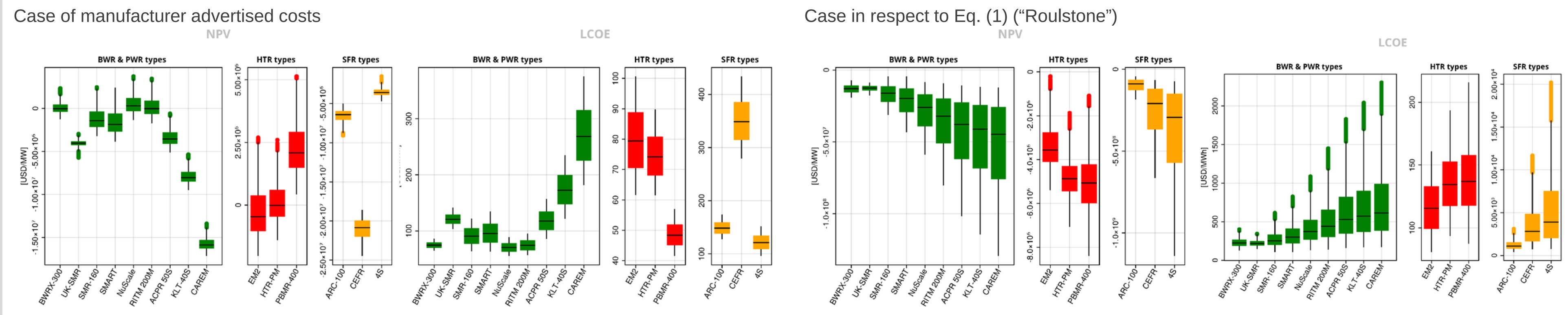


Simulation Results & Conclusion

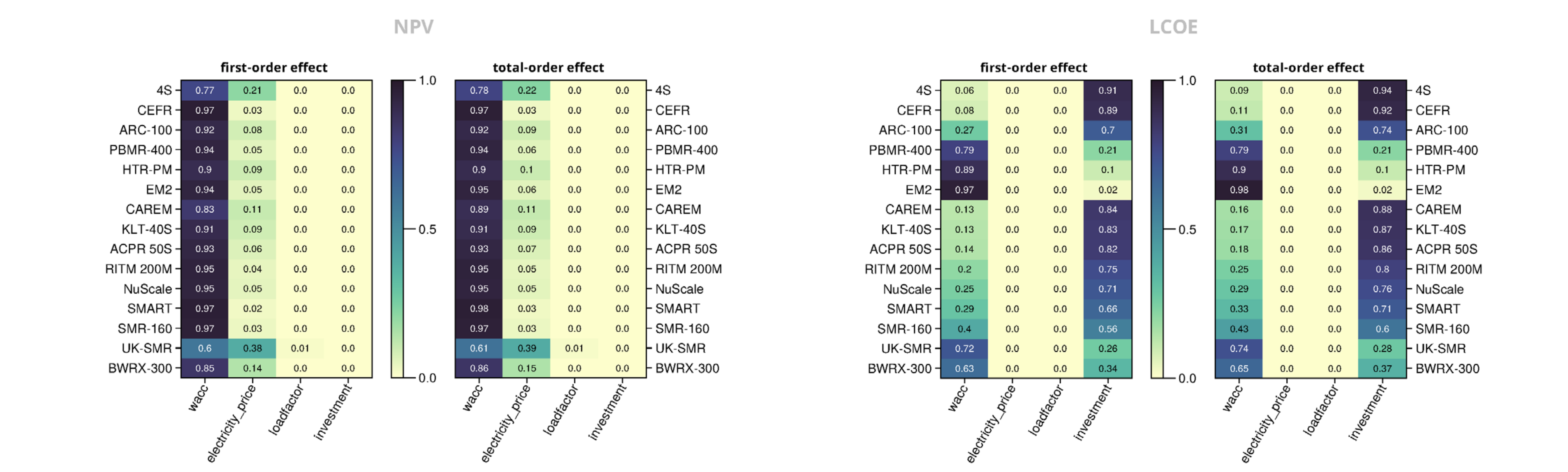
Simulation of the NPV and LCOE with Monte Carlo delivers…

Case of manufacturer advertised costs

Case in respect to Eq. (1) ("Roulstone")



Results of variance-based sensitivity analysis



Conclusion

- Currently, nuclear energy has a share of about 10% in the global energy system and is associated in current literature with the problems of longer construction time and cost increases. The research expenditure of the OECD countries for energy technologies is 21% for nuclear energy.
- In the case of high-capacity future nuclear concepts, Pistner et al. (2023) describe risks and cost uncertainties with a tendency to be able to compete against current water-cooled reactor designs.
- In the case of low-capacity reactor concepts, Steigerwald et al. (2023) assembled a large dataset consisting of both producers' and other publicly available data. Different functional forms applied in literature were identified, together with significant gaps between current cost estimations by theory and manufacturer-advertised costs.
- A large-scale Monte Carlo analysis of potential net present values (NPV) and levelized costs of electricity (LCOE) finds that the majority of examined SMR concepts cannot deliver a positive NPV or an energy system competitive LCOE.
- The variance in the simulations can be in the largest part explained by the variance of the investment costs and the WACC, whereas the load factor and the electricity price play a minor role.
- In summary, neither high-capacity concepts nor low-capacity ones seem to be competitive with renewable technologies at present.

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