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Review

Questioning nuclear scale-up propositions: Availability and economic prospects of light water, small modular and advanced reactor technologies

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ABSTRACT

This paper addresses the pressing need for rapid decarbonization of energy systems by examining the role of nuclear power in future energy scenarios collected in the IPCC database. Despite their explorative character, energy scenarios can influence decision-makers or might be used to promote certain technology developments. They are increasingly subject to the integration into real-world settings and thus the need for feasibility assessments has emerged in literature. The case of nuclear power is of particular interest, for which proponents project steep capacity increases, whereas literature shows a technology in decline. The paper investigates this discrepancy and questions the nuclear scale-up in energy scenarios by investigating proposed technology scale-up thresholds for low carbon scenarios. By doing so, it moves beyond the often-applied aggregate view of nuclear power and explores the techno-economic feasibility from a reactor-technology-specific lens. Three reactor technologies are chosen: currently dominant high-capacity light water reactors, small modular reactors, and non-light water-cooled reactors (so-called "new" or "advanced" reactor concepts). Results indicate that none of the currently proposed reactor technologies are fit for necessary rapid decarbonization due to availability constraints and economic challenges. We further suggest the adaptation of proposed thresholds to absolute metrics based on energy generation and towards the inclusion of a sub-technology specific perspective. Overall, the need for further scrutiny of energy scenarios, particularly concerning nuclear power, is emphasized in order to prevent instrumentalization by political and industry actors.

1. Introduction

The urgency of climate change requires a rapid decarbonization of energy systems until 2050 [1]. In this context, energy scenarios are a useful tool to explore variations of future energy systems and show possible pathways towards the achievement thereof [2]. However, despite their explorative character, energy scenarios can influence decision-makers or might be used to promote certain technology developments [3,4]. Consequently, energy scenarios are increasingly subject to attempts to be integrated into real-world settings. The assessment of the feasibility of such implementations has thus emerged in literature [5–7].

The role of nuclear power in future energy systems is especially controversial. While some research suggests that future energy systems can function with renewable energies only, such as wind and solar [8–10], others include nuclear power as an option [11–13] or even as a required complement to renewables [14,15]. Experience however shows nuclear power to be a technology in decline, and a nuclear industry that will likely not be able to live up to expectations of a rapid capacity scale-up [16,17].

Nonetheless, proponents envision a substantial nuclear scale-up by establishing "novel" technologies, including concepts for so-called

Abbreviations: ADS, accelerator-driven system; AEC, Atomic Energy Commission; B&W, Babcock & Wilcox; CAREM, Central Argentina de Elementos Modulares; EPR, European Pressurized Water Reactor; GFR, gas-cooled fast reactor; IAEA, International Atomic Energy Agency; IAM, integrated assessment model; IEA, International Energy Agency; LCOE, levelized cost of electricity; LFR, lead-cooled fast reactor; LWR, high-capacity light water reactors; MSR, molten-salt reactor; NEA, Nuclear Energy Agency; OCC, overnight construction costs; pp, percentage point; SCWR, supercritical water-cooled reactor; SFR, sodium-cooled fast reactor; SMR, small modular reactor; SNR, so-called new reactor concept; TCC, total construction costs; (V)HT(*G*)R, (very) high temperature (gas-cooled) reactor.

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"small modular reactors" (SMRs) or so-called "new" and "advanced" non-light water reactors (SNRs), and thus hope to reverse the current trend of decline [18,19]. This is shown by a recent declaration of 22 countries at COP28, that pledged a tripling of today's installed nuclear capacity by 2050 [20]. Especially SMRs are anticipated to accelerate the deployment and reduce costs compared to high-capacity light water reactors (LWR) [21,22]. Such plans and underlying expectations should be treated with caution as nuclear power has often been subject to overly optimistic scale-up expectations in the past, which the industry has failed to deliver upon [23,24].

Given the discrepancy between expectations of a rapid nuclear scale-up and the deficient state of the international nuclear industry, this paper aims to shed light on the proposed nuclear scale-up within the context of future decarbonization of electricity generation and thus contributes to techno-economic feasibility studies within low-carbon scenarios. The paper first explores possible nuclear future scenarios from the IPCC database for electricity generation until 2050 and contrasts these with nuclear scale-up thresholds proposed in literature [6]. Second, since related literature is often characterized by lack of rigor and research designs [25], this paper proposes a framework to assess the techno-economic feasibility of energy generation technologies in the context of energy system decarbonization. Because current literature, especially in the context of nuclear power, often applies an aggregated assessment, this paper provides a sub-technology-specific application of the proposed framework by accounting for three nuclear sub-technologies: high-capacity LWRs, light water based SMRs, and SNRs, i.e., non-light water technologies. From the current state of knowledge, each technology is reviewed following the proposed framework. The analysis focuses on key technological development and availability as well as economic characteristics. Future research can build upon this framework for other technologies, such as renewables, but also for further in-depth, more technology-specific assessments of, e.g., SNRs. The results of our analysis further indicate that above-mentioned nuclear scale-up thresholds should be revisited.

2. Background

2.1. The role of nuclear power in long-term energy scenarios

Energy scenarios do not aim to forecast future development, they instead describe variations of future energy systems. They can be derived either from bottom up energy planning or from a top-down approach, pursued by integrated assessment models (IAM) [2]. Although scenario output is not deemed to be accurate, they influence expectations of decision-makers [3,4]. Furthermore, energy scenarios are often used to promote certain developments in favor of certain actors [3]. Especially goal-orientated scenarios, such as those defined in the context of climate change mitigation, are inherently normative and thus linked to assumptions [26]. Therefore, decision-makers must understand underlying assumptions and limitations of individual approaches [27], and they should stress scenario sensitivities before drawing conclusions for real-world applications [28].

Since the beginning of long-term energy planning, nuclear power has played a prominent role because of expected technical development and envisioned economic efficiencies. For example, expectations in the 1950s and 1960s counted on reactors with fast neutron spectra[1] to deliver energy "too cheap to meter" [31] in what Seaborg [32] called the "plutonium economy". A significant increase in nuclear power generation was expected within the industry and in energy system modeling. For instance, one of the main conclusions of the 1981 "World Energy Model" of the International Institute for Applied System Analysis was the vast expansion of nuclear capacity, and the replacement of LWR capacity with fast reactors from the 2000s and 2010s onwards [33]. At the time, the model was criticized regarding the robustness of results, non-transparency of assumptions, and unsatisfactory documentation of data [34,35]. A sensitivity analysis for the US and Canadian energy systems revealed that a 16 % increase in nuclear power costs would change the original outcome completely and would result in no new fast reactor constructions and a decline of LWR capacities leading to a phase-out by 2030 [3]. Regardless, nuclear power is currently experiencing a new momentum of a proposed nuclear scale-up, which again includes technological optimism that anticipates SNRs, sometimes also called "advanced" or "Generation IV" reactors, to play a major role in decarbonized energy systems, e.g., IAEA [18], IEA [36], Duan et al. [14], and Hirschhausen et al. [37].

This momentum becomes apparent when climate mitigation pathway scenarios, gathered by the AR6 report of the IPCC [26] are examined. Figs. 1 and 2 show the projected development of the absolute electricity generation from nuclear power and its share of total electricity generation from 2020 to 2050 from 94 scenarios of the category "C1" (1.5 °C-limitation scenarios) [38], respectively. The opaque band surrounding some lines depicts the range of scenario results from a given model. 77 of these scenarios result in an increase in absolute electricity generation (TWh) from nuclear with an average annual increase of 3 %. Fig. 1 further depicts the average development of global electricity generation over the last 20 years [39,40] and the development following the announced tripling of nuclear capacities [20] (assuming an analogous increase in energy production) as dotted and dashed lines, respectively. However, for the nuclear share over the same timeframe, 63 scenarios depict a decline due to an increase in absolute electricity production. Fig. 2 also shows proposed thresholds by Brutschin et al. [6], whose transgression would merit further scenario scrutiny, marked as dotted and dashed lines, respectively, which will be discussed in Section 2.2.

The figures show that several scenarios, such as those based on the WITCH-GLOBIOM model, project a rapid ramp-up of nuclear generation, and thus a steep rise of the share of nuclear until the 2030s, while others, such as the REMIND-MAgPIE scenarios, project a steady decline in the share, albeit a rather consistent increase in absolute electricity generation from nuclear. The differences between scenarios rely on model specifications and assumptions.

For example, some models acknowledge ongoing cost decreases of renewables and apply more conservative assumptions on future nuclear costs resulting in a decreasing share of nuclear power and very high shares of renewables [9,41,42], while assumptions leaning towards an optimistic view of nuclear power consequentially lead to higher shares of nuclear in electricity generation [13–15].

The current nuclear momentum in decarbonization can also be observed in projections made by international organizations such as the International Atomic Energy Agency (IAEA) [18] or the International Energy Agency (IEA) [36]. These projections must be separated from IAMs as they are based on projections from international organizations, national estimates from individual countries, and expert groups. For example, the low-case projection in IAEA [43] assumes that current trends of nuclear development, i.e. at best a stagnation of total installed capacity, will continue. In contrast, the high-case projection considers policy adaptions towards rapid decarbonization through vast nuclear capacity expansions, see Fig. 3.

These projections aim to give technically feasible forecasts of nuclear development and do not reflect the target of remaining within a certain carbon emission limit [43]. While the low-case represents more of a forecast based on status-quo, the high-case rather seems to aim at shaping expectations. Other international organizations such as the Nuclear Energy Agency (NEA) of the OECD also envision a substantial nuclear scale-up [44]. This view is shared by the nuclear industry itself

[1] Literature often refers to these reactor types as "fast breeder reactors" because they can breed plutonium, which then could be reprocessed and used in Mixed-Oxide Fuel (MOX-fuel). This in turn would reduce the use of natural uranium [29,30]. For the remainder of this paper, we refer to these reactors as "fast reactors".

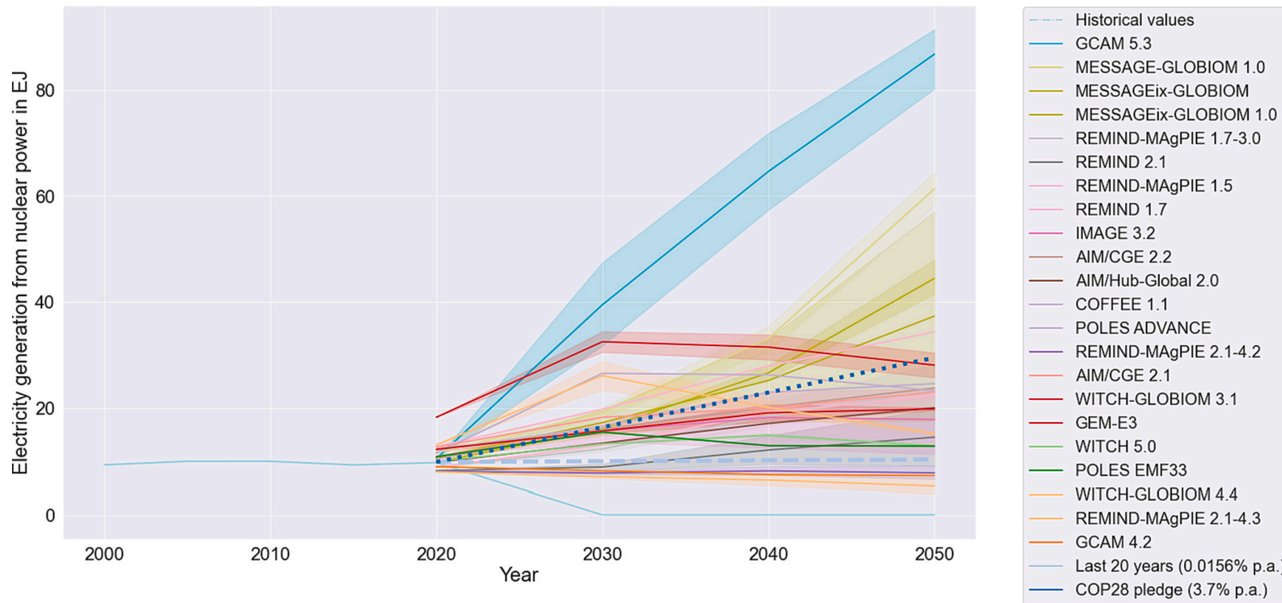

Fig. 1. Electricity generation from nuclear power in 1.5°-scenarios (Category C1), historical development, the corresponding extrapolated trend and the recently announced COP28 pledge to triple nuclear power capacities.
Sources: [20,38–40].

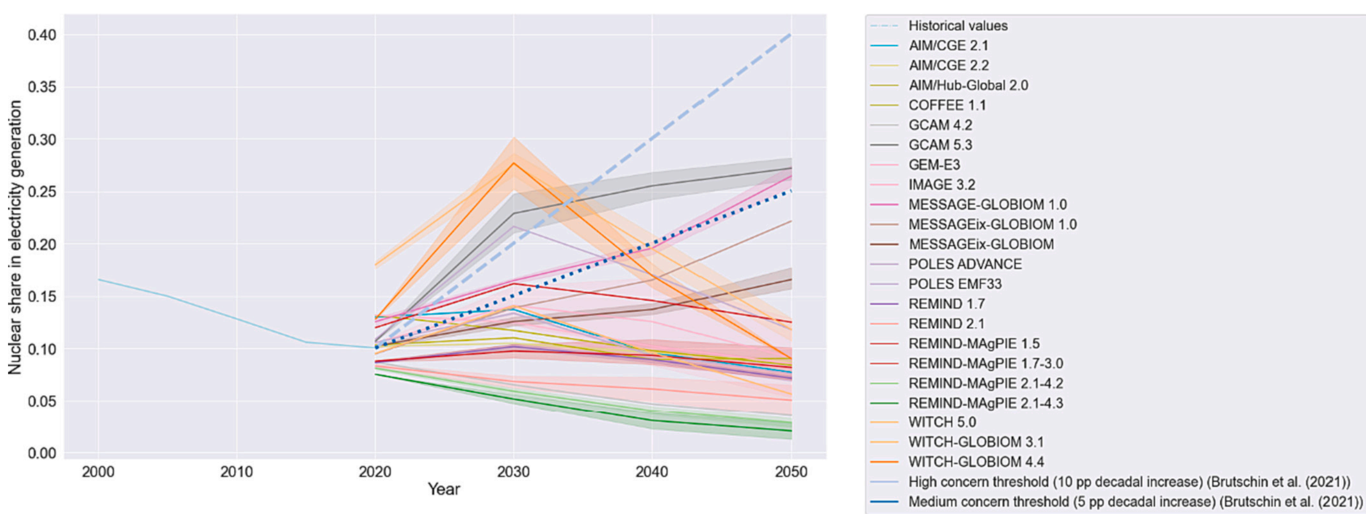

Fig. 2. Share of nuclear in electricity generation in 1.5°-scenarios (Category C1), historical development, and thresholds of feasibility concern.
Sources: [6,38,40].

[45,46] and, as recently prominently demonstrated, political decision-makers around the world [20]. However, projections of a substantial nuclear scale-up have been overly optimistic in the past and have never become a reality [23].

As seen above, the role of nuclear power in future energy systems is heterogeneous amongst models and projections, varying from a strong-growth future to a strong decline. Beyond 2050, only a few scenarios in the IPCC database project a nuclear phase-out [38]. To conclude this section, we introduce the Global Energy Assessment Report of the Council of the International Institute for Applied System Analysis. The report consists of energy pathways that limit global warming to 2 °C, enhance energy security, reduce pollution, and increase energy access. Including a heterogeneous array of nuclear development scenarios, it concludes that the consideration of nuclear power for energy system decarbonization is "a choice, not a requirement" [47] while highlighting uncertainties about future development as well as unresolved issues with proliferation risks. Challenges of radioactive waste management and decommissioning, social implications of the use of nuclear power, and the risk of accidents add to this complexity [48–50]. The role of nuclear power in future energy scenarios and agency projections results from heterogeneous modeling and data assumptions that must undergo in-depth reviews and rigorous assessments that should be further developed in future research.

2.2. Feasibility studies in low carbon scenarios with a focus on nuclear power

As stated above, energy scenarios shape expectations of a possible future and are thus valuable foundations to explore possible energy futures, but have also been subject to feasibility debates for decades, albeit a lack of clear definitions of terminology and methods [51]. However, this topic is relevant for decision-makers who draw conclusions from these scenarios, necessitating the assessment of a given scenario's feasibility in terms of policy, economics, technological development,

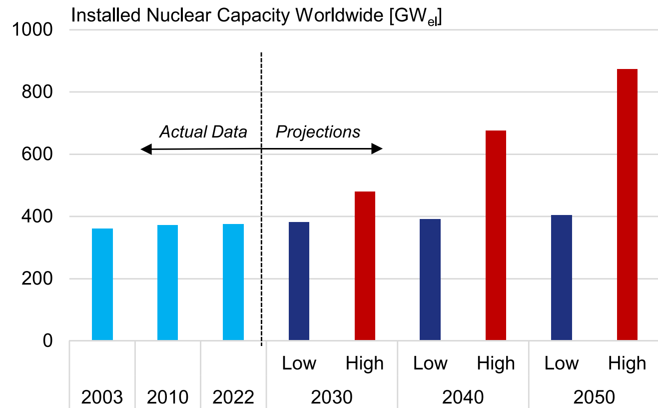

Fig. 3. IAEA projections of global nuclear capacity development.
Source: Own depiction with data taken from [39,43].

and other factors. Within literature, growing interest in assessing the feasibility of such energy scenarios, in particular IAMs, has been identified [6]. Here, a feasible option can be understood as "do-able under realistic assumptions" [51]. Thus, the assessment of feasibility is the evaluation of different types of constraints of development, such as economic, social, technological, environmental, or political. This evaluation can be done by either analyzing underlying modeling assumptions or by benchmarking model output data with current knowledge [6].

For the latter, Brutschin et al. [6] developed a multidimensional feasibility framework to assess low-carbon scenarios. Within this framework, one dimension assesses technology constraints which are represented by an indicator that constrains a technology scale-up. Regarding nuclear power, the authors propose two thresholds whose transgression in scenario results would trigger further scrutiny: a "medium concern threshold" for a "decadal percentage point [(pp.)] increase in the share or electricity generation" of 5 pp., and a "high concern threshold" of 10 pp. [6].

The thresholds were derived from two main ways of reasoning. First, nuclear power, foremost high-capacity LWRs, can be characterized as a "lumpy" technology. A technology is "lumpy" when it is characterized by high-capacity units, high investment costs, and an increased likelihood of upscaling in unit size, all in all unfavorable prerequisites for rapid decarbonization. In contrast, the deployment of "granular" technologies, such as solar and wind, that are less capital intensive and have shorter diffusion times, is better suited for the acceleration of decarbonization efforts [52]. Secondly, the nuclear industry is in decline globally, due to, e.g., its lack of economic competitiveness in liberalized energy markets, shrinking actor bases, mainly in OECD countries, and technological challenges [16,17]. However, the selection of the thresholds at 5 and 10 pp., respectively, seems to have been conducted arbitrarily. When applying these thresholds to IPCC energy scenarios of category C1 (see Fig. 2 as dotted and dashed lines), one can observe that almost none of the scenarios cross the thresholds, although some of them project a steep increase in nuclear electricity generation (see Fig. 1). The selection of the share of nuclear power in electricity generation seems less well suited for threshold definition than absolute values because a steep increase in absolute nuclear power generation could still result in a decreasing share if total electricity generation rises at a faster rate [53].

The use of varying metrics in literature requires caution when interpreting growth rates for technology scale-ups. For example, Vinichenko et al. [54] compare the technology scale-up in different countries by using a relative metric called "electricity production per electricity systems size". They conclude that nuclear power has in some cases experienced stronger growth rates than wind and solar, referring to, e.g., the specific case of the French Pressurized Water Reactor program in the 1980s. However, these results depend on a very specific national context at that time (e.g. state-owned companies, industrial capacities for manufacturing main reactor components and the entire nuclear fuel cycle) and thus may not be reproducible in other countries or even in France today [55]. Loftus et al. [56] review low-carbon studies and use (normalized) deployment rates (GW/year per $GDP) to provide a comparison with historical patterns. Regarding nuclear, they find that even the most ambitious scenarios (15–40 GW/year or 0.2–0.6 GW/year/$GDP) are in line with historic experiences. In contrast, Lovins et al. [53] point out that relative metrics are useful to compare different countries, but for a technology-based comparison, absolute generation values are more suitable. Furthermore, the authors show that regarding absolute values, renewables have historically outpaced nuclear. Feasibility studies thus use different metrics, which complicates the comparison of results, and additionally focus on contextual historical experiences of deployment with limited reproducibility.

Furthermore, nuclear is often viewed from an aggregate perspective or focuses solely on high-capacity LWRs. This can also be observed in most energy scenarios, although some scenarios and models do account for different reactor technologies [57]. Therefore, this analysis contributes to literature by providing a nuclear sub-technology-specific perspective to assess whether SMR and SNR technologies can contribute to a nuclear-scale up or whether their prospects might require the adoption of existing nuclear scale-up thresholds.

Lastly, the feasibility of nuclear power expansion can also be assessed by evaluating newcomer countries, in which factors such as financial and political capacities play a role [5]. However, the here presented analysis focuses on the global perspective.

3. Methodology

Following Brutschin et al. [6], a feasibility assessment can be conducted by benchmarking model output data with the current state of knowledge. The analysis described in Section 4 aims to provide the state of knowledge for nuclear power from a sub-technology-specific perspective. Fig. 4 demonstrates a stylized description of the methodology that was used in this analysis.

Firstly, energy scenario outputs should be assessed regarding the transgression of feasibility thresholds or whether there might be reasons for concern, e.g., in contrast to current development trends. If so, a second step should consist of the assessment whether the deployment of other sub-technologies would affect the initial assessment. Such a technology-specific lens can help to evaluate a proposed scale-up which in itself inhibits uncertainties regarding technology choice and technological advancement. Especially regarding nuclear power, it is not obvious which reactor technology could lead to the capacity scale-up proposed in many energy scenarios and projections. Furthermore, thresholds may have to be adapted because a different sub-technology might be proposed within literature. Sub-technologies could differ, amongst other aspects, in terms of economic competitiveness, deployment availability, capacity factors, safety concerns, or societal implications.

As shown in Fig. 5, for nuclear, the identified technologies are high-capacity LWRs, SMR concepts, and SNR concepts. Firstly, a prerequisite for rapid decarbonization by means of a technology is that a given sub-technology is available for rapid near-term deployment. From a technology development perspective, this necessitates that a dominant design has emerged [58,59]. This implies that designs and prototypes have been tested and licensed, and that sufficient operational experience has been gained to reduce the risk of future design adaptations. Secondly, availability also implies that the technology is deployed to produce low-carbon electricity, for which short construction durations are required. To assess these factors, analyses of the status quo and insights into historical assumptions of technology diffusion are conducted. This allows current development efforts and potential prospects to be placed into the context of historical development and to derive a first

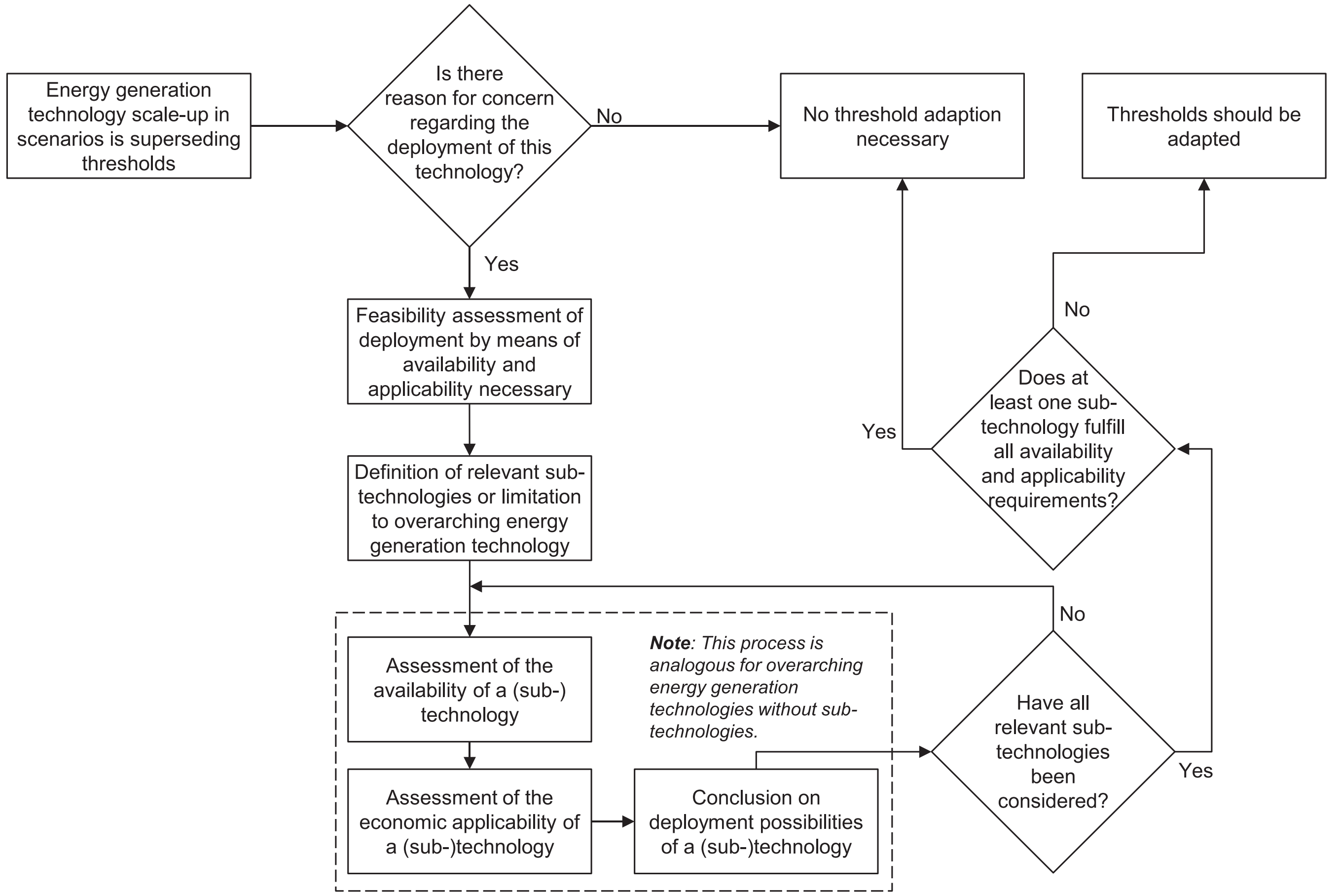

Fig. 4. Approach for the analysis of the feasibility of energy generation technologies.

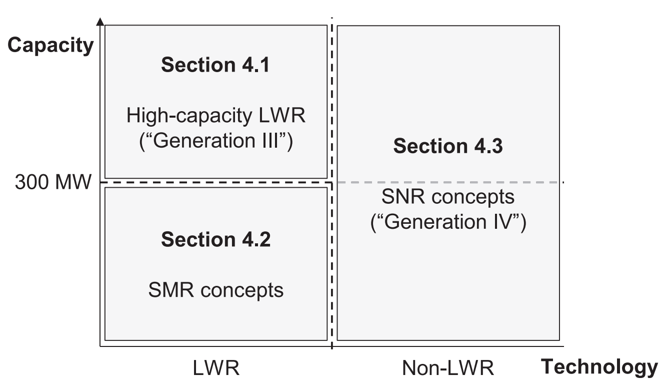

Fig. 5. Overview of the analyzed technologies.
Abbreviations used: LWR = Light water reactor, SNR = so-called new reactor technology, SMR = small modular reactor.

assessment of the availability of a sub-technology for large-scale near-term deployment. This analysis focuses on absolute metrics and uses indicators such as capacity deployment, construction times and the current status quo (design status, variety of designs) of a sub-technology, following Markard et al. [16] and Lovins et al. [53]. Other relevant factors such as the assessment of sufficient supply chain capacities can be included here. While we do not include this aspect in this analysis, certain components might be highly asset specific and manufacturing capabilities might be limited to a small number of actors [60]. Thirdly, costs are an important factor for rapid deployment due to their influence on the pace of deployment and overall deployment decisions. Thus, an economic analysis is conducted. It includes a scrutiny of the economic competitiveness of the sub-technology from an energy system perspective, either based on actual evidence or, in the case of unavailable technologies, theoretical calculations. Hereby, we compare costs from the dominant reactor technology with the proposed "new" types to assess their potential economic advantages. Finally, a conclusion on the availability and economic applicability of a given sub-technology for energy system decarbonization can be derived. These steps are repeated for all identified sub-technologies until an overall verdict of the feasibility of scenario assumptions relating to the energy generation technology can be formulated. The results of such an analysis can then shed light into the black box of the aggregated nuclear power technology perspective.

4. Results

This section provides the results of the analytical approach described above. For the analysis we scrutinize past and current development efforts for the establishment of high-capacity LWRs, SMR concepts, and SNR concepts and assess economic aspects for each of these sub-technologies, see Fig. 5.

4.1. High-capacity LWR

At present, LWRs with net electrical capacities from 600 to 1600 MW_{el} (so-called "Generation III" (and III+) reactors) are the most mature technology for future commercial nuclear fission deployment. Examples include the US-American AP 1000 (1117 MW_{el}), the French European Pressurized Reactor (EPR, up to 1600 MW_{el}), the Russian Water-Water Energetic Reactor 1200 (WWER, up to 1300 MW_{el}), and, more recently, the Chinese Hualong 1000 (1170 MW_{el}). This reactor generation was developed based on previous LWR designs ("Generation II").

4.1.1. Techno-historical context

The use of nuclear power is inherently connected to the military sector. The production of nuclear weapons necessitated production facilities and skilled personnel, leading to the accumulation of nuclear expertise and the establishment of an industry [61,62]. Following the end of World War II, nuclear weapons production continued, but efforts were also made to utilize this high-energy source for civilian purposes to reap economies of scope [63]. The first reactors for electricity generation were the light water cooled and graphite moderated reactor Obninsk in the Soviet Union (1954) and the light water cooled and light water moderated reactor Shippingport in the US (1957) [39].

Various reactor types, including gas-cooled reactors and fast reactors, were developed alongside LWRs [64]. However, LWRs have become the dominant technology for commercial nuclear power [17]. Further, the pursuit of economic competitiveness drove the attempt to reap economies of scale, resulting in larger unit sizes, with capacities increasing from less than 300 MW_{el} in the 1950s/60s to around 1 GW_{el} in just a few years [65,66], see Fig. 6. The expansion of LWRs reached its peak in the 1970s, but since then, there has been a significant decline in new builds outside of China.

Reduced reactor orders from the 1990s to 2000s have led to divestment and a consequential decline of the nuclear industry. Major reactor companies in OECD countries have either gone bankrupt, changed their business models or were sold; examples are Westinghouse and General Electric in the US, Babcock & Wilcox (B&W) in the UK, and Areva in France [67–70]. Current projects are marked by cost increases and construction delays [68,71]. Especially in OECD countries, capital costs have been increasing for decades [55,72–78].

4.1.2. Status quo

The worldwide electricity generation from nuclear power has been stagnating for the last 20 years. The absolute power generation from nuclear was 2653 TWh in 2021, just shy of the historic maximum of 2660 TWh in 2006 [40]. The share of nuclear power in global electricity generation has been shrinking, with a steady decline from its historically highest share of 17.5 % in 1996. It recently fell below 10 % for the first time in decades. After the drop of generation after the Fukushima disaster, there has been a slight increase in nuclear power production in recent years, primarily driven by the construction of new reactors in China [79].

Global electricity generation from nuclear power is expected to decline further in the coming years due to reactors' advanced ages. 66.5 GW (88 reactors) will most likely be disconnected from the grid in the 2020s, 93 GW (108 reactors) between 2031 and 2040, and 72 GW (74 reactors) in the 2040s [17]. These closures are planned to be partially offset by 58 ongoing new-build projects (about 59 GW), most of which are ongoing in China (23). 24 current projects are delayed, some by more than 10 years [17]. Most current new build projects in Europe and the US experience delays and cost increases. In 2023, Europe's first EPR at Olkiluoto in Finland began commercial operations, with a delay of 14 years and at least tripled cost [80]. Other EPR projects in France (Flamanville-3) and the UK (Hinkley Point C) are also experiencing delays and, in the case of the former, even larger cost increases [78,81]. The same pattern applies to the only US new-build project in Vogtle, Georgia, which is significantly delayed and already twice as expensive as originally planned. In July 2023, Vogtle-3 began commercial operations with a seven-year delay, and total project costs have exceeded the US-$ 30 bn mark [82]. Thus, there are two contrasting nuclear industry developments. In OECD countries, the decline can be observed, as aging fleets are to be replaced by too few costly and delayed new build projects, while non-OECD countries, especially China and Russia, are characterized by some nuclear capacity expansions [78,83]. With the lack of new capacity to replace aging reactors, regulators have shifted their approach. In the US, for example, reactor lifetime extensions of several decades aim to keep capacity on the grid. While it is argued that lifetime extensions support near-term greenhouse gas emissions reduction and even save mitigation costs, they merely push inevitable reactor closures into the future and simultaneously increase risks of spontaneous material or technical failures [84,85].

Markard et al. [16] argue that LWR technology is in decline globally and the only prospects of nuclear power lie in state-controlled "niches" because of a shrinking actor base, reduced economic opportunities in liberalized markets, and increasing competition from renewables. The importance of active state involvement (i.e., going further than subsidies) becomes apparent in countries such as China and Russia. Here, most of the new build projects are realized in a state-owned context: Rosatom, which is vertically integrated along the whole nuclear supply chain, and Chinese actors such as China National Nuclear Corporation are active domestically and internationally [17,86–88].

4.1.3. Economic aspects

Nuclear power, foremost high-capacity LWRs, can be characterized as a "lumpy" technology, that hinders rapid deployment, which is needed to accelerate decarbonization [52]. Some economic insights that relate to the "lumpiness" of LWRs are provided below.

Economic aspects for LWR technologies are generally assessed from different cost perspectives. Either via overnight constructions costs (OCC) (cost per capacity unit) and sometimes total construction costs (TCC),[2] or levelized costs of electricity (LCOE) (cost per energy produced). The latter is more appropriate for comparisons with other technologies as it, in contrast to OCC and TCC, also considers availability and other relevant factors such as fuel cost, although it still omits cost factors such as system costs or waste considerations [90].

For complex infrastructure projects that last for several years, capital costs are driven by financing costs, which are in turn influenced by construction times and interest [89]. While cost analyses based on OCC dominate, they often lack critical assessments of construction times. Long construction durations often lead to an increase in capital costs [91]. For nuclear, capital costs account for up to 80 % of total project costs [92].

When comparing LCOE, it is evident that nuclear was never economically competitive with alternative technologies. Back in 1956, nuclear power costs were at 42.5 US-$$_{1956}$/MWh compared to coal with 8.7 US-$$_{1956}$/MWh [72]. This discrepancy still exists today. Although mainly carbon pricing has made nuclear economically viable compared to fossil technologies, it now competes with other low-carbon technologies, such as solar and wind [93] (see Fig. 7). Even when system integration and flexibility costs are included, and decommissioning and waste management costs are neglected, nuclear remains the most expensive technology [94].

Most reactors had been built in regulated markets, and since liberalization, their cost disadvantages have become more apparent [77,95]. From 2010 to 2022, the closure of 13 nuclear power plants in the US was attributed to the diminished profitability of nuclear power, primarily due to the impact of low gas prices [17]. Operational capacities are thus kept on the grid via substantial subsidies (e.g., the Inflation Reduction Act of 2022 in the US [96]), and new build plans are supported through government support with guaranteed returns, e.g., a contract for difference for Hinkley Point C with a strike price of 89.5 GBP [97].

However, there have been attempts to reduce costs. Historically, standardization was seen as a main driver for cost reductions [98]. In most countries, however, this did not occur. The US, for example, has built the largest number of reactors (over 100),[3] but with limited

[2] Capital cost or total construction costs are calculated as the sum of OCC and "interest during construction", depending on the cost of capital and construction times [89].

[3] The US is currently operating 93 nuclear power reactors [39].

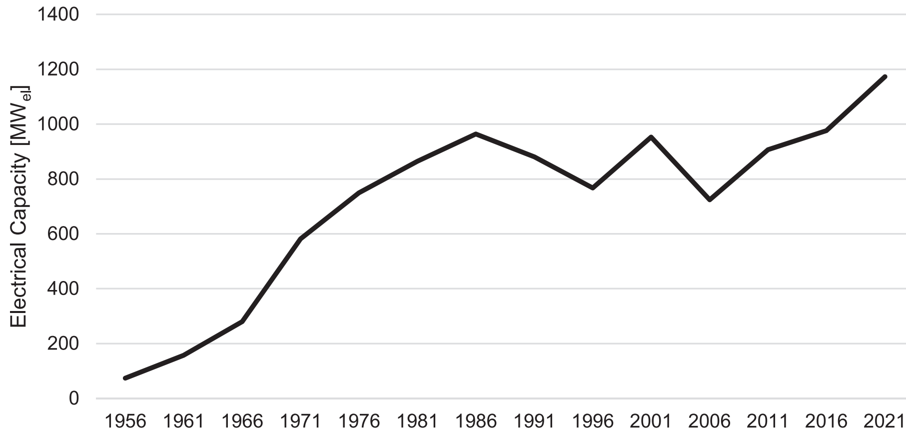

Fig. 6. Average capacity development of nuclear power plants world-wide from 1956 to 2021.
Source: Own depiction with data taken from [39].

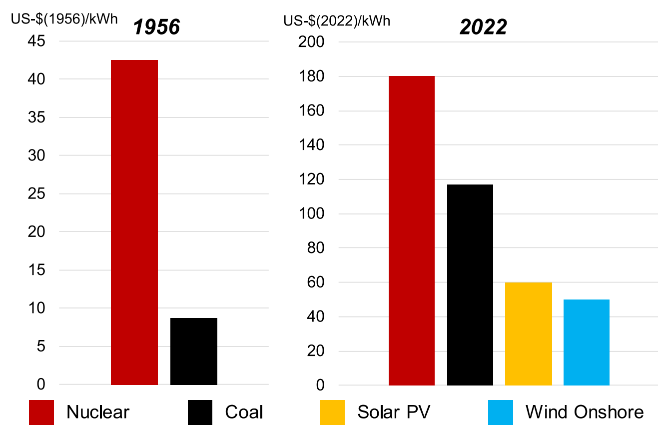

Fig. 7. Historical and current cost comparisons for nuclear power (US).
Sources: Own depiction following [72,93].

standardization and was thus unable to benefit from economies of multiples [99,100]. The largest number of reactors of similar design was built in France, but no significant learning effects could be identified [55,98,101]. One exception is South Korea, which has imported large-scale technology from the US and provided a stable regulatory environment, leading to a cost decline in OCC [102]. However, data from other non-OECD countries such as China remains unreliable and non-transparent [91].

4.2. *SMR concepts*

A proposed strategy to counter the challenges of current LWRs is to return to theoretically less "lumpy" reactors with lower capacity, usually lower than 300 MW$_{el}$ which potentially could reduce capital investments as well as construction times [103,104]. SMRs are not only being developed for electricity generation but also for niche applications, e.g., propulsion of sea-going vessels [105]. Non-light water based SMRs such as gas-cooled high-temperature reactors are considered for additional purposes such as process heat supply and hydrogen production and will be focused upon in Section 4.3. Note that the term SMR compromises research reactors, test reactors, prototype and demonstration reactors, propulsion reactors, and reactors for commercial power generation [106]. Thus, the definition also includes reactor projects that aim to further develop a reactor technology that might then be subject to future capacity increases analogous to LWR technology.

SMRs are not a "new" technology, but have garnered renewed interest in the context of energy system decarbonization [107]. For the sake of this analysis, the term SMR refers to reactors with a net electrical capacity of less than 300 MW$_{el}$ that are based on light water technology and that aim for commercial power generation. The goal here is to provide insights into technological and economic differences when building reactors of similar technology but of different dimensions.

4.2.1. *Techno-historical context*

The idea of building low-capacity nuclear plants grew out of the development and deployment of low-power reactors for nuclear propulsion systems in the 1940s and 1950s [106]. Originally, the term SMR stood for "small and medium-sized reactors" [65,66] but was later changed to "small modular reactors" [108]. However, early low-capacity reactors were used as prototypes to expand and build reactors of higher capacities. The aim was to achieve cost savings through economies of scale, resulting in an average net capacity of 500 MW$_{el}$ for nuclear power plants as early as the 1970s, and over 1 GW$_{el}$ today (see Fig. 6).

In the US, the development of SMRs originated from military research programs in the 1940s and led to the construction of submarine reactors and several low-capacity reactors in remote military locations (e.g., Antarctica or Greenland), the same type of locations that are being proposed again today [109]. While nuclear propulsion does not compete with alternative energy generation technologies and enables submarines to operate for longer distances, low-capacity reactors for electricity generation have been less successful, in some regard due to technical, but mostly economic reasons. Thus, when the AEC (Atomic Energy Commission, today: Department of Energy) funded SMR designs, they were viewed as prototypes for future high-capacity reactors stemming from hopes of achievable economics of scale [109]. In 1955, another round of funding for SMRs aimed at smaller grids in rural areas, but the construction of reactors like Elk River resulted in high costs and short operational lifetimes due to design flaws. Meanwhile, high-capacity LWRs had become the dominant reactor technology. In the 1980s, a return to lower capacities was proposed but not implemented, and the nuclear research budget had been scrapped by the 1990s. In the late 1990s, funding for different reactor types, including SMRs, was reconsidered, leading to the creation of the "Nuclear Energy Research Initiative" in the 2000s. This initiative included a predecessor of the NuScale VOYGR reactor design, which itself is unlikely to be deployed soon [71].

The current push for the development of SMRs can be viewed as a renewed attempt to promote nuclear capacity scale-ups. The repetition of such promotions over time has led to the interpretation thereof as "nuclear hype cycles" [24,107]. Previous attempts however, such as the call for a "second nuclear renaissance" in the early 2000s [106], have failed due to lack of demand, for, e.g., Westinghouse's "medium sized reactor" AP600 [107]. The current push is driven by the interpretation of necessary rapid decarbonization as a "window of opportunity" [71,110]. The uncertainty regarding the availability of SMRs and the ability of the industry to use the current narrative of nuclear power being a low-carbon technology will be discussed in the following.

4.2.2. Status quo

The operation and construction experience of SMRs for electricity generation is limited. According to the IAEA, only a few are in operation or under construction, see Table 1.

Several SMR concepts are currently under development, and some are awaiting regulatory approval to begin construction of first prototypes. For example, in the US, the NuScale VOYGR received a design certification in 2022, for which the final approval took effect in February 2023. NuScale is licensed for a plant with up to twelve modules and 600 MW_{el} capacity (50 MW_{el} per module) but is currently pursuing a license renewal for a configuration up to twelve 77 MW_{el} modules which would increase total plant capacity to 924 MW_{el} [112]. The Utah-project, for which NuScale was planning to deliver a six-reactor plant (462 MW_{el}) by 2030, was scrapped in November 2023 when several municipalities withdrew from the project after continuous cost escalations [113].

Nonetheless, other SMR developments remain underway. Most designs will require several years to be fully licensed, more time to be constructed, and then, operational experience will have to be gathered to ensure reactors are safe to operate, possibly leading to further design adaptions. In-parallel development of several designs further stretches investor and state funds and could limit or delay the maturation of SMR concepts currently under development.

Further, the few existing construction experiences for SMR projects show long construction times. For example, the two Russian state-funded floating KLT-40S (2 × 35 MW_{el}) began operating in 2020 after 13 years of construction and the CNP-300 began commercial operation in 1994 after nine years of construction. The development of the CAREM (Central Argentina de Elementos Modulares) reactor in Argentina has been underway since the 1980s, but commissioning has become a distant prospect due to a construction halt [111]. Construction times could improve as these projects can be considered as "First-of-a-Kind", and following projects might be built faster. Thomas and Ramana [71] compared national developments in the UK, the US and Canada. They found that the deployment of the first SMR within these countries will not happen before 2030. Therefore, building up a serial production for reactor modules lies decades ahead – if ever realized.

Table 1
Status of most mature SMR projects based on light water technology.

Design	Capacity [MW_{el}]	Designer	Country	Status
CNP-300	330	China National Nuclear Corporation (CNNC)	China	In operation since 1994
KLT-40S	2 × 35	JSC Afrikantov OKBM (Rosatom)	Russia	In operation since 2020
CAREM	25	Comisión Nacional de Energía Atómica (CNEA)	Argentina	Under construction since 2014
ACP-100	125	China National Nuclear Corporation (CNNC)/Nuclear Power Institute of China (NPIC)	China	Under construction since 2021
VOYGR	4/6/12 × 77	NuScale Power Corp.	US	Final licensing and equipment manufacturing in progress, but project is cancelled

Sources: [79,111].

Nonetheless, hopes of SMR deployment remain high. For example, the NEA's high case scenario projects additional SMR capacity of 21 GW_{el} (corresponding to about 100 reactors) by 2035, compared to 850 MW_{el} in the low case [19]. However, these numbers are based on assumptions made years ago. The high-case projection can be traced back to a publication from 2014 that assumes 678 GW_{el} of aggregated installed nuclear capacity by 2035 [114]. The underlying assumption of this publication is that SMRs will account for around 3 % of future nuclear capacity without explicit reasoning. Until 2050, an even stronger growth of nuclear capacity is envisaged: up to 375 GW_{el} of SMR capacity, also for non-electrical applications [19]. With a currently installed total nuclear capacity of around 390 GW_{el} [79], these projections seem rather unrealistic.

4.2.3. Economic aspects

Several publications have analyzed the economics of SMRs [22,89,105,115–120]. Some literature suggests that SMRs could reduce costs compared to LWRs because smaller unit sizes would enhance the modularization of components, allowing for factory production. Hence, the key concept of SMR economics is the economies of multiples through mass-production and learning. Other factors such as regulation, design adaptions, e.g., passive safety systems, and reduction of construction times as well as the availability of skilled labor are addressed within literature [121]. The present analysis focuses on aspects regarding learning and required reactor production volumes for SMRs.

In literature, there is consensus that specific per unit construction costs decrease as the capacity of the plant increases and vice versa [89]. These economies of scale stem from capital and operating costs. The latter, representing material costs and expenses for services and staff, do not scale linearly with generating capacity.

To specify the penalty of lower capacity, two approaches in production cost theory regarding SMR economics exist. Both approaches follow the same principle but vary in the choice of the scaling factor [119]. One approach is given below [115,122]:

$$\frac{C_{SMR}}{C_{LWR}} = \left(\frac{S_{SMR}}{S_{LWR}}\right)^b \Leftrightarrow C_{SMR} = C_{LWR}\left(\frac{S_{SMR}}{S_{LWR}}\right)^b \quad (1)$$

Here, parameter b is the scaling parameter, S (MW_{el}) represents electrical capacities of the high capacity LWR and the SMR, and C specific construction costs (USD/MW_{el}) for both reactor types. The SMR will thus face higher specific construction costs compared to the LWR depending on b. Thus, assuming technologically identical reactor designs (e.g., pressurized water reactor), $S_{SMR} = 200$ MWe, $S_{LWR} = 1000$ MW_{el}, and $b = 0.6$, the specific construction costs of the SMR C_{SMR} would be as high as 40 % of those of the high-capacity LWR while only producing 20 % of the electricity [123]. There are several theoretical factors which could, if combined, offset the diseconomy of scale through the

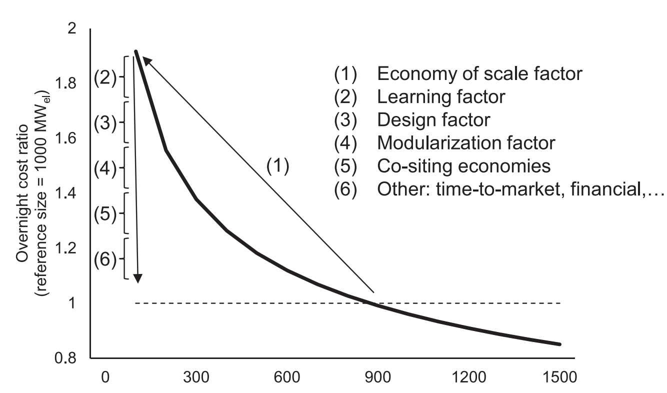

Fig. 8. Economy of scale effect on OCC and theoretical reduction factors. Sources: Own depiction following [117].

economies of multiples, see Fig. 8. The effect of learning will be described in more detail in the following.

Eq. (2) describes the effect of learning on specific cost while considering above-mentioned diseconomies of scale (Eq. (1)). The key parameters are the scaling factor b, the learning rate x (enabled through fabrication of modules and repetition of labor) and the factor for doubling of production volume d [115,122].

$$C_{SMR} = C_{LWR} * \left(\frac{S_{SMR}}{S_{LWR}}\right)^{b} * (1-x)^{d} \tag{2}$$

In order to realize such cost advantages, the industry would need to shift from economies of scale to economies of multiples in which reactors would be produced in higher quantities and with shorter construction times [124]. As historical and current construction experience for SMRs remains limited, assumptions for production volume and learning rate are hypothetical. For learning rates, literature suggests a range between 5 % and 10 % for every doubling in production [22].

A stylized production cost calculation (using Eq. (2)) reveals that a very high number of reactors would be needed in order to make a given SMR concept cost competitive with a high-capacity LWR of the same (or very similar) design: Following Pistner et al. [87], we assume an SMR with a capacity of 225 MW_{el} (S_{SMR}) and the AP1000, a pressurized water reactor at around 1100 MW_{el} (S_{LWR}) capacity. In this production calculation, this SMR design is expected to replace specific construction costs of the AP1000 design (C_{LWR}), estimated at an optimistic 6000 US-$/kW_{el}$.[4] Furthermore, a learning rate of $x = 6$ % and scaling parameter $b = 0.55$ are assumed. Under these assumptions, the specific construction costs of the SMR would be lower than those of the AP1000 as soon as about 3000 reactors would have been produced (i.e., $d \approx 11.55$ doublings of production volume), see Fig. 9. The figure also shows the development for different learning rates.

This stylized comparison refers to OCC. If total construction costs are considered, the construction time could become an influencing factor to improve economics. Due to the high capital intensity of nuclear power projects, financing costs must be accounted for: the longer it takes to build a plant, the more capital it will consume und thus cost will increase. Regarding deployment, it is assumed that SMRs could be built faster, although this expectation is formulated without any historical record. But while specific OCC are higher, costs per unit could be lower compared to LWRs, potentially reducing financial cost [104].

In order to realize hypothetical cost reductions, a serial production would have to be established. Therefore, a minimal number of orders for reactors are essential to cover initial fixed factory costs. However, determining what constitutes a minimal level of orders remains uncertain. According to Lokhov, Cameron and Sozoniuk [105], in the most optimistic scenario, tens to hundreds of SMR reactor units along with a significant number of initial SMR orders are conditional to launch a serial production and to enable future cost reductions. Westinghouse estimated they needed at least 30 to 50 orders, whereas B&Ws estimated up to hundreds [127].

Literature further suggests rather limited market demand, shown by countries such as Jordan, Ghana or Indonesia being discussed as potential off-takers of SMR technology, with none currently buying or building a single reactor [123]. However, it is argued that SMRs could be viable in niche markets, such as remote energy-intensive applications [128]. In an assessment of such a niche market, Froese, Kunz and Ramana [127] assume that SMRs could be viable in Canadian off-grid applications such as remote mining projects and communities. They conclude that the SMR potential was 600 MW_{el} at best. This would be insufficient to justify investments in SMR production facilities. Further, such locations are also attractive sites for renewable energy developments, further limiting economically viable SMR market potential [123].

Finally, SMRs not only compete with high capacity LWRs, but also with other low-carbon energy sources. By conducting a stochastic simulation of hypothetical power plant projects, Steigerwald et al. [119] show that the expected average LCOE of SMRs are likely to be in the triple digit US-$/MWh-range while manufacturers propose lower costs. Furthermore, SMRs are found to be non-competitive with renewable energy sources even if system integration costs are considered. If these prototypes were built, they would be, from today's perspective, significantly more expensive than renewable energy in combination with flexibility options.

4.3. So-called new reactors concepts

The last category of reactors to be analyzed is sometimes referred to as “advanced” or “Generation IV”, even though relevant physical-chemical principles were established back in the 1940s and 1950s. The main characteristic is that the “so-called new reactor” types, which we will abbreviate as SNRs, do not use light water, neither for moderation nor for cooling. This non-light water reactor classification includes, amongst others, sodium-cooled fast reactors (SFR), lead-cooled fast reactors (LFR), gas-cooled fast reactors (GFR), molten-salt reactors (MSR), supercritical water-cooled reactors (SCWR), and (very) high-temperature (gas-cooled) reactors ((V)HT(G)R) [129]. Their development is supported by an international research network and monitored by an international research association, the “Generation IV International Forum”. The establishment of the Forum in 2001, consisting of 14 members amongst which were the US, China, Russia, and the EURATOM states, marked an attempt to rekindle research and development of these reactor types. Additionally, there are other reactor concepts that are currently under research which are not directly assigned to the Forum, such as accelerator-driven systems (ADS) [62].

SFRs will be the focus of the following analysis. These reactors are generally considered to be the most developed, as this type has the most operating experience amongst the SNRs. Further, there are a few prototypes and demonstration reactors in operation and under construction in Russia and China [62,79]. Other SNR types, especially HTRs, will be briefly touched upon.

4.3.1. Techno-historical context

Most of the SNR concepts were developed as early as the 1940s with first prototypes realized in the 1950s but they failed to diffuse into energy generating markets [29,130]. Instead, the LWR technology became the dominant reactor type [17,64].

The SFR was conceptualized in the 1950s, particularly in Russia and the US, but also in France, Germany, Japan, and China [29,130,131]. Until the 1960s, it was expected that if nuclear power generation expanded at the envisioned rates, uranium resources would soon become insufficient and therefore concepts with higher fuel utilization, such as fast reactors, would gain importance [29]. For example, in 1962, the US AEC projected a domestic nuclear capacity of 5 GW_{el} by 1970 and 40 GW_{el} by 1980. By 1967, they even expected to have 232 GW_{el} in operation, under construction or on order by 1980 [132]. However, the wide-spread expansion of nuclear power and uranium scarcity did not materialize. Instead, new uranium deposits were discovered and fewer reactors were built than originally expected [29,30]. In addition, technical problems such as coolant fires occurred repeatedly at SFR prototype facilities because sodium is highly reactive when in contact with water or air [131].

Thus, the development of SFRs can be described primarily in terms of project cancellations. Initial demonstration projects in the US were discontinued in the 1970s due to economic, technical and proliferation risks [29]. In Germany, too, there were attempts to develop SFRs, for example the SNR-300 in Kalkar, which is operated as an amusement

[4] In literature, the OCC of AP1000 varies from historical records or projections between 4500 and 9200 $/kWe for the US [125], while the Vogtle Project was estimated at 12,000 $/kWe in 2021 [78].

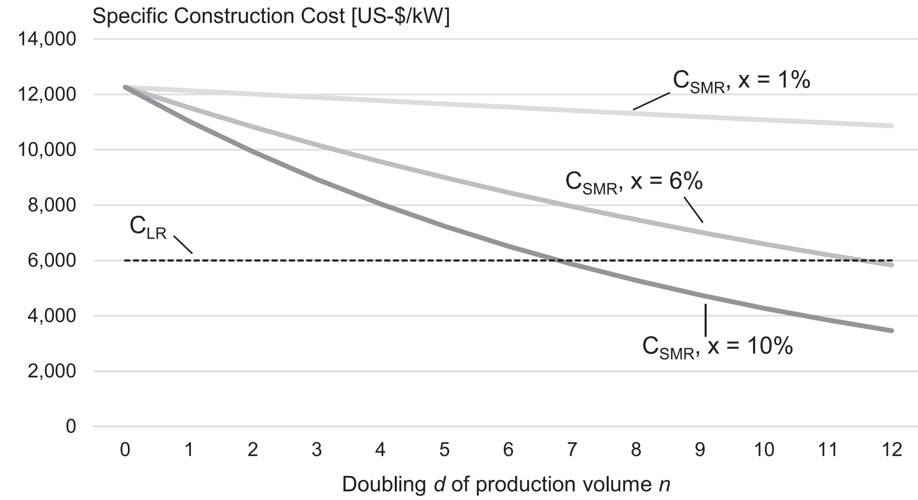

Fig. 9. Cost degression for OCC in SMR production economics.
Source: adapted from [126].

park today [133,134]. Fast reactors could not be established in France either. All three experimental reactors, Rhapsodie, Phénix, and Superphénix, have now entered decommissioning [29,135]. The ASTRID SFR was to be the successor. However, funding of the project ended in 2019 without continuation plans [136].

Russia's SFR development is the exception from the rule. Since the 1950s, Russia has built four SFRs: the research reactor BOR-60, in operation since 1969, the BN-350, in operation from 1972 to 1999, the BN-600, in operation since 1980, as well as the BN-800, in operation since 2015 [79,137]. But here, too, operating experience is characterized by technical challenges, where the use of sodium as a coolant has led to several leakages and fires [29].

Other fast reactors were also developed in the early days of nuclear reactor exploration. For LFRs, research was conducted almost exclusively in Russia, and here mostly for submarine propulsion. No such reactor is in operation today. One Russian reactor, BREST-OD-300, has been under construction since 2021, and Belgium is currently developing Myrrha, an ADS-powered LFR [62,138]. GFR developments occurred in the US and Germany in the 1960s and 1970s, in the UK in the 1970s, and in Japan in the 1990s, but to date, no GFR has been built or operated [138].

The development of HTRs operating on a thermal spectrum and gas as coolant goes back to the 1960s with the first test reactors Dragon in the UK or Peach Bottom in the US, and the THTR-300 in Germany, built in the 1970s [62]. Back then, the application of the THTR was envisioned for heat generation for coal gasification to reduce carbon emissions from fossil fuels. Hydrogen production was envisioned as possible application if fossil fuels were to be constrained by stricter emission targets [139], but the reactor was shut down after only 15 months of unstable operations [39].

4.3.2. *Status quo*

Currently, there are several operational reactors running on a fast neutron spectrum. Russia has three SFRs in operation: BN-600, BN-800, and BOR-60, which is one of the only options world-wide for irritation testing on a fast neutron spectrum. To replace the aging BOR-60, a new fast research reactor (MBIR) is currently under construction [62]. China operates the sodium cooled research reactor CEFR, which was connected to the grid in 2011 [62,79]. Additionally, four fast reactors are under construction: two SFRs, each with a capacity of 600 MW_{el} (CFR-600) began construction in China in 2017, the LFR BREST-OD-300 in Russia (300 MW_{el}), which began construction in 2021, and the sodium-cooled PFBR reactor in India (470 MW_{el}), under construction since 2004 [79].

In the US, renewed attempts to develop SFRs can be observed. After shutting down the entire fast reactor infrastructure, such as EBR-I in 1963, EBR-II in 1994 and the Fast Flux Test Facility in 1993, the US has since then been attempting new SFR constructions [29]. For example, the company TerraPower is developing a 345 MW_{el} SFR, without the intention to reprocess the fuel, but instead to combine the reactor with a molten salt tank (500 MW_{el}) to enable load following in an energy system with a growing share of renewables [140]. The company is currently undergoing pre-application activities for the design with the Nuclear Regulatory Commission [141]. It is planned that the demonstration project will be operational within this decade [142]. For this, TerraPower has received several billions of dollars through grants from the US government, most recently topped up by the Biden administration's 2021 infrastructure bill [143].

Based on HTR technology from Peach Bottom and THTR-300, China has constructed the research reactor HTR-10, which serves for testing the pebble-bed design and also provides heat for the campus of Tsinghua University [62]. Another reactor of that type, HTR-PM (211 MW_{el}), was constructed and has been operating since 2021 [87]. Although experience with HTRs exists in the US, the technology has yet to overcome the stage of prototypes and demonstration reactors. However, renewed attempts can be observed such as the development of the Xe-100 (80 MW_{el}), developed by the American company X-energy in a public-private partnership with the Department of Energy in the context of its Advanced Reactor Demonstration Program [144].

Thus, both SFR and HTR technologies are still under development and currently not available for large scale deployment. Given the long development histories, it remains questionable if they ever will succeed. LFR and GFR are even further away from commercial deployment.

As shown above, SNRs designs are heterogeneous. In contrast to SMRs, at least in the definition of this analysis, SNRs differ to a larger extent, as they use different coolants and fuels. This necessitates alternative supply chains. For large scale deployment, a dominant design must emerge, and operational experience must be gathered, which may lead to further design adaptations or shift to an entirely different reactor design. Thus, future availability of SNRs is currently characterized by high uncertainty.

4.3.3. *Economic aspects*

This section addresses economic challenges and potential prospects for the application of SNR concepts for energy generation while focusing on SFRs that are currently receiving the most attention.

4.3.3.1. *Sodium-cooled fast reactors.* One the one hand, SFRs are estimated to have higher capital costs compared to LWR [30,145]. One aspect is the use of sodium as a coolant, which results in two circuits: one for cooling the reactor with sodium, and a secondary circuit with water for steam supply. Moreover, as LWR technology is more mature, construction should (theoretically) inhibit less risk than for different, less tested, reactor types. Developing untested reactors could result in higher risk margins for borrowed capital. On the other hand, fast reactors have higher fuel utilization compared to thermal reactors because they breed additional fissile material, and thus reduce the use of natural uranium resources [23]. This could have a positive impact on operational costs. But the spent fuel must be reprocessed before it can be used again, which in turn requires the availability of extensive (and currently de-facto non-existent) infrastructure, inducing high system costs [131,146]. Currently, France and Russia are the only countries that operate reprocessing plants, while two reprocessing plants are under construction in China and one in Japan [147]. The UK closed its reprocessing plant at Sellafield in 2018 [148].

This constitutes two opposing fuel utilization pathways: The "once-through" path, which dominates today, and the so-called "recycling" path with reprocessing that would rely on fast reactors. SFR competitiveness is strongly tied to the cost-effectiveness of either path, which in turn depends on different parameters, such as uranium supply (i.e., the price of natural uranium). This is in turn influenced by how many additional nuclear capacities will be built and operated [30,149]. A calculation of the break-even price of uranium, at which the operation of a hypothetical fast reactor with reprocessing would be as expensive as an LWR without reprocessing, shows that the uranium price would have to be many times higher than current market prices [30,150].

According to Cochran et al. [29], SFRs have an inherent disadvantage compared to LWRs regarding operational utilization, which is systematically lower. A key challenge is to maintain and repair the parts of the reactor that are immersed in sodium. Sodium is highly reactive with atmospheric oxygen and can thus cause exothermal reactions. Repairs must be done under highest security measures to ensure that the sodium has been removed from the entire system. This is more complicated and takes longer compared to LWR and can take months or even years. Extended shutdowns have been a part of SFR history, e.g., Superphénix in France, Monju in Japan, the British Dounreay and Prototype Fast Reactors as well as Enrico Fermi 1 in the US.

Given the fact that SFRs are still under development and have economic disadvantages compared to other reactor technologies, and thus also to other low-carbon energy sources, the near-term establishment of SFR technology on a utility scale seems highly unlikely, if ever realized.

Muellner et al. [23], conclude that the uranium supply may become limited especially in strong-nuclear scale up futures, which therefore could make SFRs necessary from the uranium supply perspective, but they also find that SFRs will not be available in the relevant timeframe of 2020 to 2050. Thus, proposed impacts of these reactors towards necessary decarbonization of energy systems will probably be limited to individual projects.

4.3.3.2. Economic aspects of other SNR technologies. Due to insufficient operating experience and heterogeneity of the reactor types, we refrain from assessing the whole group of SNRs. Nonetheless, some aspects of each reactor technology will be highlighted in the following.

In contrast to SFR, LFRs have even less operating experience. Currently, only one demonstration reactor (BREST-OD-300) is under construction in Russia. The plan is to demonstrate a closed fuel cycle with reprocessing [62,151]. From an economic perspective, considerations of uranium scarcity and reprocessing costs are also applicable. Because lead is not as chemically reactive as sodium, cost and safety advantages might come from the non-necessity of expensive intercooling circuits to separate the primary coolant from the steam cycle [152].

Furthermore, LFRs could also operate with an external spallation source to initiate a fission reaction (ADS reactor). A prototype is under development in Belgium with the research reactor project Myrrha. The construction of the accelerator and the spallation neutron source have so far led to substantial additional cost compared to other LFR projects [62]. Furthermore, the reliability of the accelerator is a key parameter for capacity utilization [153]. In any case, for an ADS to operate commercially, it must operate at capacity factors comparable to today's LWRs, presenting a major challenge since currently available spallation sources require cool-down times of at least several hours [62].

Regarding SNRs with thermal neutron spectra, gas cooled HTRs are envisioned for non-electrical applications. Instead of water, these reactors use gas for cooling, e.g., helium, and thus enable outlet temperatures of 700 °C and more. Therefore, it is proposed that HTRs could play a role for decarbonizing process heat for industrial purposes or hydrogen production [154]. However, cost estimations depend on specific applications and technological parameters, and most reactor designs, e.g., Xe-100 in the US, are still under development. Thus, literature on HTR-economics focuses on cost comparisons of different designs or applications and relies on cost projections for "n-th of kind" reactors [155]. For example, a study analyzed that the specific OCC of a hypothetical HTR in the US were 32 % higher than for an LWR [156]. According to the study, such designs encounter the trade-off between passive safety due to lower power densities, and larger required infrastructure, such as buildings and equipment, and thus increased costs. However, their application for non-electrical uses could potentially offset a part of this cost disadvantage.

5. Discussion

Results indicate that nuclear scale-up propositions should be considered with caution. Neither LWR, nor SMR or SNR technologies will be likely to be scaled up in sufficient quantities for the proposed absolute values. Assessing feasibility thresholds with the share of electricity generation provides limited insights into the absolute generation, as the share varies with overall energy production. Thus, a strong scale-up of absolute electricity generation might not lead to an increase in the share and vice versa. Consequently, nuclear scale-up thresholds suggested by Brutschin et al. [6] should be adapted to absolute energy generation. Alternatively, we suggest to reduce the proposed threshold values (5 and 10 pp), which imply a growth in share of nuclear electricity generation from around 9 % in 2022 to 24 % (5 pp) or even to 39 % (10 pp) by 2052. Both are much higher than the historic maximum of 17.5 % in 1996 and suggest that energy scenarios with shares below these values merit no further scrutiny. Further, nuclear sub-technologies, i.e. SMR and SNR technologies, may require individual thresholds for more accurate assessments of nuclear in general.

While the focus of this analysis were techno-economic aspects, a holistic assessment within the context of energy system decarbonization is crucial. Despite economic challenges, technology deployment may persist due to geopolitical factors and considerations of supposed energy independence [157,158]. In this regard, Brutschin et al. [158] find that "context based" variables such as financial and supply chain capacities as well as relations to major technology suppliers are more important to assess global nuclear diffusion than inherent technology characteristics and thus may have to be included into future analyses.

This analysis disregarded related path dependencies of nuclear power usage that result in the need to manage radioactive waste, decommissioning, proliferation risks and societal impacts [49,68,159,160]. Especially radioactive waste management and decommissioning will occupy resources and capacities, and previously unused reactor technologies might well bring additional challenges from new types of waste [161]. Further, adaptations to nuclear power plants resulting from climate change, such as precautions against extreme weather events and sea level rise, will likely lead to further cost increases [162].

Limitations of this analysis further include the disregard of possible linkages between economics and passive safety systems, relating especially to SMRs, and of possible cost implications of adapting radioactive waste streams. Moreover, we focused on economics of learning, but other factors such as modularity (number of plants at one site, transportation) also play a role for potential cost reductions. The analysis further neglects the differences in market potential from so-called nuclear newcomer countries, such as Poland, and established nuclear industrial states, and has a Euro- and US-centric view due to data availability.

6. Conclusion

This paper investigated the role of nuclear power in energy scenarios collected in the IPCC database. Following the proposed thresholds for technology scale-up proposed by Brutschin et al. [6], it was shown that most energy scenarios would require no further scrutiny. However, we suggest the adaption of the proposed threshold metrics from relative to absolute values by also analyzing absolute electricity generation changes. Additionally, we propose assessing the availability of nuclear sub-technologies for the proposed deployments based on a proposed framework.

Based on the proposed framework, the assessment concludes that while individual reactor concepts and applications might be operational in the coming decades, large scale deployment for rapid decarbonization is unlikely. The currently dominant reactor technology design of high-capacity LWRs is a lumpy technology characterized by high costs and long construction times. Furthermore, on a global scale, the technology is in decline. SMR concepts are proposed to reverse this trend because they are supposedly cheaper and faster to build. Although SMR concepts have been known for decades, no concept is currently available for large scale deployment, and lack of operating experience further complicates the matter. From an economic perspective, SMRs suffer from diseconomies of scale. In theory, this disadvantage could be overcome by economies of multiples, but cost estimations are subject to theoretical assumptions and lack real world experience. Potential cost reductions through economics of multiples would require a regime shift towards mass production of reactors, which would in turn require the establishment of currently unavailable and expensive infrastructure. SNRs, and here most notably SFRs, could become advantageous compared to LWRs if uranium supplies became scarce, a situation that remains unlikely as of today. Further, with very few reactors in operation and a history of project cancellations, large scale deployment remains uncertain. High capital costs and increased technical complexity resulting from, e.g. sodium as coolant, add to the picture.

However, while this analysis concentrated on economic competitiveness, there are state-owned and -controlled niches in which such reactors could be deployed because of other factors such as geopolitical considerations and energy independency. Nonetheless, SMR and SNR concepts still suffer from the lack of availability.

The decarbonization of energy systems must happen rather sooner than later, but the potential contributions of nuclear power to climate change mitigation are low. While the nuclear industry continues to develop reactor technologies, policy makers of today should instead focus on technologies that are, firstly, available for deployment, and secondly, more granular, i.e., less costly and faster to build. Additionally, the tremendous challenges of decommissioning and radioactive waste management must not be overlooked. Consequentially, decision makers should treat assumed nuclear scale-ups in energy scenarios with caution as parameters and assumptions can vary strongly between different models. Future research should focus on underlying scenario assumptions on a sub-technology basis to develop more suitable feasibility thresholds for the scale-up of nuclear power.

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CRediT authorship contribution statement

Fanny Böse: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Conceptualization. **Alexander Wimmers:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Björn Steigerwald:** Writing – original draft, Validation, Data curation, Conceptualization. **Christian von Hirschhausen:** Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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