



Perspective

Towards the integration of small modular reactors in industrial hubs: A multi-dimensional discussion

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ABSTRACT

This article discusses the potential for deploying small modular reactors (SMRs) within industrial hubs, using a decentralised configuration to provide direct on-site energy for industrial processes. To assess the feasibility of such a deployment, the analysis adopts the perspective of a stakeholder considering its implementation. This approach follows a four-question discussion, gradually bringing out the main challenges a project of this kind might encounter, from regulatory and operational constraints to economic feasibility and wider societal implications. The main insights derived from this discussion suggest that SMRs could meet a significant portion of industrial energy demand, thereby supporting sectoral decarbonisation, preserving industrial capacity, and enhancing the resilience of energy grids. However, substantial challenges remain, including ensuring the safety of reactors located near industrial facilities, adapting regulatory frameworks to facilitate SMR development, and demonstrating economic competitiveness. In addition, SMR deployment requires careful consideration of nuclear proliferation risks, effective management of radioactive waste, and the prevention of potential nuclear incidents, while maintaining the support of local communities.

1. Introduction

In 2015, the 196 signatories of the Paris Agreement pledged to limit the rise in global average temperature to well below 2°C above pre-industrial levels. This landmark commitment has helped accelerate climate action worldwide [1]. Over the past two decades, technological progress has substantially improved the outlook for decarbonising the transport, building, and energy sectors, as illustrated by the rapid diffusion of renewable energy, electric vehicles, heat pumps, and improved insulation. Yet the industry sector remains far more difficult to decarbonise. Although it is fundamental to modern societies and underpins much of today's economic progress, it still accounts for roughly 30% of global greenhouse gas emissions [2]. Its exposure to intense international competition makes ambitious reductions particularly challenging. As a result, climate policies have so far tended to focus on incremental efficiency gains and marginal emissions cuts [3]. This tension between economic performance and environmental ambition now places the sector under unprecedented pressure to transform both its energy systems and production processes.

Against this backdrop, a growing body of literature points to the potential contribution of nuclear technologies to the decarbonisation of the industrial sector [4–10]. Nuclear energy is characterised by very low greenhouse gas emissions and the ability to deliver reliable, dispatchable power. In addition, it can strengthen national energy

security and can offer competitive economic performance [11]. Despite these advantages, the expansion of nuclear power has historically been limited by substantial upfront capital costs, long and frequently uncertain construction periods, and the enduring influence of major nuclear accidents on public perception and political decision-making [12,13].

Despite these challenges, renewed interest has emerged in recent years, particularly with the development of innovative concepts such as Small Modular Reactors (SMRs). SMRs represent a new generation of nuclear technologies, characterised by relatively low unit capacities (below 300 MWe), a modular architecture suitable for series production, and enhanced intrinsic safety features [14]. In contrast to conventional large-scale reactors, which have traditionally been designed for centralised electricity generation, SMRs offer significantly greater deployment flexibility, enabling decentralised configurations. This decentralised deployment paves the way for a concept in which SMRs are directly connected to industrial hubs, supplying energy on site. Owing to their small size and modular design, SMRs can be scaled by combining multiple modules to meet local energy demands. Furthermore, this deployment allows the direct use of the heat produced by the reactor within industrial processes, providing a dual benefit of dispatchable electricity and process heat. A schematic representation of this approach, illustrating how SMRs can be integrated into industrial hubs, is shown in Fig. 1.

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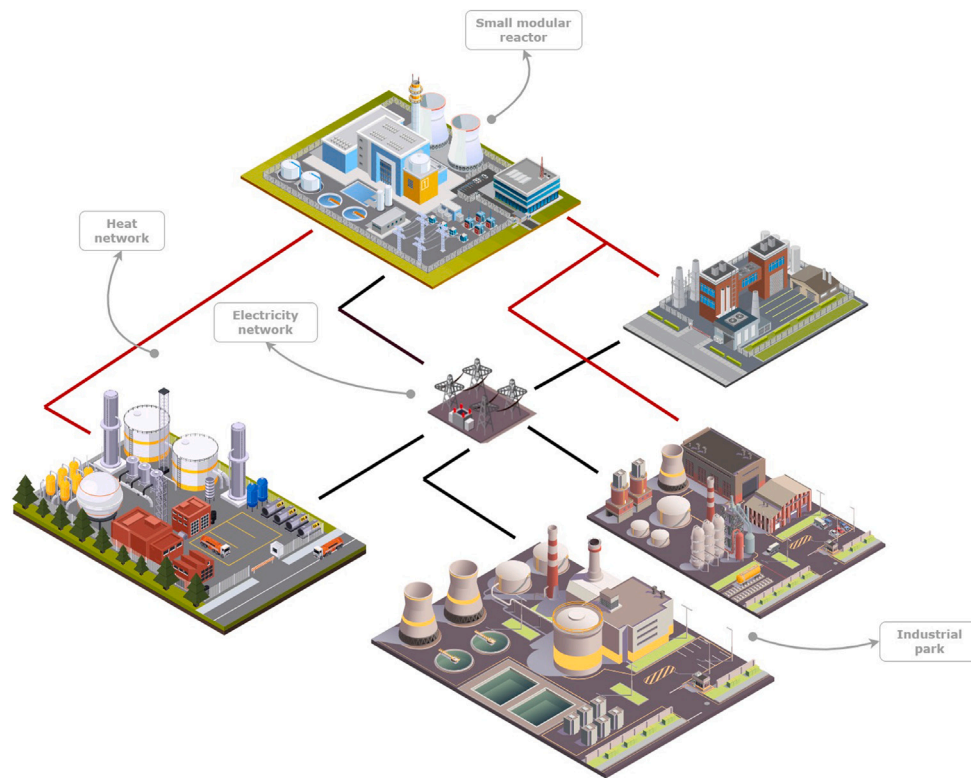


Fig. 1. Integrating an SMR into an industrial hub with heat and electricity networks.

However, the concept remains at an early stage of deployment, as most SMR designs are still under development, with only a few reaching the demonstration stage, and large-scale deployment is not expected before the early 2030s. In addition, operational experience with the use of nuclear reactors for process heat applications, particularly at high temperatures, remains limited. International experience has primarily been confined to low-temperature applications, with examples including heat supply for cardboard production in Switzerland, salt refining in Germany, and district heating in Sweden and China [15].

As a result, many complex and interdependent questions remain unexplored, and the validity of such a concept has yet to be established. For example, from a technical perspective, it is necessary to explore which industrial processes could potentially benefit from SMR integration and what infrastructure would be required to support such systems. Economically, their competitiveness compared with other decarbonisation options remains uncertain, especially given changing costs for renewables, hydrogen, and carbon capture and storage (CCS). Regulatory and societal considerations are equally important: current licensing frameworks were not designed for modular reactors, and public acceptance is likely to strongly influence any future deployment.

These examples, while not exhaustive, illustrate the breadth of the challenges and underline the need for sustained research and informed dialogue. To this end, this article aims to initiate a structured reflection on the multidimensional challenges associated with this deployment strategy, to support the development of future research perspectives and supporting reflection among industrial stakeholders and policymakers.

The article begins in Section 2 by presenting the analytical framework that organises the reflection. Sections 3 to 6 examines various aspects of SMR integration. Finally, Section 7 serves as a conclusion, offering a broader discussion and highlighting the main challenges to SMR deployment in industrial contexts.

2. Framework

The deployment of SMRs has received growing attention in recent years, leading to an expanding body of literature that explores both their potential benefits and their associated challenges. Previous studies have examined a wide range of issues, including financing schemes, regulatory frameworks, operational constraints, as well as broader concerns related to nuclear proliferation and radioactive waste management [10,14,16–18].

Building on this multidimensional literature, this article revisits these questions within a more specific context: the decentralised deployment of SMRs as on-site energy sources for industrial hubs. Rather than aiming at an exhaustive review, the objective is to organise and connect the main dimensions identified in the literature, and to examine how they interact when SMRs are considered for industrial energy supply.

To assess the feasibility of such deployments, the analysis adopts the perspective of a stakeholder considering the installation of an SMR for industrial use. This viewpoint follows a decision-making framework and progressively highlights the main hurdles such a project would face, ranging from regulatory and practical constraints to questions of economic viability. The discussion is structured around four cascading questions that together frame the socio-technical and economic assessment of SMR deployment:

- **Can an SMR meet all industrial energy needs?** This first, high-level question examines whether existing or near-term SMR designs are technically capable of supplying a significant share of industrial energy demand. The focus is on the compatibility between SMR energy outputs (electricity and heat) and the specific requirements of industrial processes.

- **Can an SMR be seamlessly integrated into an industrial complex?** Assuming that these needs can be met, this question addresses the integration of SMRs within industrial hubs. It considers site-specific constraints, spatial organisation, safety requirements, and the supporting infrastructure necessary for integration.
- **Is it cost-competitive?** Conditional on technical feasibility and site integration, this question evaluates the economic viability of SMRs for industrial energy supply. It examines historical and projected costs of nuclear technologies and identifies the conditions under which SMRs could become competitive.
- **Is it socially and ethically sustainable?** Finally, even if technical, spatial, and economic conditions appear favourable, broader societal and ethical considerations remain decisive. This question covers issues highlighted in the literature, such as public acceptance, nuclear proliferation, and the management of radioactive waste.

Overall, this framework provides a structured overview of the main challenges associated with SMR deployment for industrial hubs. By guiding the reader through these four interrelated questions, it aims to clarify both the potential of decentralised SMRs for industrial energy supply and the fundamental limitations that may constrain their deployment.

3. Can an SMR meet all industrial energy needs?

These needs are far from homogeneous and can vary widely across industrial sectors, production processes, and operating conditions. This heterogeneity is particularly pronounced when heat is involved. The heat supplied must be compatible with the characteristics of industrial processes, especially with respect to the required temperature levels. These range from relatively simple operations such as boiling or drying to far more energy-intensive processes, including cooking, melting, or sintering (see Table 1) [19,20].

In existing industrial configurations where a centralised energy system supplies an industrial site or hub, this role is most commonly fulfilled by gas- or coal-fired thermal power plants. These technologies are capable of meeting a wide range of thermal demands while simultaneously generating electricity. As a result, most industrial equipment has been designed to operate on combustion-based processes, enabling the produced heat to be adjusted across a broad range of temperature requirements.

When considering the replacement of a conventional cogeneration system with an SMR, it is therefore essential to ensure that the reactor's outlet temperature is compatible with the thermal requirements of the targeted industrial processes.

Furthermore, the suitability of SMRs for industrial applications also depends on their ability to meet industrial operational requirements. Industrial processes typically require a continuous and highly reliable energy supply in order to avoid interruptions and to ensure both safety and economic performance. Their assessment must therefore also consider operational performance criteria such as reliability, availability, and flexibility [22].

In this context, assessing whether SMRs can effectively meet industrial energy demands requires an examination of the different SMR designs currently under development. The following paragraphs therefore focus on the characteristics of the heat produced by these reactors, particularly in terms of temperature levels, as well as their ability to provide a stable and secure energy supply.

Thermal capabilities of modern and advanced nuclear reactors

Most of the nuclear reactors currently in operation correspond to Generation III. These reactors primarily rely on pressurised water (PWR) and boiling water (BWR) technologies, producing steam at approximately 300°C [23]. This temperature is compatible with certain industrial processes, such as those found in the paper industry or in desalination [24]. However, for operations requiring higher-temperature heat, these designs are not suitable. This limitation is significant, especially considering that, at the European level, more than three-quarters of industrial process heat demand is estimated to require temperatures above 250°C, with more than half falling within the 250–550°C range [24].

Regarded as a technological evolution of Generation III, Generation IV reactors are already operational and incorporate innovations, particularly in coolant selection. By replacing water with alternative fluids such as liquid metals, molten salts, or inert gases, they can achieve significantly higher outlet temperatures. Each reactor design is therefore associated with a specific temperature range reflecting its underlying technological characteristics.

The Generation IV International Forum (GIF) has selected six reactor designs for further research and development [25] (see Table 2). For instance, the gas-cooled fast reactor (GFR) can reach outlet temperatures exceeding 800°C, enabling integration into high-temperature industrial processes such as aluminium production, ammonia synthesis, and oil refining [26].

The diversity of reactor designs inherently enables the delivery of a broad range of temperature levels suited to different industrial applications. However, for very high-temperature processes, such as cement production or steelmaking, where operating temperatures may exceed 800°C, current reactor technologies remain outside the required operational range. This limitation is primarily associated with the constraints imposed by the materials used in heat transport and heat exchange systems, which must withstand particularly severe thermal and mechanical stresses. Research efforts are therefore still required to identify and validate alternative solutions able to operate reliably under very high-temperature conditions [22].

Nevertheless, SMRs could already play a complementary role in these industrial sectors by providing preheating for raw materials or combustion air. In this way, they could help reduce the energy demand currently supplied by conventional sources in cement kilns and blast furnaces [26].

Operational requirements of SMRs

Nuclear power plants are characterised by high capacity factors, frequently exceeding 75% over their operational lifetime [27], ensuring a high level of energy availability. Nevertheless, periodic shutdowns remain unavoidable to carry out maintenance, inspections, and fuel reloading operations. In this context, multi-module architectures prove particularly well-suited to maintaining continuity of supply: certain reactor modules can remain in operation while others are temporarily shut down, thereby limiting the risk of a complete interruption of energy provision. Conventional back-up systems, generally based on fossil fuels, may furthermore be integrated to meet the reliability requirements specific to the industrial site [28].

Beyond these considerations relating to availability and continuity of service, energy systems dedicated to industrial applications must also

Table 1
Temperatures ranges of heat application processes [21].

Temperature level (°C)	
<100	Low-temperature heat (hot water) used in the food industry and others
100–200	Steam, mostly used in paper, food and chemical industries
200–500	Steam, mostly used in the chemical industry
>500	Industrial furnace in steel, cement, glass and other manufacturing processes

Table 2

Outlet temperature ranges of different types of GEN IV nuclear reactors [25].

Reactor	Outlet temperature (°C)
SFR (sodium-cooled fast reactor)	500–550
SCWR (supercritical-water-cooled reactor)	510–625
GFR (gas-cooled fast reactor)	850
LFR (lead-cooled fast reactor)	480–570
MSR (molten salt reactor)	700–800

be capable of adapting to fluctuations in demand. Unlike large conventional nuclear power plants, which have historically been operated in baseload mode to deliver stable and continuous electricity, SMRs integrated into industrial hubs may require operating under more variable load profiles. Such variations may arise during start-up and shutdown sequences, in response to fluctuations inherent to industrial processes, or following equipment failures and other unforeseen disturbances.

Load-following operation may be achieved through direct actions on reactor systems, including adjustment of control rods, regulation of primary coolant flow rates, or management of steam generators, depending on the SMR design considered. It may also be implemented indirectly through the integration of thermal energy storage systems capable of decoupling nuclear energy production from instantaneous industrial demand [29]. Amongst the various storage technologies available, molten salt systems are particularly interesting due to their thermophysical properties: they allow the reactor to operate under relatively stable conditions, with flexibility provided through the charging and discharging cycles of the storage system [30].

Each of these approaches, however, introduces specific technical constraints, particularly with respect to ramp rates, operational ranges, and the thermomechanical stresses imposed on reactor components.

Modern light-water reactors already possess advanced manoeuvring capabilities, with some recent designs allowing both planned and unplanned load variations over a wide operating range, with ramp rates reaching up to 5% of nominal power per minute [31]. Although load-following operation induces repeated thermal and mechanical transients [32], which may accelerate the ageing of certain components in older reactor designs, modern reactors are increasingly being engineered to incorporate such operational flexibility while limiting impacts on major structural components. Nevertheless, some secondary systems, such as valves, may still experience increased wear, potentially leading to higher maintenance requirements and operating costs. Consequently, SMRs intended for industrial applications will need to be specifically designed and dimensioned to accommodate the expected demand profiles while controlling the effects of power modulation on component lifetime and overall system durability.

Discussion

Owing to the wide diversity of reactor concepts, characterised by different outlet temperature ranges and the potential to provide a reliable and flexible energy supply, SMRs appear, in principle, well-suited to meeting a broad spectrum of industrial energy demands.

The variety of designs, combined with the heterogeneity of industrial requirements, suggests that each type of SMR is likely to find its most suitable applications in sectors whose technical characteristics align closely with its own. At present, however, it remains challenging to identify any single concept that clearly stands out: no SMR has yet been deployed directly on industrial hubs, let alone across multiple design variants. It is not yet possible to determine whether a process of technological “natural selection” will lead to the emergence of a limited number of dominant designs, or whether the current diversity of concepts will persist in response to differentiated sectoral needs and application contexts.

High-temperature SMRs appear particularly well suited to industrial applications, as their elevated outlet temperatures enable them to meet

a broader range of industrial demands while also limiting the need for additional temperature upgrade solutions. This, in turn, enhances their overall attractiveness [26].

Moreover, the thermal output temperature of a reactor should not be regarded as a hard ceiling for industrial applications, as several complementary pathways exist to reach higher process temperatures. These include hydrogen production and combustion, as well as heat pump technologies and electric superheating [33–35], collectively broadening the range of industrial processes that SMR-based energy systems could serve. Assessing the practical relevance of such hybrid configurations, however, requires site-specific studies to determine the technical and economic conditions under which these systems become genuinely advantageous.

In parallel, industrial processes themselves can be adapted to better align with the heat supplied by SMRs, thereby enabling operation at lower temperatures that are compatible with current reactor technologies. An example of this evolution is the development of a membrane-based steam–methane reforming process, which achieves sufficient efficiency for hydrogen production within a temperature range of 600–650°C, compared with the 850–900°C required in conventional industrial processes [22].

4. Can an SMR be seamlessly integrated into an industrial complex?

Having established that SMRs have the potential to meet a wide range of industrial energy demands, it remains to be determined whether they can be integrated into existing industrial hubs, where various constraints must be considered, particularly in terms of regulation and safety.

Indeed, nuclear technology is subject to extremely stringent safety standards, while industrial hubs are governed by their own operational and security requirements. Reconciling these two regulatory and operational frameworks represents a challenge: it not only limits the feasibility of directly integrating SMRs into existing facilities but also complicates the identification of suitable sites and the development of new industrial hubs specifically designed for this purpose.

This section therefore aims to analyse the various associated constraints, whether arising from nuclear exclusion zone regulations, infrastructure requirements, or certification and licensing procedures. In parallel, it assesses the potential benefits that SMRs could provide in addressing these challenges.

Considerations for SMR siting

Primarily, due to the risk of radiological impact on neighbouring populations in the event of a severe accident involving releases, the site must be capable of ensuring an extended exclusion zone. As with large nuclear power plants, SMRs would generally need to be located at a safe distance from densely populated areas. Traditionally, the exclusion zone around a reactor extends over several kilometres, beyond which only industrial activities are considered feasible. For reactors with a thermal output between 100 and 1000 MWth, the IAEA recommends an emergency planning zone (EPZ) radius of between 5 and 25 km [36]. Even the lower limit of 5 km, although less than that typically adopted for current conventional reactors, could pose a major obstacle in industrial environments where available space is limited and interactions with existing facilities are already heavily constrained.

In addition, selecting a site for a nuclear facility involves a comprehensive assessment that considers geological and climatic conditions, cooling needs, and logistical accessibility, as well as the availability of essential infrastructure such as electricity supply, security systems, and communication networks. The process must also account for environmentally protected areas, which can restrict land use and lead to additional regulatory constraints [37,38]. In cogeneration applications,

energy performance considerations also necessitate a degree of proximity between the reactor and the industrial process, in order to minimise thermal losses and the costs associated with heat transport. While heat losses remain limited when transferred as hot water, they become more significant when heat is supplied as steam due to pressure constraints and transport conditions [28].

However, increasing proximity also introduces additional safety constraints. When nuclear installations are sited near potentially hazardous industrial activities, neighbouring facilities such as chemical plants, refineries, fuel terminals, and storage depots may represent external sources of risk to nuclear safety. Such hazards may result from a range of events, including the release of flammable, explosive, or toxic substances. In this context, IAEA safety guidance provides indicative screening distances for such hazards, with a reference value of around 5 km used as an example in early siting assessments for actual nuclear installations, although site-specific evaluations remain essential [38].

Expected benefits of SMRs

Nevertheless, the development of SMRs comes with a number of promising characteristics that could alleviate some of the constraints outlined above. Compared with large reactors, SMRs offer the advantage of compactness, which facilitates their integration into a wider range of environments. For example, the AP300 SMR (225 MWe) developed by Westinghouse can be installed in an underground silo approximately 30 m deep and 30 m in diameter, occupying only 30% of the footprint of an AP1000 reactor [28]. Similarly, the SMART SMR (110 MWe) integrates all primary circuit components into a single pressurised module, simplifying its architecture and further reducing its physical footprint.

This trend becomes even more pronounced in the case of microreactors, a sub-category of SMRs generally producing between 1 and 20 MWe, whose output is more closely aligned with the energy requirements of many industrial facilities (typically on the scale of a few megawatts and only rarely exceeding several hundred megawatts). Owing to their significantly lower power output compared with conventional reactors, the potential release of fission products is substantially reduced, which supports reconsideration of the regulatory requirements governing the size of emergency planning and protective action zones surrounding the facility [39,40].

Beyond considerations of scale, SMRs are also associated with technological developments expected to improve safety performance. Frequently cited features include passive cooling systems, lower operating pressures, increased thermal margins, underground installation concepts, and reduced radioactive inventories. Taken together, these characteristics are often presented as offering enhanced intrinsic safety relative to conventional nuclear plants. Such improvements could, in turn, justify adaptations to certain regulatory requirements currently applied to nuclear facilities, particularly those relating to staffing levels, containment robustness, or the complexity of emergency planning arrangements [41,42].

From a siting perspective, several constraints commonly associated with nuclear installations are already addressed within existing large industrial sites. Such facilities typically benefit from established infrastructure, including road access, navigable waterways, and grid connections, while geological and meteorological conditions, flood risk management, and environmental restrictions are likewise factors already considered in industrial planning and site development. Furthermore, many major industrial hubs are situated in close proximity to substantial water resources, including ports, canals, and rivers, that may serve as cooling sources. It should be noted, however, that SMRs may be less dependent on immediate access to high-capacity water sources than conventional reactors. Depending on the technology selected, certain designs rely on alternative heat transfer fluids or incorporate air-cooling systems, potentially offering greater flexibility in site selection [43,44].

Regulatory challenges

However, none of these potential improvements have, to date, been incorporated into existing regulatory frameworks. Regulations applied in major nuclear markets have been designed for large reactors and may hinder the deployment of SMRs. Many innovative design elements will need to be justified by designers and validated by the competent authorities before a licence can be granted.

Industrial facilities are also subject to strict regulatory requirements, including ATEX zones (Explosive Atmosphere), networks transporting steam or hazardous fluids, and the management of large personnel flows. The precise definition of the boundaries between nuclear regulations and those of other industries for co-located installations is an essential prerequisite for developing configurations suitable for integrating SMRs into industrial processes. Such a regulatory framework has yet to be established [26].

Furthermore, the regulations governing licensing processes are derived from national legislation, which varies significantly between countries. This regulatory diversity limits the ability of SMRs to fully exploit their potential for standardisation and modularity. In this context, the World Nuclear Association and the IAEA emphasise the benefits of leveraging SMR standardisation to simplify licensing processes [45, 46]. A single certification of the reactor module design (including primary safety systems) would allow its reuse for identical modules and potentially facilitate cross-border acceptance. This approach could significantly reduce the regulatory burden, avoid redundant analyses, and ease the construction and operation of multiple SMR modules on the same site. However, this model would still need to be supplemented by additional licences, such as overall installation authorisation, site approval, external risk authorisation, or emergency plan approval.

Discussion

The question of whether SMRs can be seamlessly integrated into an industrial complex reveals that such integration is far from straightforward. This integration actually raises multidimensional challenges and continues to fuel significant uncertainties regarding its feasibility.

For an SMR to be considered acceptable within an industrial hub, its safety performance should be of a high level, comparable to that required for existing nuclear power plants. Although SMR designs may offer additional safety margins, these theoretical advantages must effectively offset the increased risks associated with the proximity of potentially hazardous industrial processes. Forecasts of safety gains and, consequently, the possibility of relaxing certain standards remain based on assumptions that have yet to be proven under real-world conditions. Reducing protection zones too drastically in a complex industrial environment could, in practice, introduce new vulnerabilities rather than enhance safety.

The very concept of SMRs is based on modularity and standardisation, which are supposed to allow the serial manufacture of reproducible modules and simplify design and licensing processes. However, deploying such reactors within industrial hubs subject to highly specific safety requirements raises the question of whether this standardisation can truly be maintained. Each industrial hub has its own constraints, linked to technological hazards, existing infrastructure, or operating regimes, and adapting a “standard” SMR to this diversity of configurations could, in practice, limit its potential for redeployment and diminish the expected economic benefits of modularity.

This issue is compounded by the lack of harmonisation of nuclear regulations at the international level. The ability of SMRs to capitalise on standardisation will depend largely on the convergence of licensing frameworks between countries, a necessary condition to avoid the proliferation of adaptations specific to national jurisdictions. Yet such convergence can only emerge through strong, sustained, and shared political will among regulators and governments. Without this alignment, SMRs risk remaining highly context-dependent products, far from the initial ambition of a truly modular and exportable model.

5. Is it cost-competitive?

Building on the initial two steps of analysis, it becomes apparent that the deployment of SMRs within industrial hubs rests on a complex set of assumptions, and their integration cannot be taken for granted. Significant uncertainties remain concerning the actual safety gains achievable within industrial hubs, the harmonisation of safety standards between SMRs and industrial operations, and the ability to establish licensing procedures that preserve SMRs as standardised units. Nevertheless, it remains essential to assess whether such an initiative could offer long-term economic viability.

Unlike conventional nuclear reactors, whose size has historically increased to exploit economies of scale, with fixed costs rising more slowly than installed capacity, thereby reducing the unit cost of electricity, SMRs follow an economic logic based on economies of series. Their competitiveness is enabled by simplified designs, modular fabrication, and extensive standardisation thanks to the repeated deployment of similar reactor models [47]. These features not only offset the loss of scale effects but also significantly shorten construction times [48], potentially allowing SMRs to achieve cash-flow break-even up to a decade earlier than new large reactors [49].

To discuss the cost of nuclear energy, it is insightful to examine both the evolution of costs over time and the regions where it is implemented. This is how the following section begins, followed by an analysis of the projected costs specific to SMRs. The aim is to assess the extent to which these modular reactors could enable the industrial sector to reduce CO₂ emissions while maintaining competitiveness.

Evolution and disparities of nuclear costs

Unlike most technologies, whose costs generally decline with expanded use and development, nuclear power has seen a marked increase in costs over the decades, particularly in Western countries [50, 51]. During its early development, nuclear power benefited from substantial public investment and the rapid expansion of nuclear capabilities, which helped keep construction costs relatively low. Today, new large-scale reactors often reach overnight capital costs (OCC) of around 10,000 US\$₂₀₂₆/kW [52], whereas in the 1960s they typically ranged between 1500 and 2500 US\$₂₀₂₆/kW [51], reflecting growing implementation challenges, repeated delays, and persistent cost overruns. Recent projects, such as the EPR reactors in France, Finland, and the United Kingdom, or the AP1000 units in Georgia (USA), illustrate these difficulties particularly clearly.

By contrast, significant disparities persist at the international level. In several Asian countries, new nuclear capacity is still being deployed at costs far below those observed in the West. These projects are frequently delivered on schedule, within their planned budgets, and achieve strong operational performance [53–55]. A major reason for this divergence lies in the high degree of standardisation, both technical through the repeated use of similar reactor designs, and organisational via stable industrial ecosystems and long-term partnerships that enable learning across projects [47]. Strong state involvement also plays a key role [53], with governments often absorbing a substantial share of the upfront investment required for large reactors.

These observations indicate that nuclear costs do not inevitably rise over time. For SMRs to become economically competitive, it will be crucial to build efficient industrial ecosystems in Western countries, with standardised designs, stable supply chains, and accumulated operational experience, conditions that have enabled lower-cost deployment elsewhere. Nevertheless, precise cost estimation for SMRs remains challenging, as the sector has not yet fully benefited from the economies of scale expected from serial production. Supply chains remain limited, and many reactor designs are still under development. However, current studies already provide useful cost estimates [49,56–59] that allow an assessment of SMR competitiveness and their potential to enable low-carbon industrial production while maintaining economic viability.

Projected SMR costs

Industrial energy demand is broadly structured around two principal needs: electricity and process heat. Situating SMRs within this landscape therefore requires assessing their competitiveness along both dimensions, both as a source of electricity generation and as a supplier of thermal energy to industrial processes.

The levelised cost of electricity (LCOE) is widely used as a central indicator. It represents the average electricity production cost over the economic lifetime of a facility, encompassing investment, operational and maintenance expenditures, fuel, carbon costs, and decommissioning expenses. Nuclear installations are characterised by high upfront capital costs but relatively low fuel costs compared with other dispatchable technologies. Moreover, their high capacity factor, often exceeding 75%, contributes to limiting their LCOE [49].

Published LCOE estimates for SMRs span a wide range, reflecting genuine uncertainty over first-of-a-kind costs, financing conditions, and reactor design maturity. For instance, Steigerwald et al. [56] report median LCOE values exceeding 255 US\$₂₀₂₆/MWh for pressurised water reactor (PWR) SMRs and around 195 US\$₂₀₂₆/MWh for high-temperature gas-cooled reactors (HTGRs). In contrast, Asuega et al. [57] estimate significantly lower costs, in the range of 100–110 US\$₂₀₂₆/MWh for light-water, gas-cooled, and molten salt SMRs, with similar values also reported by Van Hee et al. [59].

Projections for 2040 produced by IEA [49] for different markets illustrate how SMRs could compare with other electricity generation options. The costs presented in Table 3 correspond to a value-adjusted LCOE, which accounts not only for the production cost of electricity but also for the value it provides to the electricity system in terms of energy, flexibility, and capacity.

According to these projections, SMRs could become competitive in the future under scenarios where current climate policies are maintained and significant investments in nuclear development are made. Competitiveness is particularly sensitive to the cost of capital: for example, in China and the EU, SMRs could rival solar PV or wind associated with storage solutions if nuclear financing costs remain low (WACC 4%). Competitiveness relative to new fossil-fuel plants is also influenced by carbon pricing. Combined-cycle gas turbines (CCGTs) may remain competitive in some regions. However, their economics are also highly sensitive to natural gas price fluctuations.

Evaluating the competitiveness of an SMR solely in terms of electricity production costs is reductive, as these reactors also offer an advantage in industrial settings through the utilisation of the heat they produce. This cogeneration represents a key lever for enhancing overall system profitability.

Indeed, Vanatta et al. [58] have shown that supplying process heat to industry with an SMR can become competitive compared to natural

Table 3

Projected electricity generation costs (US\$₂₀₂₆/MWh) for different technologies across three world regions. Adapted from *The Path to a New Era for Nuclear Energy*^b [49].

	US	EU	China
New SMR	75–120	75–120	65–95
Gas CCGT with CCS	100	155	100 ^a
Solar PV	65	70	70
Solar PV + 8h storage	70	75	65
Onshore Wind	55	75	65
Onshore Wind + 8h storage	60	75–80	60

^a Cost assumes coal-based generation.

^b CCS = carbon capture and storage; CCGT = combined-cycle gas turbine. The OCC assumed for new SMRs is 6400 US\$/kW in the US and the EU, and 3600 US\$/kW in China. Two values of the weighted average cost of capital (WACC) are considered, namely 4% and 8%. The average nuclear capacity factor is assumed to be in the range of 75–90%. The WACC for solar PV is assumed to be 4–5%. Coal capacity factors were assumed to be 50% and 30–50% for gas CCGT. Technology costs for solar PV are from [60].

Table 4

Cost of heat supply options for high-temperature industrial processes (US\$₂₀₂₆/MWh). Adapted from *Low-carbon heat solutions for heavy industry: sources, options, and costs today* [19].

	Low	High
H ₂ SMR ^a (0% CCS)	45	60
H ₂ SMR ^a (53% CCS)	55	70
H ₂ SMR ^a (89% CCS)	65	90
H ₂ renewable	185	330
Biomass	70	135
Advanced nuclear	45	65
Electric heating (EU)	75	150
Electric heating (US)	55	120

^a SMR: here *Steam Methane Reforming*, not *Small Modular Reactor*.

gas at prices around 10 US\$₂₀₂₆/MMBtu, and even 5 US\$₂₀₂₆/MMBtu when the SMR also participates in the wholesale electricity market. This potential is particularly pronounced in sectors with high thermal demand, such as refineries, chemical production, nitrogen-based fertiliser manufacturing, and ethanol plants, where large heat requirements align well with the technical characteristics of SMRs. Despite significant uncertainties surrounding SMR costs, the study indicates some robustness to modest capital cost increases (+10%). However, when capital costs rise by 50% or 100%, SMRs become less competitive, although they may remain attractive if natural gas prices for process heat increase to approximately 12–20 US\$₂₀₂₆/MMBtu.

Friedmann et al. [19] broaden this picture by surveying low-carbon heat supply options for heavy industry. Their analysis, summarised in Table 4, highlights the scarcity of technically viable low-carbon solutions for high-temperature industrial processes and positions advanced nuclear amongst the most cost-effective alternatives currently available, comparing favourably with hydrogen across multiple production pathways, biomass-based heat, and direct process electrification.

Economic opportunities of SMRs

Beyond their inherent performance, SMRs could make use of their flexibility to provide services to the electricity grid. With the growing penetration of renewable energy sources, they could, to some extent, help meet capacity and frequency needs thanks to their dispatchable generation capability, and potentially derive an economic benefit from participating in these markets. Furthermore, industries may be exposed to peak pricing dynamics and compelled to curtail their consumption in order to avoid the substantial surcharges associated with tight market conditions. SMRs could offer an advantage in this regard: rather than simply reducing their grid offtake during peak episodes, an SMR-equipped facility could reallocate its generation capacity by exporting electricity to the grid at precisely the moment prices are at their highest, transforming a cost-avoidance strategy into a net revenue opportunity. In parallel, carbon pricing emerges as a critical determinant of SMR competitiveness. Higher carbon prices generally favour low-carbon technologies such as nuclear power over coal- and gas-fired generation. In particular, Asuega et al. [57] show that if a carbon price in the range of 125–160 US\$₂₀₂₆/tCO₂ were applied, SMRs could become economically viable compared to fossil fuel-based power plants. Additional cost reductions could also be achieved through the repurposing of former coal- or gas-fired power plant sites for modular nuclear deployment. By leveraging existing infrastructure, such as grid connections, cooling water access, permitting frameworks, and available land, investment costs could be substantially reduced. According to a study referenced by IEA [49], this strategy could lead to construction cost savings of up to 35%, with more than 300 existing or retired coal sites identified as technically suitable for conversion in the United States. Finally, another potential economic advantage lies in the local integration of SMRs within industrial parks. By producing their commodities on site, industrial operators can reduce their dependence

on energy grids, where costs are likely to rise due to the substantial investments required for decarbonisation and the increasing integration of variable renewable energy sources [61].

Discussion

Although the competitiveness of SMRs remains to be demonstrated, past experience and various studies indicate that a viable path exists for the development of this sector and its future economic viability. They appear particularly promising in the industrial context, where heat is often the primary energy vector.

However, achieving this level of economic viability is still subject to significant uncertainties, particularly regarding the ability to develop a robust ecosystem around SMRs, which is essential to fully realise the benefits of standardisation and serial production. To benefit from these effects, a significant number of units would need to be deployed. At present, there is no clear evidence that demand will be sufficient: a sufficiently large or committed customer base capable of supporting the emergence of a mature market has yet to materialise. The question of how many SMRs could realistically be deployed, and whether this volume would be adequate to generate economies of scale, remains unresolved.

From a market standpoint, SMRs could potentially supply a substantial share of industrial energy demand, as well as meet electrification needs in other sectors. However, their deployment is not determined solely by techno-economic considerations; regulatory frameworks and societal factors may also constrain their diffusion and reduce the market share they are ultimately able to capture.

Furthermore, as long as the advantages of series production remain uncertain, some manufacturers may be inclined to develop progressively larger SMRs in order to exploit potential economies of scale. This trend has already given rise to several designs of about 1000 MWth, such as Westinghouse's AP300 and EDF's NUWARD [62,63]. However, the number of industrial hubs capable of accommodating reactors of such power levels may be limited. Increasing unit size could make SMRs less suitable for certain industrial applications, thereby increasing the risk that some SMR designs may end up performing functions similar to those of conventional reactors, while potentially being less competitive.

Moreover, the current proliferation of SMR designs under development may, in some ways, hinder their competitiveness. On the one hand, it risks generating multiple industrial supply chains for each individual design, thereby slowing the emergence of more efficient ecosystems. On the other hand, it may complicate the harmonisation of regulatory frameworks needed to deploy a standardised model across different regions or countries. This, in turn, could restrict the development of an international market. Such rationalisation may prove particularly challenging in a context where several countries seek to promote their own designs for industrial or strategic reasons.

Finally, the role of the state seems critical, especially in the initial phases, providing financial support to compensate for the non-competitiveness of first-of-a-kind units and to foster industrial engagement. Actors in the sector wishing to enter SMR manufacturing often depend on the establishment of a sufficiently substantial order book, particularly since the expected cost and efficiency performance is generally achievable only after several production cycles. It is also unlikely that these projects could be funded solely through private capital, given the long-term commitments involved. The lifespan of an SMR, ranging from 40 to 60 years, requires assurance of stable demand throughout its operational period, which represents a major challenge for maintaining industrial engagement over several decades.

6. Is it socially and ethically sustainable?

The successful deployment of SMRs in industrial hubs depends primarily on their ability to generate net societal value. While their potential benefits are considerable, it is important to acknowledge the associated risks and challenges. Such deployment will only be technically and economically meaningful if, on balance, the benefits it brings to society outweigh the drawbacks and risks it entails, accepting that no energy technology is entirely free from trade-offs.

Indeed, although these technologies pursue a legitimate objective, namely the decarbonisation of the industrial and energy sectors in line with climate commitments, their implementation entails complex challenges that require careful consideration of the broader societal implications of nuclear energy. Beyond environmental objectives, SMRs could play a pivotal role in sustaining the industrial fabric and enhancing strategic autonomy. Industrial activity remains a cornerstone of economic development, representing a substantial share of national value added and employment. Furthermore, their decentralised deployment offers an additional advantage: by directly supplying energy-intensive industries, SMRs can reduce their load on the broader electricity grid, allowing existing generation capacity to be reallocated to other consumers. This feature is especially valuable in areas where networks are congested, contributing to the overall resilience and efficiency of the national energy system.

At the same time, while SMR-powered industrial hubs offer potential benefits, their development raises longstanding concerns associated with nuclear energy that must be carefully considered. These include the risk of accidents with potentially severe consequences, the generation of long-lived radioactive waste, and issues related to nuclear proliferation. Furthermore, deploying small reactors across several sites as part of a decentralised energy strategy may increase opposition from local communities and pose significant challenges in terms of social acceptability.

A range of SMR concepts, featuring diverse characteristics, have been proposed to address several of these challenges. This section examines these claims, while also highlighting the persistent uncertainties and limitations associated with the large-scale integration of SMRs.

Nuclear safety

The major nuclear accidents at Chernobyl (1986) and Fukushima Daiichi (2011) have profoundly shaped public perception and policy debates, underscoring the potentially catastrophic consequences of a loss of control over nuclear systems. These events have had a lasting impact on the social acceptability of nuclear energy and have reinforced demands for increasingly stringent safety requirements in future installations. In this context, SMRs are frequently presented as a technological response to these concerns. Several design features are claimed to enhance safety performance.

The simplified architecture of many SMR concepts may eliminate certain components that are critical in accident scenarios, such as large primary circuit piping, whose failure can lead to rapid-loss-of-coolant accidents. In addition, numerous SMR designs rely on passive safety systems capable of removing residual heat without external power supply or active human intervention, instead exploiting natural phenomena such as gravity, natural circulation, or convection. Some concepts also incorporate seismic isolation systems to improve resilience against extreme external hazards, particularly earthquakes [64].

Another frequently cited safety advantage of SMRs is their lower thermal power. While conventional reactors typically operate at thermal power levels ranging from 1000 to 3000 MW, SMRs are generally limited to approximately 300 MW [65]. This reduced power implies that, in the event of an accident, a smaller amount of energy must be dissipated, potentially facilitating core cooling and reducing the demands placed on safety systems, especially under severe accident conditions.

Nevertheless, these purported advantages remain largely theoretical and must be rigorously assessed through comprehensive safety analyses that account for real operating conditions, system interactions, and extreme external events.

Management of nuclear materials and proliferation risk

The management of nuclear materials, particularly radioactive waste, represents one of the most complex challenges associated with nuclear energy, encompassing technical, societal, and ethical dimensions. Fission-based technologies inherently produce radioactive waste, some of which remains highly radiotoxic over extremely long timescales. This persistence raises critical questions of intergenerational responsibility, as decisions made today will have long-lasting consequences for future generations. Additionally, societal concerns related to the transport, interim storage, and final disposal of nuclear waste frequently provoke public opposition, potentially complicating the deployment of nuclear projects [66].

In this context, SMRs have been proposed as a potential alternative offering improvements in waste management compared with conventional large-scale reactors. In particular, fast neutron SMRs enable the recycling of a portion of nuclear waste into fuel, notably plutonium contained within mixed oxide (MOX) fuels [67,68]. This approach provides dual benefits: it reduces both the initial demand for nuclear fuel and the mass of high-level waste. Certain advanced reactors are estimated to decrease the mass of high-activity waste by up to 94% and reduce its long-lived radiotoxicity by approximately 80% [69].

Nevertheless, SMRs in general, due to their smaller size and the associated physical characteristics, do not resolve all waste-related challenges. According to Krall et al. [69], SMRs may increase the volume of low and intermediate-level waste per unit of energy produced compared with gigawatt-scale light water reactors. The study, which analyses various SMR concepts (pressurised water, molten salt, and sodium-cooled designs) indicates that it could require between two and thirty times more effort for the management and final disposal of waste. Moreover, they do not confer any significant advantages regarding the physicochemical characteristics of spent fuel, thereby constraining treatment and disposal options.

Beyond waste management, nuclear proliferation risks represent another critical concern. Fast neutron reactors tend to produce higher concentrations of plutonium in spent fuel, thereby increasing the potential risk of diversion for military purposes [65,70]. To address this issue, some SMR designs seek to limit the frequency of fuel handling operations, which are typically the most sensitive stages from a proliferation standpoint. Certain concepts allow for multi-year operation without refuelling, or even for lifetime operation without fuel replacement [26, 28]. However, these approaches involve a significant trade-off: extending the fuel cycle often necessitates the use of highly enriched uranium or plutonium, rich fuels, which may in turn exacerbate proliferation risks, either directly through the characteristics of fresh fuel, or indirectly through the enrichment infrastructure required [65].

Public perception

The deployment of SMRs near industrial hubs, as part of a decentralised energy strategy, presents significant challenges in terms of social acceptability. While this approach has the potential to meet local electricity and/or heat needs while contributing to decarbonisation efforts, it may also raise concerns among nearby communities. If these concerns are not anticipated or addressed, they could hinder, or even prevent, the development of SMRs within industrial complexes.

A study by Durdovic et al. [71] provides valuable insights into public attitudes towards SMRs in Europe. Its findings, summarised below, not only shed light on current perceptions but also identify key determinants of social acceptability.

Firstly, public perceptions of SMRs are highly heterogeneous and reflect differences in national energy policies. While some European countries view SMRs as a promising response to climate constraints and energy security challenges, others remain cautious due to persistent economic, regulatory, and social uncertainties. The study further highlights that SMRs remain largely unfamiliar to the general public, in part because their integration into national energy strategies has so far been limited and uneven. Perceptions also vary across several dimensions, including safety, costs, socio-economic benefits, and the role of SMRs in the energy transition. Overall, SMRs tend to benefit from a relatively positive image in terms of reliability and potential socio-economic advantages. However, significant concerns persist regarding construction costs, safety performance, and environmental impacts. Opinions are also divided on the extent to which SMRs could contribute effectively to climate change mitigation, with some critics arguing that deployment timelines would be too slow to address the urgency of the climate crisis. However, a majority of Europeans consider SMRs as a possible component of the energy mix by 2050, particularly when located at existing nuclear sites. Nevertheless, translating this general openness into support for concrete projects remains uncertain.

The study underscores the importance of transparent, realistic public communication to encourage meaningful citizen engagement and to avoid disillusionment driven by overly optimistic narratives.

Experience from analogous projects suggests that genuine community involvement can yield positive outcomes. The Swedish repository project for long-lived radioactive waste offers an instructive precedent: by building relationships with local residents, supporting community associations, and providing targeted reassurance on safety concerns, the project developer secured broad local support [72]. Central to this success was the emphasis placed on the tangible benefits the project would bring to the host region. This dimension is relevant for SMR deployment. Beyond their contribution to decarbonisation, such projects could, under favourable conditions, generate local co-benefits in terms of employment and regional economic activity, which may in turn foster greater acceptance among host communities.

Discussion

The development of SMRs for industrial hubs could contribute to reducing greenhouse gas emissions and, consequently, to meeting environmental commitments while preserving an autonomous industrial base. However, these benefits must be considered in light of the ethical and societal challenges mentioned above.

SMRs appear to offer several theoretical advantages. They could reduce the risk of severe accidents, limit the volume of nuclear waste, and decrease proliferation risks. Nevertheless, it is important to emphasise that each design prioritises certain criteria rather than comprehensively addressing the full range of constraints [65]. In other words, while SMRs may help mitigate some of these challenges, they may not fully resolve them by themselves.

Furthermore, while SMRs promise improved safety, it remains to be demonstrated that, in an industrial context, safety levels will not be compromised, and that their large-scale global deployment will not significantly increase the overall risk of nuclear incidents. A similar concern applies to proliferation: expanding access to nuclear technologies among a wider range of actors entails a non-negligible risk of proliferation, despite the implementation of dedicated protective measures. It remains difficult to determine to what extent the potential benefits of SMRs outweigh their constraints. Long-term impacts are difficult to quantify and to compare with the expected environmental benefits.

Even if the development of SMRs is pursued as part of a decarbonisation strategy, their actual deployment will depend on social acceptance. Local communities affected by their integration may oppose such projects, thereby limiting their practical feasibility. Even with improved public information and awareness about SMRs, public

support is by no means guaranteed. In this regard, Durdovic et al. [71] shows that SMRs tend to be more readily accepted when they are integrated within existing nuclear sites, which runs counter to the logic of a decentralised deployment strategy. Similar dynamics are already observed for renewable energy infrastructures, where NIMBY (“Not In My Back Yard”) effects increasingly slow down deployment processes. This challenge is likely to be even more pronounced for nuclear installations, given that public support for nuclear facilities is generally weaker than for renewable energy projects [73].

The challenges outlined above must, however, be assessed within a comparative rather than absolute framework. Societal questions of this nature are rarely reducible to a binary choice between deploying or foregoing a given technology. They involve weighing competing options, each carrying its own risks and uncertainties. Continued reliance on fossil fuels entails well-documented climate risks, whilst dependence on energy imports from potentially unstable or hostile suppliers raises distinct concerns regarding strategic autonomy and energy security. Exclusive reliance on renewable energy is not without limitations either: not all national configurations can necessarily meet the full energy demands of the industrial sector from these sources alone, and their variable and intermittent nature complicates the management of electricity supply whilst imposing greater flexibility requirements on the grid. Safety and security can thus take many forms, and the relevant question is not whether SMRs are risk-free, but whether the risks they entail are preferable to those of the available alternatives. Taken together, these considerations suggest that the most credible pathways to decarbonisation are unlikely to rest on any single dominant technology, but will rather emerge from diversified energy mixes in which SMRs may play a complementary role alongside renewables and other low-carbon sources.

7. Conclusion

This article has examined the relevance of a decentralised deployment strategy within industrial hubs, departing from the traditional nuclear model based on centralised electricity generation, and instead considering the direct coupling of nuclear production with on-site electricity and process heat supply. To assess this concept in a structured manner, we adopted a cascading questioning approach, integrating technical, economic and societal perspectives. Four guiding questions framed the analysis: (i) Can an SMR meet all industrial energy needs? (ii) Can an SMR be seamlessly integrated into an industrial complex? (iii) Is it cost-competitive? and (iv) Is it socially and ethically sustainable? This stepwise progression allows both the potential and the structural limitations of the concept to emerge progressively.

From the very first question, the analysis highlights significant potential: SMRs could cover a substantial share of industrial energy demand, providing both electricity and medium- to high-temperature heat. The main technical limitations relate to processes requiring very high temperatures (above 800°C). Hybrid configurations combining energy production with the generation of synthetic molecules such as hydrogen may extend the range of applications, but demonstrating their technical feasibility and techno-economic relevance lies beyond the scope of the present work.

However, from the second stage of the reasoning onwards, constraints become more apparent. The effective integration of SMRs within industrial hubs raises technical and regulatory challenges. Demonstrating nuclear safety in complex industrial environments, aligning nuclear requirements with site-specific industrial constraints, and adapting regulatory frameworks are all essential conditions. At the same time, such adaptations must remain compatible with the promise of standardisation and cost reduction that underpins the expected economic advantages of SMRs. The most-critical issues arise precisely in the sectors where the decarbonisation potential is greatest, particularly heat-intensive industries. In these contexts, there are, limited low-carbon alternatives and the relative economic advantage of SMRs may

be strongest, yet integration challenges are also most acute: complex thermal infrastructures, stringent safety requirements, and potentially more demanding regulatory conditions.

This work therefore constitutes a first step in assessing the deployment of SMRs within industrial hubs, which remains largely prospective. Future research should combine complementary approaches. On the one hand, a detailed mapping of the existing industrial hubs within a given region, including their sectoral characteristics, energy needs, and electricity and heat demand profiles, will be essential to estimate the number of potentially suitable sites, identify the most appropriate SMR concepts, and determine the most relevant regional contexts. On the other hand, in-depth case studies focusing on a specific industrial site and a given SMR design will be necessary in order to better characterise the technical constraints, including thermal coupling, process integration and infrastructure, as well as economic performance and regulatory requirements.

Glossary

- CCGT: Combined Cycle Gas Turbine
- CCS: Carbon Capture and Storage
- EPZ: Emergency Planning Zone
- GFR: Gas Cooled Fast Reactor
- HTGR: High-Temperature Gas-cooled Reactor
- IAEA: International Atomic Energy Agency
- LFR: Lead-cooled Fast Reactor
- MSR: Molten Salt Reactor
- OCC: Overnight Capital Costs
- PV: Photovoltaic
- SCK-CEN: Studiecentrum voor Kernenergie ou Centre d'Etude de l'Energie Nucléaire
- SCWR: Supercritical Water Reactor
- SFR: Sodium-cooled Fast Reactor
- SMR: Small Modular Reactor

CRediT authorship contribution statement

Antoine Larbanois: Writing – original draft, Investigation, Formal analysis, Conceptualization. **Bardhyl Miftari:** Writing – review & editing. **Guillaume Derval:** Writing – review & editing, Conceptualization. **Damien Ernst:** Writing – review & editing.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT in order to correct the readability, grammar, and spelling of the writing. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Larbanois Antoine and Derval Guillaume reports financial support was provided by the SCK-CEN. The other 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.

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Data availability

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

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