The Version of Record of this manuscript has been published and is available in Science as Culture - 22 may 2026 - https://www.tandfonline.com/doi/10.1080/09505431.2026.2666078

Small Modular Reactors: scaling down to better scale-up?

Dr. Mathias Sabbe (Liège University)

Dr. Céline Parotte (Liège University)

Abstract:

While vendors and international nuclear organizations increasingly publicize Small Modular Reactors (SMRs) as a compelling solution for current and future global energy landscapes, little is known about whether this broad promissory discourse is shared among scientists and engineers directly involved in SMR research and development.

Juxtaposing publicly voiced SMR expectation narratives on cost, flexibility, environment, safety, and proliferation with the situated expectations of 25 European engineers and nuclear physicists involved in the design of a sodium-fast SMR (ESFR-SIMPLE) reveals overall alignment between international proponents' and experts' expectations. Despite some noteworthy discrepancies, interviewees only tempered the expectation narratives constitutive of the broad SMR promissory discourse, drawing on their technical expertise to challenge peripheral claims also contained in these narratives.

This relative alignment was enabled by the interpretative flexibility embedded in the SMR promissory discourse, with expectation narratives offering broad frames of reference for experts to interpret and adjust their assessments to. Additionally, the SMR techno-scientific promise also acted as a discursive umbrella, providing a shelter for experts' situated expectations. Specifically, interviewees valued the broad SMR promissory discourse as it was perceived as an opportunity to rebrand nuclear power and attract resources to the nuclear sector – albeit via less efficient but highly marketable, downsized reactors. Ultimately, SMRs were not seen as an end in themselves but as a steppingstone toward the long-term revival of large-scale nuclear projects.

Keywords: Small Modular Reactors; nuclear energy; sociology of expectations; innovation community; strategic promises; narratives; advanced nuclear technology.

Acknowledgements: The authors would like to express their sincere gratitude to the two anonymous reviewers, as well as to the editors of Science as Culture, for their insightful comments and careful editorial work, which greatly contributed to improving this article. The authors also wish to thank their colleagues at the SPIRAL Research Centre (University of Liège) for their valuable feedback and stimulating discussions on earlier versions of this work. Finally, this article has benefited from numerous enlightening exchanges with contributors to the ESFR-SIMPLE project, whose insights have been essential to this research.

Funding: The ESFR-SIMPLE project is funded by the European Union under Grant Agreement 101059543. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union. The European Union cannot be held responsible for them.

Introduction

In the ongoing quest for flexible, cheap, and decarbonized energy solutions, Small Modular Reactors (SMRs) are increasingly touted as a compelling avenue heralding the future of nuclear power generation. On March 21, 2024, in her address at the International Atomic Energy Agency (IAEA) Nuclear Energy Summit, European Commission President Ursula von der Leyen stated that SMRs are, and will be, at the forefront of advanced nuclear technology developments to meet the Paris Agreement targets. SMRs are at the center of an innovation race among leading actors, poised to attract substantial European and national investment:

> Innovation in nuclear technologies is a very dynamic space, particularly for nuclear power technologies such as Small Modular Reactors, or SMRs. Of course, as with every emerging technology, there are ups and downs, successes and failures, that is quite normal. But SMRs are a promising technology and there is a race underway. The race is among leading countries and companies to prove this technology and bring it to market. (European Commission, 2024).

The IAEA defines SMRs as 'advanced nuclear reactors with a power capacity of up to 300 Mwe' (IAEA, 2023). SMRs are *small* in both footprint and power output compared to large reactors that typically generate around 1000 MWe. They are also designed for large-scale *modular* factory-based production: standardized components would be manufactured in assembly lines and transported for rapid on-site construction, allowing for future plant capacity expansion via additional modules. Although these *reactors* rely on nuclear fission to generate power, SMRs encompass a wide range of reactor technologies, including conventional pressurized water reactors (PWRs) as well as advanced Generation IV designs such as sodium-cooled fast reactors (SFRs), lead-cooled fast reactors, and molten salt reactors.

Although SMRs have attracted some interest since the 1980s, it was not until the early 2010s that they really gained traction in the media, policy, and scientific debates – reflecting growing interest from societal actors worldwide. This momentum is currently being bolstered by an international discursive community of vendors, developers, and (supra)national organizations positioning SMRs as central to a sustainable and resilient energy future – one that would unshackle nuclear power from the immense costs and chronic delays that have plagued large-scale nuclear projects in recent decades (Sovacool & Ramana, 2015). SMR vendors in particular advance bold claims about game-changing features, investments, and ambitious timelines. In this context, the EU and countries such as the United States, China, France, Canada, and the United Kingdom, have announced plans to support and fund SMR R&D (Thomas & Ramana, 2022).

Yet concrete achievements remain sparse, with only a handful of SMRs currently operating or under construction in Russia, China, Canada, and Argentina. Most first-of-a-kind units are expected by the 2030s (NEA, 2024). Global innovation efforts are being spearheaded by startups (e.g., NuScale, Oklo, and TerraPower in the United States; Naarea, Newcleo, and Jimmy Energy in France), traditional nuclear actors and utilities (e.g., Westinghouse, EDF, General Electric Hitachi), national laboratories, and some universities. As of 2024, the Nuclear Energy Agency (NEA) listed 98 SMR projects in various development stages, most based in the United States, Canada, and the United Kingdom (NEA, 2024).

Social scientists have generally taken a critical stance on whether SMRs will help consolidate the so-called nuclear renaissance (e.g., Thomas & Ramana, 2022; Derdevet & Mazzucchi, 2021). Despite increasing prominence in public discourse and policy – most studies have only assessed SMR techno-scientific promises from the perspective of their technical (e.g., Thomas & Ramana, 2022; Ramana & Mian, 2014) and economic viability (e.g., Cooper, 2014). Some have also drawn on the sociology of expectations to examine the rhetorical visions (Sovacool, 2019; Sovacool & Ramana, 2015) and hype mechanisms surrounding SMRs (Kari et al., 2023). Yet, while these contributions shed light on the manner in which the SMR promise is publicly narrated and promoted, little is known about whether this promissory discourse is shared by scientists and engineers directly involved in SMR research and development (R&D).

This paper foregrounds the *situatedness* of expectations, which assumes that expectations about science and technology are contextually embedded and hence not homogeneous across actor groups within communities of promise (Brown, 2003). While an expanding body of literature explores divergences in situated expectations across developers, marketing departments, and other stakeholders (e.g., Dandurand, 2020; Konrad, 2006), few studies have systematically juxtaposed these with the broader promissory discourses publicly articulated by communities of promise. Yet doing do could provide valuable insights into the versatility of umbrella promises – defined as broad, open-ended, promissory discourses devised to facilitate choice among possible options – (Parandian et al., 2019; Van Lente, 2012) and their complex relationship with situated expectations. This should clarify how broad promissory discourses accommodate situated expectations within a community of promise, allowing actor groups to position and articulate their own situated future-oriented visions in relation to the umbrella promise. It would also illuminate how the legitimacy and credibility of umbrella and situated promises are distinctly enhanced to better resonate with distinct audiences (Joly, 2010).

Accordingly, we focus on those who run the SMR innovation race in Europe – nuclear engineers and physicists involved in SMR R&D – to address the following question: to what extent does the promissory discourse upheld by the international SMR community of promise align with the situated expectations of experts involved in SMR R&D in Europe? To this end, we identify five key expectation narratives from documentation published by international SMR proponents and juxtapose them with the situated expectations of 25 researchers and engineers involved in the design of a sodium-cooled fast reactor (SFR) SMR under the ESFR-SIMPLE project. Results indicate that while interviewees use their technical expertise to challenge specific promissory claims, they generally temper, but do not challenge, the framing articulated in expectation narratives. This relative alignment is enabled by the interpretative flexibility of the SMR techno-scientific promise, which functions as a discursive umbrella sheltering experts' situated expectations. While broad promissory discourses emphasize downsizing nuclear reactors as a way to scale-up production of one-size-fits-all reactors, the experts present SMRs as a critical step toward the revival of large-scale nuclear projects. Interviewees value the umbrella promise for its performative potential, seeing it as a means to generate public interest and attract investment to the nuclear sector, laying the groundwork for future large-scale reactor projects.

The article is structured as follows. First, we ground our approach in the sociology of expectations and then present our methodology. We then juxtapose the main expectation narratives pertaining to the broad SMR promissory discourse with the situated expectations of engineers working on a European SMR R&D project. The conclusion synthesizes our findings, notably emphasizing that, while broadly aligned, international SMR proponents' and experts' visions convey distinct nuances in how scaling can be leveraged by the nuclear sector to frame problems and their solutions.

Analytical perspectives

Theory: Unraveling expectations within communities of promise

The sociology of expectations defines expectations as 'real-time representations of future technologies, situations and capabilities' (Borup et al., 2006, p. 286) that are embedded in the collective discourses and the social repertoires of various groups, such as governments, experts, and scientists (Konrad et al., 2016). Expectations carry values, promises, and visions connected to the possible advantages, or disadvantages, assumed to derive from an innovation or a techno-scientific field. As such, they can take on a positive or a negative valence that expresses the (un)desirability of a technological future (Konrad et al., 2016; Borup et al., 2006). Terms such as promises and visions largely coincide with expectations, albeit with a particular normative emphasis on their role as wishful enactments of a desired future (Borup et al., 2006). Consequently, expectation research often empirically focuses on the analysis of value-laden narratives reflected in promotional material, policy documents, or press releases.

Expectations are also performative (Suckert, 2022; Van Lente, 2012; Borup et al., 2006), shaping collective practices and strategies in the development of science and technology. Techno-scientific promises, in particular, are positive expectations that articulate strategic claims about the beneficial outcomes of an innovation. They serve as rhetorical devices through which 'promise-makers' seek to secure funding and support from 'promise-takers' as part of a regime of economics of techno-scientific promises (Joly, 2010). This is apparent in Van Lente's (1993) promise-requirement cycle, whereby statements about *what can be* are used to legitimize and justify requirements for action, orienting policy choices and potentially locking-in technological pathways (e.g., Berti & Levidow, 2014). Likewise, promissory organizations (Pollock & Williams, 2010) strategically generate interest through exaggerated promises, thereby shaping the innovation market with self-fulfilling prophecies. Such practices aim to trigger and master the hype-disappointment cycle, where initial enthusiasm gives way to disillusionment and an eventual recalibration of expectations (e.g., Van Lente et al., 2013).

Expectation research mostly focuses on the study of collective expectations (Budde & Konrad, 2019; Van Lente, 2012; Borup et al., 2006; Konrad, 2006) made 'available in public statements' (Van Lente, 2012, p. 775) by communities of promise: a complex network of actors – comprising promissory organizations, investors, vendors, and developers – in which exchange relationships are negotiated, structured and organized by expectations regarding a given techno-scientific field or innovation (Martin et al., 2008; Brown, 2003). Yet, such collective expectations can mask a remarkable heterogeneity of visions and representations about what *can* and *should be*. Indeed, expectations about science and technology may vary across actor groups, leading to possible frictions between diverging or competing visions (e.g., Palm & Nikoleris, 2021; Kerr et al., 2020; Van Lente & Bakker, 2010).

For instance, building on Konrad (2006), Dandurand et al. (2020) show that beneath seemingly aligned optimistic outlooks, actors' contributory expertise within an AI project is associated with differing expectations about the technology's capabilities and potential. These differences prompt negotiations that complicate the seamless enactment of collectively envisioned technological futures (Dandurand et al., 2020). This echoes Brown and Michael's (2003) observation that expectations within innovation communities vary depending on research involvement, access to information, and degrees of uncertainty. Similar findings come from transition (e.g., Kriechbaum et al., 2023) and management scholars, who have long highlighted the divergences in expectations, interests, and concerns between stakeholders in new product development projects – such as marketing departments and R&D teams (e.g., Linberg, 1999).

These contributions underscore the situatedness of expectations (Brown, 2003): expectations about science and technology are formulated by actors anchored in a particular spatio-temporal situatedness and position within networks, and are thus embedded in specific socio-economic contexts (e.g., Borup et al., 2006; Brown, 2003; Brown & Michael, 2003). *Situated* expectations include shared *specific* expectations (Konrad, 2006) that can vary significantly across actor groups depending on their expertise, interests, and involvement within a community of promise (e.g., Dandurand et al., 2020; Eames et al., 2006; Brown & Michael, 2003). They also include *individual* (Konrad, 2006), or privately held (Berkhout, 2006), expectations that are not necessarily communicated. However, these boundaries remain 'fuzzy', as private expectations are arguably largely shaped by shared visions of the future (Berkhout, 2006, p. 307). Few studies have juxtaposed collective expectations – and corresponding techno-scientific promises – with situated expectations held by actors within communities of promise. Yet, this effort can illuminate the versatility of techno-scientific promises and their complex relationship with situated expectations – particularly considering broad, open-ended *umbrella* promises that refer to relatively vague visions devised to facilitate choosing among possible options (Parandian et al., 2019; Van Lente, 2012; Joly, 2010).

As expectations result from social interaction (Konrad, 2006), techno-scientific promises emerge through strategic compromises and adjustments among actors within a community of promise. Hence, besides the articulation of frames that allow for the emergence of broad 'intersubjectively shared meaning structures' about the nature and purpose of a technology (Kriechbaum et al., 2023, p. 2), broad promissory discourses must also incorporate some degree of *interpretative flexibility* (Konrad et al., 2006; Eames et al., 2006) through the formulation of broadly interpretable, and noncommittal consensual guiding visions for shaping technological development. Umbrella promises must also provide a form of *protection* (Parandian et al., 2019; Rip & Voß, 2013; Konrad, 2006), accommodating and sheltering a plurality of specific expectations and promises under a broader discursive umbrella that maximizes performative potential. Actor groups whose expectations and promises diverge from the umbrella promise may tolerate, or even endorse, such discrepancies as long as they are perceived as beneficial for the realization of their own situated expectations (e.g., Konrad, 2006; Eames et al., 2006).

Further, to attract interest and foster investment, techno-scientific promises must also resonate with choice audiences, such as investors, policymakers, and civil society at large (Joly, 2010; Borup et al., 2006). Hence, they tend to rely on narratives about technology that reinforce their perceived legitimacy and credibility (Van Lente, 2012; Joly, 2010). Yet, this may also lead to promissory inflation, with bold speculative claims potentially overlooking key issues (Joly, 2010) and divergent expectations within a community of promise. Common discursive motifs, such as scalability, are arguably indicative of promissory inflation. Indeed, Pfotenhauer et al. (2022) highlight how scalability functions as a central component in promissory discourses, framing collective issues and their solutions yet also glossing over alternate visions (Pfotenhauer et al., 2022). While such dynamics are well understood in relation to broad promissory discourses, it is unclear how they apply to situated promises expressed by particular actor groups within communities of promise who may try to appeal to different audiences.

Methods: analyzing and juxtaposing narrated forms of expectations

We implemented a two-step research process to capture and analyze the promissory discourse voiced by the international SMR community of promise and the situated expectations of engineers working on a European SMR project. To this end, we drew on much of the existing expectation research that focuses on the identification and analysis of narratives reflecting expectations about science and technology (e.g., Suckert, 2022; Brown & Michael, 2003). Narratives are understood as the *narrated* form of expectations – i.e., plots and storylines that describe 'how an imagined future may unfold' by assigning roles, providing roadmaps, and simulating outcomes (Beckert & Bronk, 2019, p. 9). Hence, by expectation narratives, we designate recurring, and thematically coherent, discursive assemblages about the projected capabilities and role of a technology.

Numerous claims regarding the expected benefits of SMRs have been expressed by developers and startups, international nuclear organizations (e.g., IAEA, NEA, WNA), and initiatives that promote nuclear R&D (e.g., GIF, SNETP). In the first step of our research, we aimed to identify key expectation narratives pertaining to the broad SMR techno-scientific promise. To this end, we conducted a non-systematic review of the grey literature including white papers, commercial factsheets, analytical reports, and website content published by the aforementioned actors. Although we acknowledge that, depending on the technology, different SMR concepts may come with their own sets of promises (Kari et al., 2023), we argue that there are also striking commonalities in SMR proponents' promissory discourses (Sovacool & Ramana, 2015; Sovacool, 2019).

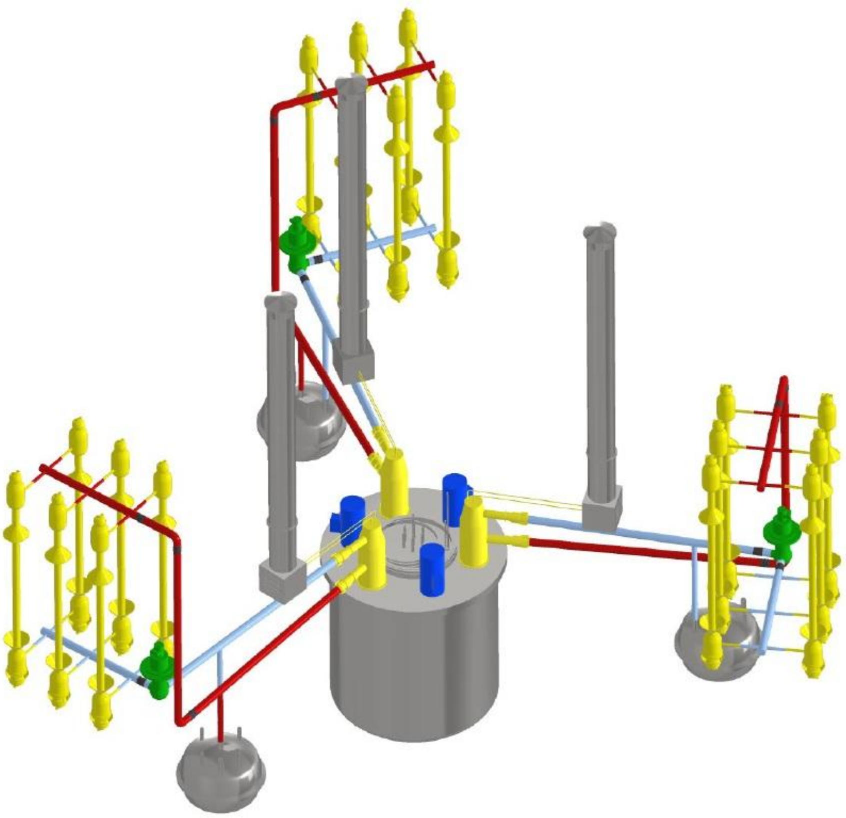
Table 1 – The document corpus

Organization type	Organization	Document type	Date of publication
International nuclear organizations	Nuclear Energy Agency (NEA)	Analytical report	2016
		General report	2020; 2021; 2022
		Annual report	2021
		Website content	2021
	World nuclear association (WNA)	Analytical report	2015
		General report	2019; 2020
		Website content	2023
	International Atomic Energy Agency (IAEA)	Analytical report	2014; 2020; 2020
		Conference proceedings	2020
		Technical meeting proceedings	2021; 2021
		Technological roadmap	2021
		General Report	2022
		Website content	2023
Nuclear R & D promotion	Generation IV International Forum (GIF)	Technological roadmap	2014
		Analytical report	2021; 2022
		Presentation	2021
		White paper	2021
		Annual report	2022
		Position paper	2022
	Sustainable Nuclear Energy Technology Platform (SNTEP)	Factsheet	2018
		Position paper	2018; 2021
		Research agenda	2021
		General report	2021
	European Commission	Analytical report	2022
		Funding report	2023
Vendors & developers	EDF	Website content	2023
		Press Release	2023
	GE Hitachi Nuclear Energy	Technical report	2011
		Commercial factsheet	2022
	General Atomics	Website content	2023
		Commercial factsheet	2018
	Holtec International	Website content	2023
		Commercial factsheet	2019
	Terrestrial Energy	Commercial factsheet	2023
	NuScale	Technical presentation	2015
		Research paper	2012
		Commercial factsheet	2022
		Website content	2023
	TerraPower	Website content	2023
		Commercial factsheet	2023
	ThorCon	Commercial factsheet	2018
	Westinghouse	Website content	2023
		Commercial factsheet	2023
	Newcleo	Website content	2022; 2023
	Moltex Energy	Promotional content	2022

Between January 2023 and July 2023, a total of 54 documents articulating SMR expectations were collected and integrated in the review. As shown in table 1, this documentation was published by a total of 17 organizations between 2011 and 2023 (appendix A). Mirroring the sampling logic used in step 2, the aim of the document selection process was to increase variation by diversifying emitting organizations and document types. Documents were collected until theoretical saturation was reached (Glaser & Strauss, 2017). The textual corpus was then analyzed thematically (Paillé & Muchielli, 2021) using inductive coding to identify key expectation narratives in SMR proponents' promissory discourse. Five main narratives emerged from this analysis: *costs*, *safety*, *flexibility*, *environment*, and *proliferation*.

In the second step of the research, we conducted semi-structured interviews with a total of 25 researchers and engineers involved in the ESFR-SIMPLE project. This EU funded project (2022–2026) coordinated by the French *Commissariat à l'Energie Atomique* (CEA) gathers 99 experts from 16 European research institutions and aims to develop a novel SMR design (see Figure 1) based on the SFR technology. SFRs are Generation IV reactors that rely on liquid sodium as coolant and operate in the fast neutron spectrum, thus allowing more efficient use of nuclear fuel.

Figure 1 – Model of the ESFR-SMR primary and secondary systems (ESFR-SIMPLE, 2026)



Sampling followed a maximum variation logic (Flick, 2018) and interviews were conducted until theoretical saturation was reached. We deliberately included a diversity of profiles involved in the nine work packages (WPs) of the project (appendix B), either as WP leaders or as simple contributors, to capture the broadest possible range of situated expectations. All interviewees were significantly involved in SMR R&D but in a variety of fields of expertise (e.g., reactor physics, fluid dynamics, data), and filled a variety of positions (e.g., research engineers, heads of research departments), organizations, and past experience. Table 2 groups the interviewees' profiles according to their organization, position, and field of expertise. Most of the interviewees were involved in several WPs (up to 5).

Table 2 – The interviewees' background

Organization	
Commissariat à l'Energie Atomique (CEA)	8
Helmholtz-Zentrum Dresden-Rossendorf (HZDR)	3
Karlsruhe Institute of Technology (KIT)	1
Italian National Agency for New Technologies, Energy and Sustainable Economic Development	2
University of Cambridge (UCAM)	2
Paul Scherrer Institut (PSI)	2
École Polytechnique Fédérale de Lausanne (EPFL)	1
Argonne National Laboratory (ANL)	1
Framatome	1
Institute of Physics of University of Latvia (IPUL)	1
Electricité de France (EDF)	1
Slovenská technická univerzita v Bratislave (STUBA)	1
Laboratoire Énergies & Mécanique Théorique et Appliquée (LEMTA)	1
	25

Position	
Research Engineer	8
Head of research group	8
Head of research institute	3
Head of engineering office	2
Emeritus	2
Postdoc	1
PhD student	1
	25

Expertise	
Reactor safety	3
Reactor physics	9
Fluid mechanics	6
Data scientist / AI	1
Fuel Performance	4
Measurement techniques	2
	25

WP role	
Contributor	17
WP leader	6
Advisory role	2
	25

The interview guide was prepared considering the following question: what are ESFR-SIMPLE experts' expectations and visions regarding the development of SMRs? The guide revolved around experts' general expectations concerning SMRs to avoid restricting discussions to the development of ESFR-SIMPLE and SFR SMR alone. The interviews were conducted online between April and September 2023 and typically lasted more than 60 minutes. The anonymized transcripts were subjected to thematic analysis using the MAXQDA software[1]. Coding followed both a deductive and inductive logic.

Although the boundary between private and specific expectations can be tenuous, broad commonalities in experts' expectations – as well as occasional references to the broader expert collective – suggest that experts' situated expectations are shared to some degree. Nonetheless, some variations across interviewees' expectations may possibly, but not necessarily, point to instances of privately held expectations. For instance, generational dynamics seem to be at play, with senior experts typically more reserved in their expectations than their younger counterparts. Disciplinary background also likely contributed to some differences: while nuclear physicists and engineers tended to be more skeptical of SMRs' projected technical capabilities, experts further removed from core design (i.e., instrumentation, data scientists) were generally more optimistic.

[1] Results were triangulated and validated via a presentation to the ESFR-SIMPLE consortium in October 2023.

Results: Juxtaposing experts and international SMR proponents' expectations

Reviewing the international SMR promise community's public statements revealed that expectation narratives are articulated around five key topics: costs, flexibility, environment, safety, and proliferation. In the following subsections, each of these narratives is juxtaposed with ESFR-SIMPLE experts' situated expectations. The final subsection outlines inductive findings regarding experts' general outlook on the SMR techno-scientific promise

Cost expectations: An affordable option, but only to some extent

The first expectation narrative pertaining to the SMR umbrella promise claims that, compared to large reactors, SMRs are an affordable solution for nuclear power generation and a safer option for investors.

This narrative centers on the expectation that SMRs will cost less to construct and require shorter lead times. *Modular factory production* of large series is expected to result in improved labor productivity, cost reductions, and to reduce the risk of schedule overruns. Productivity gains are also expected to be more durable than in conventional plants construction, because, while the adoption of advanced manufacturing techniques might help, the factory workforce is 'easier to train and qualify' and less affected by staff turnover (IAEA, 2021a, p. 8). The *shipping of pre-assembled modules* by truck, train, or waterway for direct onsite installation is expected to significantly shorten construction schedules and cut the costs of 'transportation and site infrastructure that is often necessary for building larger plants' (IAEA, 2021a, p. 19).

Greater *design standardization* due to lower customization requirements to fit local conditions, would reduce design costs and further facilitate large scale production. *Design simplification*, through the use of passive systems and enhanced integration, is expected to reduce the number of components and lower the costs usually associated with complex systems. For instance, active components such as 'reactor cooling pumps and their associated auxiliary systems, may no longer be necessary in novel SMR designs' (NEA, 2021, p. 22).

The other main dimension of this narrative consists of the expected reduction in *operation and maintenance costs,* as less staff would be required to operate and maintain simpler designs. Vendors such as NuScale also emphasize the cost-efficient serviceability of their design through 'greater use of 'commercial off-the-shelf' items that need not be supplied under stringent and costly nuclear standards' (NuScale, 2022, p. 1). Additionally, the modularity and transportability of SMRs is associated with quick and easy dismantling, implying *lower decommissioning costs*.

European physicists and engineers engaged in SMR R&D usually concurred with the affordable energy solution narrative. Even though first-of-a-kind SMRs were not expected to be particularly affordable, modular factory production and shipping for direct onsite installation were resolutely associated with lower capital costs, quick and easy deployment, and reduced schedule overruns. Overall, SMRs were viewed as a more attractive, less risky investment option, particularly for investors with limited funds and nuclear experience.

Although lower capital costs are expected, many interviewees highlighted that downsizing would inevitably generate diseconomies of scale leading to similar, or worse, capital costs per kilowatt installed compared to larger reactors. Similarly, interviewees noted that there would always be drawbacks when designing a small reactor. From a physics perspective, SMRs' smaller thermal capacity should improve safety, but at the expense of overall system efficiency, resulting in higher costs per kilowatt of electricity generated.

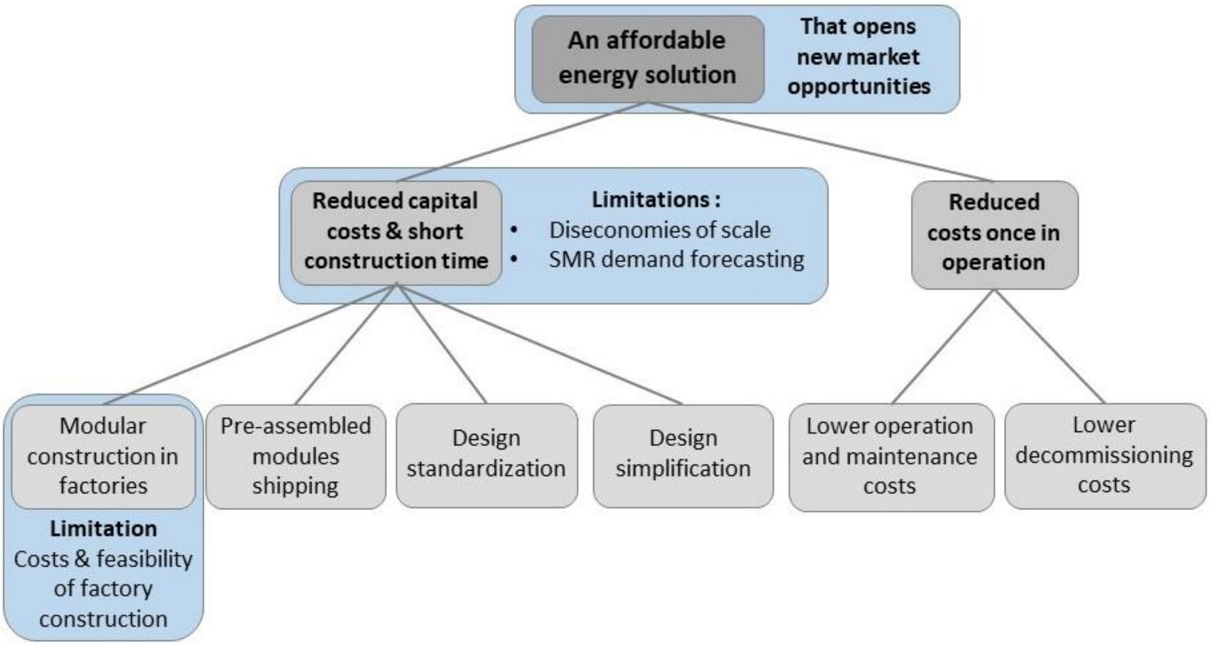
> The problem is, it doesn't work. There are some devices and some parts of the reactor which are not scalable. […] One of these is the reactor core. Reducing the size of the core reduces the efficiency of fuel utilization. Even in NuScale, in light water type, fuel utilization is getting worse because when you have smaller core dimensions, more neutrons tend to escape the core. It's called neutron leakage, and neutrons which are leaked are actually wasted neutrons. (H, Research engineer, Reactor safety).

Furthermore, uncertainties were expressed regarding the viability of large scale SMR production. Doubts did not only apply to the costs and feasibility of SMR assembly lines, but also to demand forecasting. This is important, as the expected benefits of factory production rely on the premise that future demand for SMRs will be high.

> So what we're hoping to do is to offset the economy of scale with an economy of numbers, which is what factory manufacturing is all about. One of the big caveats of factory manufacturing is that you have to take into account the cost of a factory. So, to do that […] you also need to be fairly certain about the number of reactors you hope to sell. (Q, Head of research group, Reactor physics).

Although the interviewees raised several issues, such as SMRs' diseconomies of scale and uncertain demand forecasting, their situated expectations broadly aligned with those of international SMR proponents. SMR design characteristics are expected to compress costs and timeframes at all the steps leading to, and following, plant commissioning. SMRs are also expected to open new market opportunities as an accessible and low-risk investment option for both traditional and new investors. Figure 2 synthesizes the affordable energy solution narrative expressed by international SMR proponents (grey) and the elements put forward by the European experts (blue).

Figure 2 – Juxtaposed SMR cost expectations



Flexibility expectations: A smart energy solution, but not suitable for every context

The second main expectation narrative expressed by international SMR proponents posits that SMRs represent a smart approach to energy generation, offering a flexible solution to a variety of grid requirements and energy challenges.

First, this narrative builds on the expectation that SMRs will contribute to grid stability. Although the rapid adoption of renewable energy sources such as wind and solar power is depicted as beneficial, their variable nature causes load fluctuations that can negatively affect grid stability. Consequently, large nuclear plants used for baseload power are increasingly constrained to operate in less optimal load-follow modes. In this context, SMRs are touted as a *flexible energy source* that can seamlessly integrate with renewables to reinforce grid stability. Small reactors would possess 'inherent load-following characteristics that make them capable of operating flexibly' (NEA, 2021, p. 26) and quickly adapt to load variations, enhancing the overall grid stability.

This inherent flexibility is expected to be further reinforced by instantly transferring reactor power from electricity generation to other 'non-electric applications (hydrogen, synthetic fuels and desalination)' (NEA, 2021, p. 26). SMRs would also contribute to the supply of *stable baseload power* in circumstances when renewables are not available. As such, they are often envisioned as a convenient replacement for aging fossil and nuclear baseload power capacity.

Second, this narrative reflects the idea that SMRs can satisfy diverse energy needs and requirements. SMRs' lower output and modular upgradability would conform to *smaller national and regional electrical grids*. This is particularly the case in emerging markets that cannot accommodate large reactors in local grids. Similarly, SMRs could be well adapted to *outlying power grids*. Their smaller size and modular nature would allow their easy transport and onsite assembly, overcoming the logistical challenges associated with building complex infrastructures in hard-to-access areas. Finally, SMRs are also promoted for their non-electric applications, ranging from hydrogen production and desalination to industrial heat. This is expected to *meet the demands of industries and other consumers* who are looking for a reliable source of energy that meets their specific requirements.

The interviewees – particularly younger European nuclear engineers and those less involved in reactor core design (e.g., instrumentation, AI experts, fluid dynamics) – generally supported the smart energy narrative, suggesting that SMRs could integrate with renewable energy sources and enhance grid stability in decarbonized energy systems. SMRs were also seen as suitable for smaller electricity grids or remote areas. Many interviewees emphasized their potential as export products, easily tailored and upgraded to meet the needs of newcomer countries that have smaller grids, limited funds and experience. Experts, especially from Germany, also expected SMRs to appeal to industries that require stable access to large amounts of electricity or industrial heat in direct proximity, but also to residential areas where heat or electricity could be distributed with minimum grid losses.

However, SMRs were not expected to be useful in every context. For instance, interviewees mentioned that SMRs would have limited purpose in countries with large, integrated electricity grids. According to European experts, large nuclear reactors should always be privileged when sufficient funds are available, and if the local grid supports it. Several French engineers, in particular, expressed that SMRs would make little sense in France, where large reactors are already operated flexibly to compensate for load variations on the grid:

> For me, big reactors make a lot more sense if you're in a country like France, with EDF, a company with huge capital that can afford to buy a big reactor, and which also has the backing of the government to help it if all goes wrong. So, under these conditions, a big reactor makes a lot of sense. (Q, Head of research group, Reactor physics).

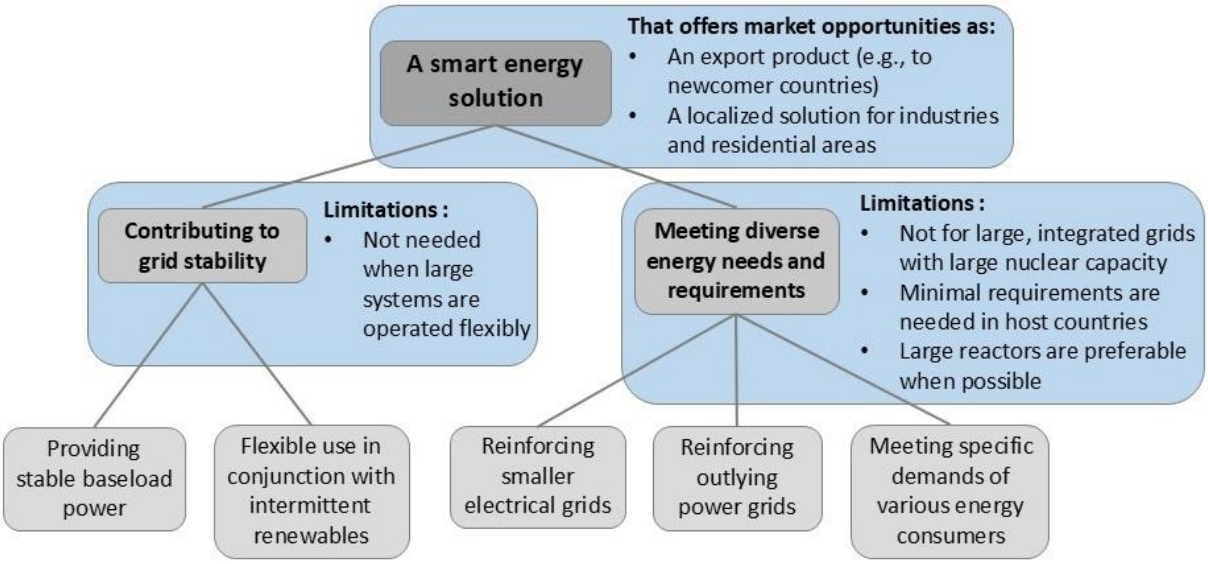
European experts also doubted that newcomer countries would simply be able to acquire and operate SMRs. They pointed out that in the absence of competent and independent national safety authorities, waste management structures, or qualified engineers, many such countries would not meet the basic requirements to install and safely operate a nuclear power plant, irrespective of its size.

> You can't really have a proper nuclear industry and safety authority in a country where you don't have many engineers, or if you don't have many industries, many welders… It all seems very complicated

to me, this image of the SMR that arrives by ship to be installed (S, Head of engineering office, Fluid dynamics).

In their situated expectations, European experts generally depicted SMRs as flexible energy sources that can attenuate the harmful impacts of load variations caused by renewables, plus represent solutions for smaller grids and remote areas. In so doing, these experts insisted on the market opportunities offered by SMRs either as a localized solution for industrial or heating applications, or as an export product that meets the needs of newcomer countries. Yet, SMRs are considered to be less suitable for countries like France, where large nuclear plants are already operated flexibly in a well-developed grid. Doubts also persist as to the feasibility of operating SMRs in countries that lack the necessary nuclear infrastructure and expertise. In the end, practical use is context-dependent, with large reactors being framed as preferable when conditions allow. Figure 3 synthesizes the smart energy solution narrative expressed by international SMR proponents (grey) and the elements brought up by the European experts (blue).

Figure 3 – Juxtaposed SMR flexibility expectations



Environmental expectations: A green energy solution, but no greener than other nuclear options

The third expectation narrative expressed by international SMR proponents asserts that SMRs are an environmentally friendly approach to energy generation that will contribute to the decarbonization of future energy systems while minimizing the risks of radiotoxic pollution resulting from nuclear waste.

First, this narrative rests on the promise that SMRs will provide a steady supply of much needed clean and affordable energy in a context of climate change. SMRs are expected to *fill the gap left by the phase-out of fossil fuels*, serving not only as replacements for baseload power generation, but also for off-grid or edge-of-grid and non-electric applications. For example, SMRs are proposed as a cost-effective way to decarbonize district heating systems, which still rely heavily on fossil fuels (IAEA, 2022, p. 37). As mentioned above, SMRs are believed to adequately *complement variable renewable energy sources* thanks to their better handling of grid fluctuations and their ability to swiftly transition from electricity generation to other applications such as district heating, hydrogen production, or energy storage. Additionally, companies such as NuScale and Terrestrial Energy call for *retrofitting old fossil fuel power plants* with SMRs to produce cleaner energy. Old coal boilers would be replaced with SMR modules while other systems would be reused.

Second, some international proponents consider that SMRs offer promising solutions to the longstanding radioactive waste management issue. Despite major variations in design, their generally small size and simplicity are expected to *reduce the volumes of waste* produced during operation and dismantling compared larger reactors, thereby facilitating waste management and reducing costs. Furthermore, some advanced SMR designs are touted as a means to *address the high-level waste management issue*. Unlike PWRs, many of these advanced designs operate in the fast neutron spectrum and can function either as breeders or as burners of plutonium and other long-lived actinides. These so-called fast SMRs are often described as 'sustainable' because they are expected to minimize waste volume and radiotoxicity while utilizing legacy waste as fuel, thereby reducing the long-term waste stewardship burden (IAEA, 2021b).

European experts embraced the narrative that SMRs will contribute to the energy transition through better integration with variable renewable energy sources and through their use for a variety of applications in hard-to-abate sectors. Eastern European experts, in particular, were optimistic about the prospect of SMRs becoming a necessary alternative – combined with other decarbonized energy solutions – to fossil fuels in a variety of applications, including the retrofitting of ageing fossil plants for combined heat and power production.

However, all the interviewed experts insisted that nuclear energy, in general, remains the best option for decarbonizing energy systems and that, compared to larger reactors, SMRs do not imply any significant advantages in terms of CO2 emissions reductions. To some extent, larger reactors were even considered to be a better option thanks to their greater power generation efficiency.

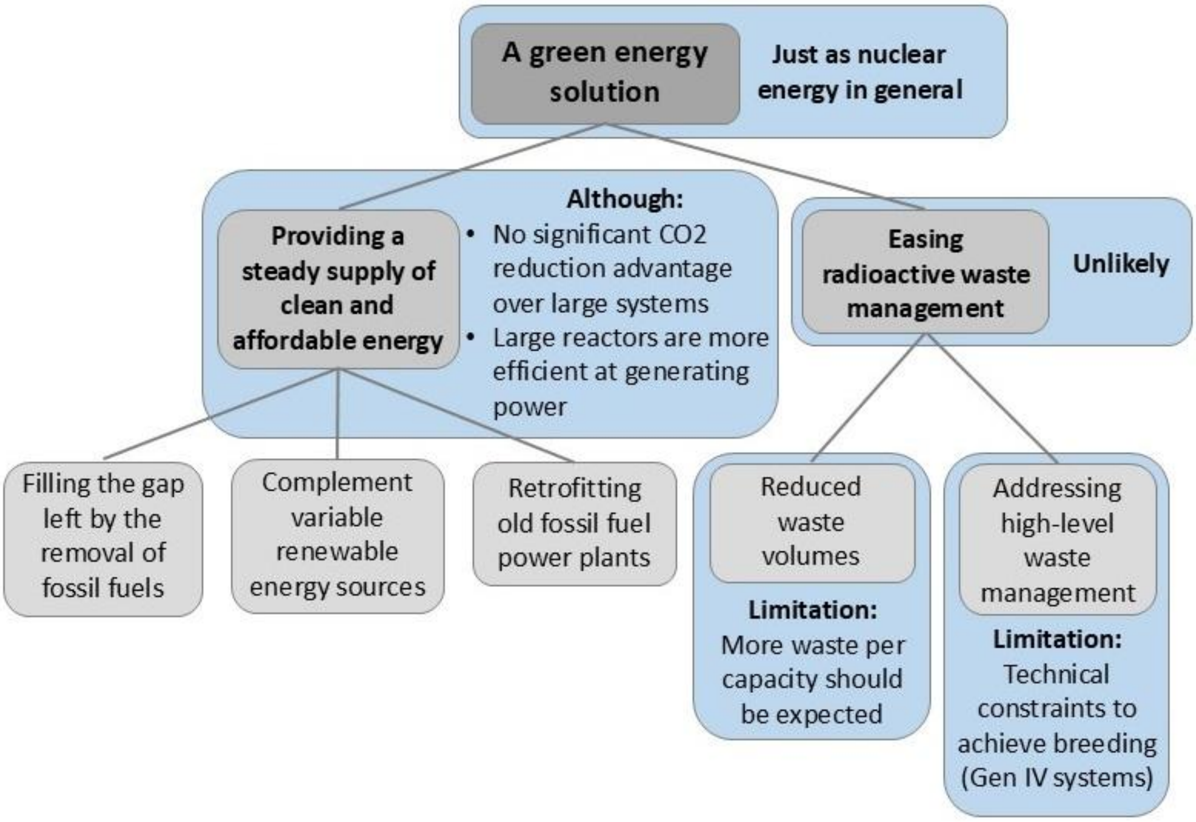
> They [larger reactors] may be more dangerous, less safe, whatever you want… but in terms of the environmental problem, if I look up the figures, I think a big one will be better than a small one. […]. As far as I'm concerned, I don't think SMRs contribute anything more than a large [reactor] system. (R, Research engineer, Reactor physics).

European nuclear engineers also doubted that SMRs would be a solution to the issue of radioactive waste management. At equivalent capacity, SMRs would likely produce more waste than larger, more efficient, reactors. This skepticism also applies to fast SMR designs that would struggle to operate as breeders due to the high neutron leakage that occurs in smaller designs. This somewhat diminishes the alleged advantages of Gen IV SMR concepts at least with respect to high-level radioactive waste management.

> Smaller reactors are typically safer, but in the case of SFRs we have a positive void effect. You can make it negative when you go for a small reactor because you can really increase the neutron leakage. But if you do that, you lose the breeding capability. So, you can make it safer but you will not do it because then the reactor will lose its meaning. (L, Research Engineer, Reactor Physics).

Interviewees' situated environmental expectations generally concurred with those voiced by international SMR proponents. However, European experts believe that SMRs will likely not have any major advantages over large reactors when it comes to reducing CO2 emissions, as large reactors are considered to be more efficient in that respect. SMRs' purported waste management benefits were also the subject of skepticism, with concerns that they would generate more waste per capacity, or that Gen IV designs would struggle to achieve breeding. Figure 4 synthesizes the green energy solution narrative expressed by international SMR proponents (grey) and the elements mentioned by the European experts (blue).

Figure 4 – Juxtaposed SMR environmental expectations



Safety expectations: A safer energy solution, but with a few serious caveats

The fourth expectation narrative expressed by international SMR proponents rests on the premise that SMRs represent a generally safer approach to electricity production than large nuclear reactors.

First, this narrative builds on the expectation that SMRs will be inherently safer than larger reactor systems because their design approach aims to eliminate the 'possibility for an accident to occur, rather than dealing with its consequences' (Gonçalves Filho, 2011, p. 2332). SMRs' *small thermal capacity* is expected to significantly reduce the amount of energy that needs to be removed in accident conditions, thus limiting the risks of core meltdown. This lower power output should also ease the implementation of *passive cooling and safety systems* that rely on natural forces like buoyancy, gravity, and heat convection to remove heat and slow down reactions in accident conditions. This would greatly reduce the likelihood of severe accidents caused by an active safety system failure (NEA, 2021, p. 19).

Design simplicity is also believed to improve safety because the reliance on simpler, yet reliable, passive systems should limit possible failure points. By contrast, the complex safety systems found in large reactors can generate many unforeseen problems and 'require a significant amount of online testing that contributes to plant unreliability' (WNA, 2023). It is also expected that SMRs will offer *greater containment efficiency* in the case of an accident. Some vendors claim that their designs will come fully enclosed in containment structures that can be further sheltered on site, while others consider underground or underwater installation for additional protection against natural disasters.

Second, international proponents argue that these inherent safety characteristics will allow the *relaxation of the emergency planning requirements* that are associated with large units. They also believe that SMRs' enhanced safety properties would *positively sway public perceptions* and engagement in favor of this technology. For example, the NEA suggests that while 'successful siting of SMR-based plants will require close attention to the preferences of host communities,' the 'inherent safety features presented by SMR designers could be viewed as an opportunity' to educate the public and alleviate concerns (NEA, 2021, pp. 45–56).

European nuclear engineers shared the expectation that SMRs' smaller thermal capacity, passive features, and design simplicity would enable significant improvements to safety, limiting the probability of serious accidents and their consequences. However, such proclaimed safety advantages were usually tempered by experienced engineers closely involved in reactor core design. Although the risk of severe accident would admittedly be more limited than for large reactors, they pointed out that, for an equivalent power capacity, the accident probability would likely remain similar.

> When you reduce the power, you make it safer which means, in that language, that the probability of something terrible happening will be reduced by a factor of ten. […] In fact, you decrease the probability by a factor of ten for each small reactor but, at the same time, you have ten reactors. Yeah, so theoretically, the probability has not changed. (L, Research Engineer, Reactor Physics).

Some noted that SMRs will not necessarily be safer than larger reactors in the sense that current safety requirements will likely be just as strict for SMRs. Hence, they speculated that – to keep costs acceptable – SMR developers would probably not strive to exceed current safety standards.

> Perhaps this is something that manufacturers and SMR designers are putting forward [safety], because they want to stand out from the crowd. But as far as I'm concerned, the safety requirements are the same. And what's more, I don't think we're trying to go beyond what's required, because nuclear power is already very restrictive. You can always go further, to make them safer, but it becomes more expensive. (I, Head of engineering office, Reactor physics).

Experienced nuclear engineers also mentioned that the association between reduced thermal capacity and improved safety is not necessarily straightforward as it also depends on the design of the SMR and on the properties of the coolant used in the reactor. For instance, using liquid metals such as sodium or lead as coolant can create specific safety issues if the coolant boils, freezes (lead), or comes into contact with air or water (sodium).

> To say that smaller is safer may be too straightforward. Because smaller, for example, means higher heat losses. And if you are using, for example, a heavy metal [for cooling], then the probability of freezing will be higher for a small system. It's evident and this is a very dangerous accident for a lead-cooled fast reactor, for example (M, Head of research group, Reactor physics).

Similarly, some interviewees pointed out that relying on passive cooling and safety systems may lead to reduced vigilance from plant operators who reasonably assume that nothing will fail during operation. Yet, the reliability of such systems should be questioned as they will probably be inaccessible and unserviceable once installed.

European experts, including those who are knowledgeable about reactor safety, also expressed some concern regarding the possible multiplication and dispersion of safety-critical nuclear infrastructure across territories. Although individually, SMRs may prove safer, they still pose considerable challenges in terms of safety, security, and proliferation management.

> Honestly, I have a hard time convincing myself that we'll be able to spread out objects, in this case, nuclear reactors, all over a parking lot, on an industrial site, however secure it may be… […] Because at a nuclear power plant, you've got fences, you've got a security force, you've got the national police force… In short, you have a defense, a protection which is important, yet people still sometimes manage to get in during demonstrations. (I, Head of engineering office, Reactor physics)

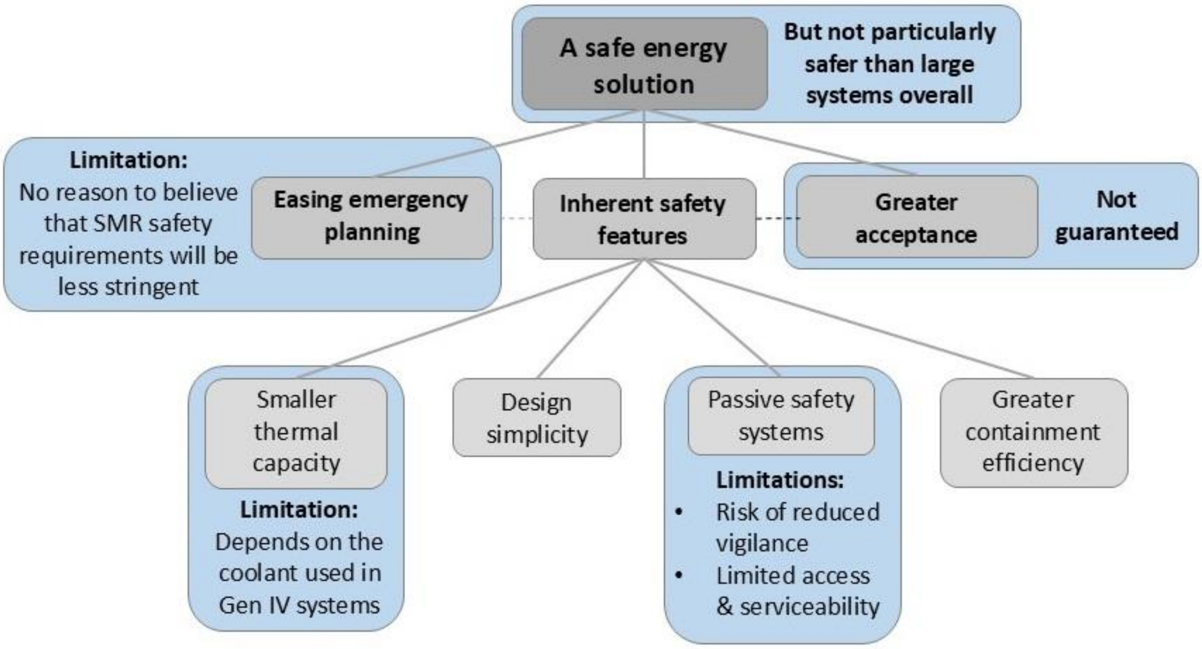
Although not specialized in such issues, reactor safety experts remained somewhat skeptical of SMRs' ability to win public acceptance. Their skepticism also extended to the idea that lay people would be more likely to accept SMRs than a large nuclear plant in their neighborhood.

> Why should they be less reticent about an SMR than a big reactor? They [SMRs] are not here yet, but they're already grumbling when they have big reactors next door. Now, I'm not saying it's a bad thing, but I'm not sure they're going to accept having a small reactor in their backyard, are they? (P, Head of research group, Nuclear safety).

In their situated expectations, interviewees generally concurred with international SMR proponents' claim that SMRs' design characteristics will yield considerable safety advantages, reducing the likelihood of accidents and their severity. Although they agreed with the technical soundness of this line of reasoning, they stressed that, for an equivalent capacity, the risk of an accident would likely remain similar to that of larger reactors. Additionally, they surmised that SMR safety requirements will likely not be stricter than those applied to conventional reactors and the fact that they are spread out across a territory will create acute safety, security, and proliferation management challenges.

From a technical standpoint, a few shortcomings were attributed to passive systems and to the coolant used in some Gen IV designs. Figure 5 synthesizes the safe energy solution narrative expressed by international SMR proponents (grey) and the elements put forward by the European experts (blue).

Figure 5 – Juxtaposed SMR safety expectations



Proliferation expectations: A proliferation-resistant solution, or is it really?

The fifth and final expectation narrative expressed by international SMR proponents posits that SMRs, and particularly Gen IV SMR designs, offer advantages regarding the non-proliferation of radioactive material.

First, this narrative emphasizes that SMRs could improve proliferation resistance by minimizing the accessibility of fissile material during refueling operations. Some vendors emphasize *the ease and speed at which refueling operations can be carried out*. In its earliest concepts NuScale highlighted a quick and easy refueling approach that 'eliminates the need for retaining, training, and establishing security' typically required for refueling (Reyes, 2012, p. 2). Other designs consider 'module replacement or offsite refueling or both', precluding storage on site and reducing the risk of diversion (IAEA, 2020, p. 19). Likewise, several vendors and startups claim less *frequent or no refueling*. While some vendors advertise extensive periods of operation without on-site refueling, others, such as Terrestrial Energy, advertise a sealed design approach whereby the fuel remains encapsulated in the reactor module from production to decommissioning in specialized facilities, further reducing access to the core and the risk of diversion.

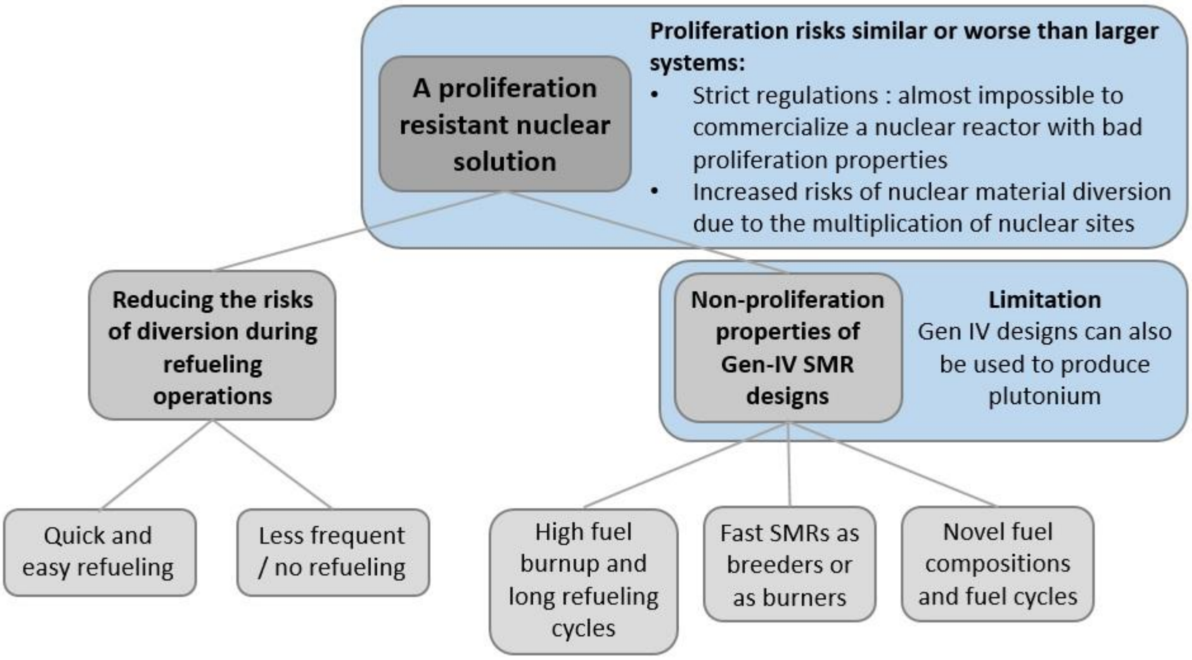
Second, this narrative builds on the expectation that Gen-IV SMR designs will have *long refueling cycles and high fuel burnup rates* that either reduce the risk of diversion or the suitability of spent fuel for military use. Fast SMRs are touted for their use as *breeders or burners* in closed fuel cycles. As burners, they would consume plutonium and other long-lived minor actinides contained in legacy waste. As breeders, proponents expect high fuel burnup and the breeding of fissile material from spent fuel that 'reduces or eliminates the need of fuel enrichment facilities, thus enhancing proliferation resistance' (IAEA, 2021b, p. 334). Similarly, the use of *novel fuel compositions and fuel cycles* is expected to further enhance proliferation resistance (IAEA, 2021b). For example, the fuel-salt mixture used in ThorCon's thorium-based molten-salt SMR is claimed to have anti-proliferation properties as it complicates the separation of plutonium from thorium (ThorCon, 2018).

European experts expressed skepticism regarding the proliferation resistance narrative. Instead, they expected that the proliferation characteristics of SMRs will be similar to - or worse than – those of larger reactors. On the one hand, they noted that regulations are already particularly restrictive and that it would be difficult to develop and sell reactors with poor proliferation properties. On the other hand, they acknowledged that the multiplication and dispersal of small nuclear infrastructures across national territories would likely increase the risk of nuclear material diversion.

> I think SMRs are much more dangerous than big nuclear power plants, because if you a have big nuclear power plant, you have physical protection. Everything is in one place. But if you have, like Westinghouse is saying… that they are going to construct 1 000 SMRs in the near future, how would you protect 1 000 SMRs against the robbery of nuclear material? So, I think this narrative is incorrect. (F, Head of research institute, Reactor physics).

The interviewees were aware of the risks associated with the possible dual use of radioactive materials. European expert's expectations regarding SMR proliferation resistance were only marginally aligned with those formulated by international SMR proponents as they are expected to be, at best, similar to those of larger reactors. The multiplication of small nuclear infrastructures that require material and human protection is perceived as a significant challenge that may hamper marketability. Figure 6 synthesizes the proliferation resistant energy solution narrative expressed by international SMR proponents (grey) and the elements put forward by the experts (blue).

Figure 6 – Juxtaposed SMR proliferation resistance expectations



Experts' outlook on the SMR promise: an opportunity to revitalize the nuclear industry

Despite some disparities, the analysis revealed broad commonalities in interviewees' expectations. European experts' common outlook concerning SMRs is that they offer a potential pathway for revitalizing the nuclear sector by reshaping its public image and helping to rebuild nuclear skills and competences. First, many interviewees envisioned SMRs as a means of presenting nuclear energy in a more favorable light to the general public. SMRs would help rebrand nuclear energy with an approach to nuclear power generation less burdened by the negative connotations typically associated with large nuclear plants. Some Gen IV concepts, in particular, are considered even further removed from these associations and thus more likely to spark public curiosity and interest.

> We should always find new words and change the vocabulary to detach (nuclear power) from big bad associations. […] If we manage to find a way to decouple from the bad past we can be successful, I think. With molten-salt SMRs, they are doing very good job with it. They managed to sell it as a very innovative new solution (M, Head of research group, Reactor physics).

Hence, SMRs embody promises of innovation that primarily target public. Contrary to international proponents' discourses, the European experts did not view SMRs as particularly innovative: small reactors are an old concept in nuclear engineering history and, with some exceptions, most of the designs under development are based on known technologies. Additionally, they observed that many of the qualities attributed to SMRs could in fact equally apply to conventional reactors.

> It's also often the same when we, for example, talk or read about thorium… It's sort of similar. You say, okay, thorium will solve all the problems and especially because it's good for decarbonization. But what's wrong with MOX? It's… it's the same. So, you should always compare, because people take the advantages of nuclear and attribute them to SMRs. (M, Head of research group, Reactor physics)

Secondly, instead of a one-size-fits-all solution to energy and climate problems, European experts often depicted SMRs as an opportunity to revitalize a declining nuclear industry sector. In the past decades, budget constraints and a lack of construction projects have led to a decline in the skills and know-how needed to build large nuclear plants and an erosion of the supporting industrial network. For instance, French engineers usually attributed the significant time and cost overruns in EPR construction to this factor. In this context, SMRs were depicted as an accessible endeavor to reactivate the sector and progressively restore skills and industrial capabilities.

> And maybe this is actually the biggest advantage of SMRs. It is much easier to come back to nuclear with SMRs than to come back to nuclear with big nuclear power plants. Because, if you lose personnel, you lose the industry and everything which is somehow connected to big nuclear power plant. It is much easier to come back to nuclear using SMRs. (F, Head of research institute, Reactor physics).

In the long term, large-scale SMR production is expected to provide a steady source of activity and revenue, while regenerating the sector's capabilities in the process.

> That's why the SMR can also play a role. It's because it's a way of maintaining the industrial fabric more easily. Because if we build the EPR fleet and then just stop… Well, 20 years or 30 years later you would have lost everything again and you would have to start from scratch [to build new reactors]. (R, Research engineer, Reactor physics).

Although they embody the promise of a consolidation of the nuclear industry, SMRs remain at the periphery of experts' vision for the future of nuclear power generation. Indeed, for many interviewees, the underlying ambition would be to restore the competences and skills needed to reliably deliver large-scale nuclear projects. This echoes many observations discussed in previous sections, signaling a sharp preference for larger, more optimized reactors that can generate large amounts of nuclear power in the most efficient way possible.

> So, modularity can help us to get back the competences. But once we have the competences, we can forget about small and forget about… Okay. Keep modular wherever we can, but once we have the competencies, we can build big and not small modular reactors (L, Research Engineer, Reactor Physics).

Conclusion: scaling-down to better scale-up

Navigating the versatile nature of SMR expectations, this article has examined the extent to which international SMR proponents' promissory discourse aligns with the situated expectations (Brown, 2003) of experts involved in SMR R&D in Europe. Using a two-step approach, we first reviewed documents published by international SMR proponents and identified five key expectation narratives (on costs, flexibility, environment, safety, and proliferation) constitutive of the SMR umbrella promise. This broad promissory discourse displays strong performative ambition, seeking to attract investment and public interest by presenting SMRs as scalable, one-size-fits-all solutions. Second, 25 semi-structured interviews with ESFR-SIMPLE experts allowed to move beyond hype-laden promises, shedding light on experts' situated expectations. Drawing on theoretical knowledge, research experience, and general nuclear expertise, the interviewees critically assessed SMRs' projected capabilities, tempering key promissory claims made by international proponents. They also articulated value-laden assessments reflecting generalized hopes about how SMRs could contribute to the nuclear sector's future.

Although our results reveal discrepancies between European experts' situated expectations and the expectation narratives pertaining to the SMR umbrella promise, they also indicate that interviewees did generally align with the overarching frames articulated in these narratives. European experts typically tempered and complemented, rather than disputed, the SMR expectation narratives identified in our review — only challenging some specific claims contained in those narratives through technical reasoning. Even where situated expectations diverged more markedly, such as on proliferation, interviewees did not entirely reject the general framing, suggesting that SMRs would likely not perform much worse than large reactors in this respect.

These findings point to a productive tension. While the experts consistently questioned aspects of the broad SMR promissory discourse – including claims regarding superior safety, environmental performance, proliferation resistance, and cost-effectiveness – they nonetheless positioned their situated expectations in ways that fit the SMR umbrella promise. In other words, they simultaneously endorsed SMRs as a credible and necessary pathway while still emphasizing potential inefficiencies, diseconomies of scale, or safety challenges.

This apparent paradox can be understood through the *interpretative flexibility* (Konrad et al., 2006; Eames et al., 2006) afforded by the SMR umbrella promise. Rather than operating as a rigid blueprint, the umbrella promise (Parandian et al., 2019) provides an elastic discursive space in which heterogeneous and sometimes ambivalent situated expectations can coexist provided they do not fundamentally challenge overarching frames. Indeed, the expectation narratives identified in this research successfully accommodated experts' situated SMR expectations and promises by offering sufficiently broad meaning structures for experts to interpret and adjust assessments to – allowing experts to navigate between forecast and foresight positions. For instance, while the costs expectation narrative emphasizes general SMR affordability in terms of capital, operational, and maintenance costs, it tends to overlook other key aspects of SMR economics, such as cost-effectiveness. Although interviewees acknowledged that downsizing reactors may lead to diseconomies of scale and higher electricity costs per kilowatt, they still aligned with the overarching cost framing – arguing that, from a capital costs perspective, SMRs would still represent a more affordable and predictable investment option than large reactors.

The SMR umbrella promise also offers a form of *protection* (Parandian et al., 2019; Rip & Voß, 2013; Konrad, 2006) for experts' own situated promise, which can be summed-up as follows: although less efficient than large reactors, SMRs are a technically feasible and highly marketable transitional solution that could enable the durable revitalization of the nuclear sector and help restore the competences needed for future large reactor projects. This promise appears nested in the SMR umbrella promise, which presents SMRs as an affordable, standardized, safe, and flexible solution for a sustainable and resilient energy future. While experts often voiced a preference for large reactors when given the choice, they acknowledged that the erosion of nuclear skills and competences in Europe compromises this option. In this context, the interviewees generally endorsed the broad SMR promissory discourse for its perceived ability to rebrand nuclear energy and rekindle interest in the nuclear sector among investors, policymakers, and citizens – thus indirectly supporting their own situated promise. Consistent with other studies (e.g., Rip & Voß, 2013), interviewees acknowledged that their vision for the nuclear sector is more likely to materialize if sheltered under a broader promissory discourse. Here, experts' situated promise also builds on expectations about the perceived performative efficacy of the SMR umbrella promise, suggesting that umbrella and situated promises are not only co-constructed but also form a symbiotic relationship, reinforcing one another and strengthening the overall promissory regime.

Moving further, these findings suggest that – in line with a regime of economics of techno-scientific promises (Joly, 2010) – interviewees are well aware of how promises can be strategically employed as rhetorical tools to generate interest and support among choice audiences. Interviewees' reflective distance regarding the umbrella promise's target audience also underscores that broad SMR promissory discourses and experts' situated promises are in fact directed at different publics. While the former primarily targets potential investors, policymakers, and citizens, the latter is aimed at peers and other actors within the nuclear sector. To engage these distinct audiences, both international SMR proponents and European experts draw on a common discursive motif in the form of scalability (Pfotenhauer et al., 2022) to enhance the credibility and legitimacy of their respective promises. Yet, the umbrella and situated promises reflect nuances in how *scaling-up* and *scaling-down* are leveraged by the nuclear sector to frame problems (thereby enhancing legitimacy) and readily available technological solutions (thus reinforcing credibility) for distinct audiences.

In the umbrella promise, international SMR proponents suggest *scaling-down nuclear reactors to better scale-up the deployment of small, one-size-fits-all systems*: smaller, simpler, cheaper, safer, more flexible, and environmentally-friendly reactors that open-up broad market potential due to their wide range of applications across diverse grid configurations. Here, scaling is used to frame the problem for future investors, policymakers, and citizens. Problem framing emphasizes the urgent need for scalable low-carbon energy solutions capable of addressing a variety of local energy needs and requirements in current and future energy systems. Large-scale nuclear reactors are depicted as ill-adapted for tackling these issues, given their construction costs, recurrent schedule overruns, limited flexibility, and negative public image. Promise credibility is then reinforced by stressing how downscaling reactors, through modular factory-based production, should resolve most of these issues and enable large-scale deployment.

By contrast, European experts envision *scaling-down nuclear reactors to better scale-up the deployment of large-scale systems*. Here, scaling is used to frame both the problem and its solution for peers – namely nuclear engineers, and researchers — and other actors concerned with declining skills and competences in the nuclear sector (e.g., supply chain, engineering firms). The problem is framed around the gradual erosion of the nuclear industry's ability to deliver highly complex and resource-intensive large-scale nuclear projects at reasonable cost and within reliable timeframes. In response, experts propose a (temporary) shift toward smaller reactors which should prove more manageable for the industry both in terms of R&D and deployment. Although less efficient and optimized than large reactors, SMRs are expected to attract sufficient resources to recover the skills and industrial base required to support future large-scale nuclear projects. In that sense, and as already highlighted by other scholars, they are portrayed as a transitional 'steppingstone' (Lehtonen, 2024) in a much-awaited revival of the European nuclear sector.

This suggests that the scalability motif serves a similar function in both umbrella and situated promises by establishing credibility and legitimacy through the distinct framing of problems and solutions for different target audiences. Both experts' and international SMR proponents' promissory discourses revolve around addressing issues that are perceived as core constraints on nuclear energy deployment. While international proponents advocate scaling-down reactors to overcome challenges commonly associated with large reactors in the eyes of broader audiences, experts present SMRs to their peers as a transitional steppingstone, capable of replenishing skills and rebuilding the industrial base required for future large-scale projects. In both cases, scalability operates as a strategic response to perceived sectoral limitations, albeit articulated for different audiences and purposes. In line with Pfotenhauer et al.'s (2022) politics of scaling, we call for further research into how scaling is mobilized to elicit the perceived credibility and legitimacy of promissory discourses, and with what performative effects on future nuclear R&D trajectories.

This shared orientation toward overcoming perceived constraints on nuclear power deployment invites a broader reflection on the function of the SMR promissory discourse. In particular, one may ask whether it really functions as a driver of technological transformation or rather as a strategic rebranding of nuclear power under conditions of uncertainty and industrial fragility. On the one hand, our findings show that experts' relative alignment with the SMR umbrella promise does not necessarily reflect belief in a fundamentally superior technology, but rather recognition of its performative capacity to mobilize attention, resources, and legitimacy for the nuclear sector – and potentially to open pathways toward future large-scale projects. From this perspective, the SMR promissory discourse may indeed operate, at least in part, as a rebranding device that distances nuclear energy from the economic, organizational, and political challenges often associated with recent large-scale reactor projects.

On the other hand, reducing SMR promissory discourses to a mere rebranding act would only provide a narrow account of how different actor groups may distinctly relate and contribute to the SMR umbrella promise. Indeed, although our findings carry broader analytical implications, they are also grounded in the situated expectations of a particular group of European technical experts, whose views are closely tied to concerns about skills erosion, industrial continuity, and the long-term consolidation of the nuclear sector. Many interviewees had prior experience in large reactor R&D, which likely shaped their SMR-related assessments and overall stance toward the umbrella promise. Moreover, unlike most commercial ventures, the ESFR-SIMPLE project does not include economic experts who might have counterbalanced these expectations with a market-oriented perspective.

Building on the situatedness of expectations (Brown, 2003), it is reasonable to assume that actors embedded in different R&D environments – such as those within industrial firms, utilities, or startups – would distinctly engage with the SMR umbrella promise, attributing different meanings and stakes to its promissory claims. Future research should therefore examine how situated expectations held by different actor groups within a community of promise align – distinctively and selectively – with broader promissory discourses. More specifically, comparing situated expectations across commercial and non-commercial SMR projects would help capture how and why actor groups selectively align with, reinterpret, or challenge the SMR umbrella promise. Such work would further clarify how umbrella promises maintain relevance across heterogeneous actor groups within communities of promise, despite distinct and potentially diverging situated expectations.

References

Beckert, J., & Bronk, R. (2019) Uncertain Futures: Imaginaries, Narratives, and Calculative Technologies, *Max-Planck-Institut für Gesellschaftsforschung Discussion Papers*, *19*(10), pp. 1–18.

Berkhout, F. (2006) Normative expectations in systems innovation, *Technology Analysis & Strategic Management*, *18*(3–4), pp. 299–311.

Berti, P., & Levidow, L. (2014) Fuelling expectations: a policy-promise lock-in of UK biofuel policy, *Energy Policy*, *66*, pp. 135–143.

Borup, M., Brown, N., Konrad, K., & Van Lente, H. (2006) The sociology of expectations in science and technology, *Technology analysis & strategic management*, *18*(3–4), pp. 285–298.

Brown, N. (2003) Hope against hype-accountability in biopasts, presents and futures, *Science & Technology Studies*, *16*(2), pp. 3–21.

Brown, N., & Michael, M. (2003) A sociology of expectations: Retrospecting prospects and prospecting retrospects, *Technology analysis & strategic management*, *15*(1), pp. 3–18.

Budde, B., & Konrad, K. (2019) Tentative governing of fuel cell innovation in a dynamic network of expectations, *Research policy*, *48*(5), pp. 1098–1112.

Cooper, M. (2014) Small modular reactors and the future of nuclear power in the United States, *Energy Research & Social Science*, *3*, pp. 161–177.

Dandurand, G., Claveau, F., Dubé, J. F., & Millerand, F. (2020) Social dynamics of expectations and expertise: AI in digital humanitarian innovation, *Engaging Science, Technology, and Society*, *6*, pp. 591–614.

Derdevet, M., & Mazzucchi, N. (2021) Les petits réacteurs modulaires, une nouvelle ère nucléaire? Approche géopolitique et stratégique, *La Revue de l’Energie*, (657), pp. 45-57.

Eames, M., McDowall, W., Hodson, M., & Marvin, S. (2006) Negotiating contested visions and place-specific expectations of the hydrogen economy, *Technology Analysis & Strategic Management*, *18*(3–4), pp. 361–374.

ESFR-SIMPLE Consortium (2026). *D3.2 Description of the SMR system design* (Unpublished project deliverable).

European Commission. (2024) Speech by President von der Leyen at the Nuclear Energy Summit. Available at: https://ec.europa.eu/commission/presscorner/detail/en/speech_24_1624 (last accessed July 2024).

Flick, U. (2018) *An introduction to qualitative research* (London: Sage). Glaser, B.G., & Strauss, A. L. (2017) *Discovery of grounded theory: Strategies for qualitative research* (New York: Routledge).

Gonçalves Filho, O.J.A. (2011) INPRO economic assessment of the IRIS nuclear reactor for deployment in Brazil, *Nuclear engineering and design*, *241*(6), pp. 2329–2338.

IAEA. (2023) What are Small Modular Reactors (SMRs)?. Available at: https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs (last accessed May 2024).

IAEA. (2020) *Considerations for Environmental Impact Assessment for Small Modular Reactors* (Vienna: International Atomic Energy Agency).

IAEA. (2021a) *Technology Roadmap for Small Modular Reactor Deployment* (Vienna: International Atomic Energy Agency).

IAEA. (2021b) *Benefits and Challenges of Small Modular Fast Reactors – Proceedings of a Technical Meeting* (Vienna: International Atomic Energy Agency).

IAEA. (2022) *Climate Change and Nuclear Power 2022 - Securing Clean Energy for Climate Resilience* (Vienna: International Atomic Energy Agency).

Joly, P.B., (2010) On the economics of technoscientific promises. In: M. Akrich, Y. Barthe, F. Muniesa, P. Mustar, (Eds.) *Débordements - Mélanges offerts à Michel Callon*, pp. 203-222 (Paris, Presses des Mines).

Kari, M., Lehtonen, M., Litmanen, T., & Kojo, M. (2023) Technology hype, promises, and expectations: The discussion on small modular reactors in the Finnish newspaper ’Helsingin Sanomat’in 2000 – 2022, *Zeitschrift für Technikfolgenabschätzung in Theorie und Praxis*, *32*(3).

Kerr, A., Barry, M., & Kelleher, J.D. (2020) Expectations of artificial intelligence and the performativity of ethics: Implications for communication governance, *Big Data & Society*, *7*(1), pp. 1–12.

Konrad, K. (2006) The social dynamics of expectations: The interaction of collective and actor-specific expectations on electronic commerce and interactive television, *Technology Analysis & Strategic Management*, *18*(3–4), pp. 429–444.

Konrad, K., Van Lente, H., Groves, C., & Selin, C. (2016) Performing and Governing the Future in Science and Technology, in U. Felt, R. Fouche, & C.A. Miller (Eds) *The handbook of science and technology studies*, pp. 465–493 (Cambridge: The MIT press)

Kriechbaum, M., Terler, N., Stürmer, B., & Stern, T. (2023) (Re)framing technology: The evolution from biogas to biomethane in Austria, *Environmental Innovation and Societal Transitions*, *47*, 100724.

Lehtonen, M. (2024) Taking stock of the SMR promise, *Nuclear Engineering International*.

Linberg, K. R. (1999) Software developer perceptions about software project failure: a case study, *Journal of systems and software*, *49*(2–3), pp. 177–192.

Martin, P., Brown, N., & Kraft, A. (2008) From bedside to bench? Communities of promise, translational research and the making of blood stem cells, *Science as Culture*, *17*(1), pp. 29–41.

NEA. (2024) *The NEA Small Modular Reactor Dashboard: Second Edition* (Paris: Nuclear Energy Agency).

NEA. (2021) *Small Modular Reactors: Challenges and Opportunities* (Paris: Nuclear Energy Agency).

Newcleo. (2025) *reactors-SMR* [Illustration]. Newcleo. https://www.newcleo.com/our-technology/reactors/

NuScale. (2022) NUSCALE Cost Competitive. Available at: https://www.nuscalepower.com/-/media/nuscale/pdf/fact-sheets/cost-competitive-fact-sheet.pdf (last accessed July 2024).

Paillé, P., & Mucchielli, A. (2021) *L'analyse qualitative en sciences humaines et sociales - 5e éd*. (Paris: Armand Colin).

Palm, E., & Nikoleris, A. (2021) Conflicting expectations on carbon dioxide utilization, *Technology Analysis & Strategic Management*, *33*(2), pp. 217–228.

Parandian, A., Rip, A., & Te Kulve, H. (2019) Dual dynamics of promises and waiting games around emerging nanotechnologies. In: A. Rip (Ed) *Nanotechnology and Its Governance*, pp. 34–55 (London: Routledge).

Pfotenhauer, S., Laurent, B., Papageorgiou, K., & Stilgoe, A.J. (2022) The politics of scaling, *Social studies of science*, *52*(1), pp. 3–34.

Pollock, N., & Williams, R. (2010) The business of expectations: How promissory organizations shape technology and innovation, *Social Studies of Science*, *40*(4), pp. 525–548.

Ramana, M.V., & Mian, Z. (2014) One size doesn't fit all: Social priorities and technical conflicts for small modular reactors, *Energy Research & Social Science*, *2*, pp. 115–124.

Reyes Jr., J. N. (2012) NuScale plant safety in response to extreme events, *Nuclear Technology, 178*(2), pp. 153–163.

Rip, A., & Voß, J. P. (2013). Umbrella terms as mediators in the governance of emerging science and technology. *Science, technology and innovation studies*, *9*(2), 39-59.

Sovacool, B.K. (2019) *Visions of energy futures: Imagining and innovating low-carbon transitions* (New York and London: Routledge).

Sovacool, B.K., & Ramana, M.V. (2015) Back to the future: Small modular reactors, nuclear fantasies, and symbolic convergence, *Science, Technology, & Human Values*, *40*(1), pp. 96–125.

Suckert, L. (2022) Back to the future. sociological perspectives on expectations, aspirations and imagined futures, *European Journal of Sociology/Archives Européennes de Sociologie*, *63*(3), pp. 393-428.

Thomas, S., & Ramana, M.V. (2022) A hopeless pursuit? National efforts to promote small modular nuclear reactors and revive nuclear power, *Wiley Interdisciplinary Reviews: Energy and Environment*, *11*(4), p. e429.

ThorCon. (2018) ThorCon The Do-able Molten Salt Reactor. Available at: https://thorconpower.com/docs/domsr20180119.pdf (last accessed July 2024).

Van Lente, H. (1993) *Promising Technology: The Dynamics of Expectations in Technological Developments* (Ph.D. dissertation, University of Twente).

Van Lente, H. (2012) Navigating foresight in a sea of expectations: lessons from the sociology of expectations, *Technology analysis & strategic management*, *24*(8), pp. 769–782.

Van Lente, H., & Bakker, S. (2010) Competing expectations: the case of hydrogen storage technologies, *Technology Analysis & Strategic Management*, *22*(6), pp. 693–709.

Van Lente, H., Spitters, C., & Peine, A. (2013) Comparing technological hype cycles: Towards a theory, *Technological Forecasting and Social Change*, *80*(8), pp. 1615–1628.

WNA. (2023) Small Nuclear Power Reactors. Available at: https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx (last accessed June 2023).