SMR/AMR Outlook in France

Report commissioned by the Société Française d'Energie Nucléaire (SFEN)

E-CUBE STRATEGY CONSULTANTS

Version 1.1 – May 15, 2025

Table of Contents

1 Executive summary

1.1 Context, objectives, and scope

1.1.1 Context

A large number of companies are developing small modular reactor (SMR or AMR) concepts with plans to deploy them in France. For instance the France 2030 program supports ten fission reactor projects.

These projects are prompting interest from manufacturers, policymakers, and the general public in the future development of these reactors and more specifically in their number, location, and role in the French energy system.

1.1.2 Objectives

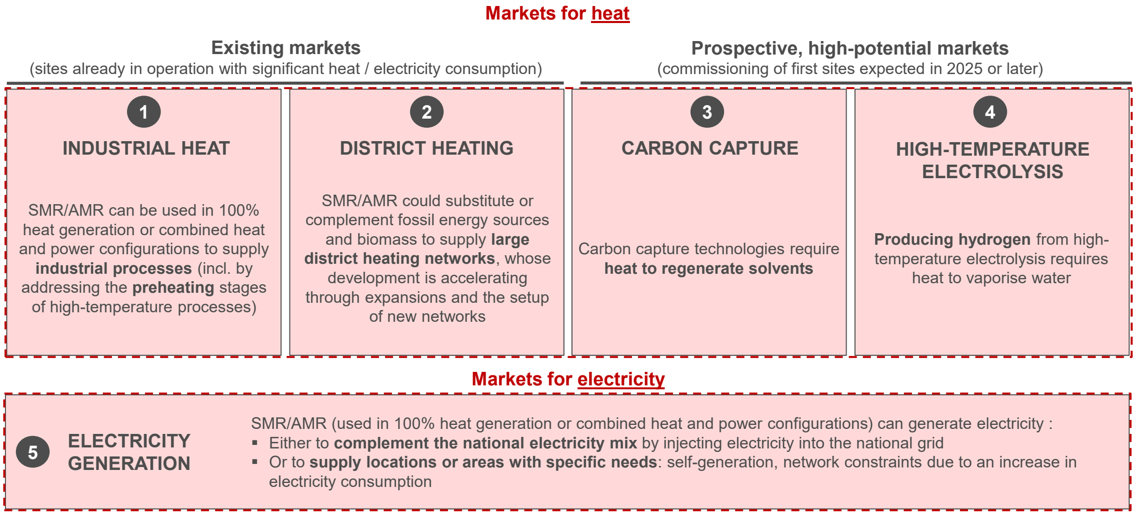
The SFEN commissioned E-CUBE Strategy Consultants to conduct a study aimed at providing answers to the following questions:

- What market can SMR/AMR technically address in France (decarbonised electricity and heat)?
- How could they distribute geographically across continental France?

This study quantifies the « technically addressable » market for SMR/AMR. However, it does not quantify the « economically addressable » nor « commercially addressable » market for SMR/AMR, which depend on the specific cost, price, acceptance and time-to-market parameters of each SMR/AMR project. On these aspects, the report provides qualitative insights.

1.1.3 Scope

This study focuses exclusively on fission reactors. The analyses cover the following applications:



1.2 Key findings

1.2.1 Decarbonization context for heat and electricity in industry and district heating networks

SMRs/AMRs are **one of the possible sources of decarbonized heat and electricity for industry and district heating networks**. France has committed to achieving carbon neutrality by 2050, with intermediate targets for industry and heating networks.

The heat consumed in industry currently comes primarily from fossil fuels: final energy consumption in French industry will account for circa 294 TWh_{th} in 2022, more than half of which will be in the form of heat. Fossil fuels account for more than 50% of this heat consumption. Most industrial sectors have a low level of heat decarbonization. **Conversely, district heating networks already have a largely decarbonized energy mix**: in 2022, these networks delivered 26 TWh_{th} of heat to consumers, 64% of which came from renewable energy sources or heat reuse.

As for **electricity, it is already almost entirely decarbonized in France.** SMR/AMR power could generate electricity:

- Either to **complement the national electricity mix** by injecting electricity into the national grid
- Or to **supply locations or areas with specific needs**: self-generation, network constraints due to an increase in electricity consumption

1.2.2 Key drivers for SMR/AMR siting in France

For heat production, **the geographical distribution of SMR/AMR will be partly driven by local demand**, and constrained by technical limitations and local acceptance. Indeed, **heat is currently only transported over a few kilometers** (1 km to ~25 km depending on the temperature of the heat delivered). Each SMR/AMR concept could address certain types of heat demand: the applications that fit each reactor depend on its **power and output temperature range.**

The location of **SMRs/AMRs for electricity generation is less driven by closeness to consumer sites,** because the national transmission grid connects generation and demand efficiently**.** In general, SMR/AMR sites could include sites that sit**es that have already hosted electricity generation** (e.g. former thermal generation plants) or **that have hosted nuclear operations.**

SMRs/AMRs could be located on or near industrial sites or data centers **with specific needs or opportunities** (connection constraints to the transmission grid, opportunities for self-generation). By 2035 building and SMR/AMR may be considered as an **alternative or a complement to electricity supply** when network reinforcement is necessary to set up a large load: in most cases, SMR/AMR could **lower the need to build up the electricity network, without entirely substituting it**. However, it is important to note that connecting SMRs/AMRs to the public electricity transmission network will remain necessary for various reasons. In most cases, SMRs/AMRs could thus **reduce the need for the public grid but not replace it entirely**.

On a local scale, several **technical constraints may limit possible locations**: the nature and the extent of these constraints depend on each SMR/AMR technology: available land, accessible transmission / distribution grid connection capacity, water supply… **Acceptance and industrial safety** will also play a key role in the effective implementation of SMR/AMR.

All markets combined, **SMR/AMR developments would mostly target large industrial areas and large district heating networks**.

1.2.3 Technical potential for heat production by SMRs/AMRs

The **heat demand that SMRs/AMRs can technically address is over 100 TWh_{th} by** 2050[1] [2] . Industry is the primary potential market for SMR/AMR heat, with ~70 TWh_{th}. These 70 TWh_{th}/year are spread across approximately sixty *clusters* in France. Depending on its specific characteristics, each technology will be able to address part of these 70 TWh_{th}/year. Heating networks represent a technically addressable market estimated at 12 TWh_{th} to 33 TWh_{th}/year.

In reality, **the "economically" and "commercially" addressable market is smaller** due to other constraints (in particular competition from other heat decarbonization technologies). The commercially addressable market could vary significantly from one technology to another.

Furthermore, the emergence of new heat-consuming sectors (**carbon-free hydrogen production, CCUS**) could represent an **opportunity of >10 TWh_{th}/year for SMR/AMR by 2050.**

1.2.4 Technical potential for electricity generation by SMRs/AMRs

In RTE's N3 scenario, SMR/AMR produce 27 TWh_e of electricity per year by 2050, which could correspond to ~4 GW_e of installed electricity generation capacity[3]. They could develop based on **supply contracts with large consumer sites[4]** (industrial or data centers), whose consumption is expected to sharply increase in the coming years.

Industrial processes

As a key solution to decarbonize industry, process electrification is expected to lead to a significant increase in electricity demand at certain industrial sites, in the form of:

- **Direct electrification**: according to RTE estimates, the increase in direct industrial electricity consumption could add 10 to 50 TWh_e by 2050 compared to 2019[5].
- **Indirect electrification**: the replacement of fossil fuels with carbon-free hydrogen produced by water electrolysis could account for ~50 to ~100 TWh_e of electricity consumption by 2050.

---

[1] Excluding process changes and any destruction/creation of industrial sites

[2] As a indication, 100 TWh_{th} corresponds to the output of 250 SMR modules of 50 MW_{th} operating 8,000 hours per year

[3] 27 TWh_e of electricity corresponds to ~4 GW_e of installed electrical power, assuming ~7,000 full load hours

[4] In the rest of this document, the term "large consumer" refers to a site whose consumption is at least of the same order of magnitude as the thermal power of an SMR/AMR (i.e., minimum 1 MW)

[5] Source: RTE *Energy Futures 2050*, additional electricity consumption by industry in the "electrification +" and "reindustrialization" scenarios (excluding hydrogen production)

Data centers

According to RTE, data center consumption in France could reach **~29 TWh_e by 2040**, driven by the increase in the number of data centers and growing AI-related needs.

When latency is not a major constraint (e.g., cold data storage, AI model training), **locations can be picked on a national, continental, or even global scale**. In this context, data center operators are looking for **competitive, high-quality, carbon-free electricity that is available as quickly as possible**.

In recent years, data center operators have been exploring various avenues to obtain **large amounts of controllable electricity production close to data centers**, for two main reasons:

- Constraints on **connection capacity**
- Strong growth in solar and wind power generation that increases intraday price differences and **limits the economic appeal of renewable PPAs "as produced"** (particularly solar) to cover the baseload consumption of data centers

This context explains **the growing interest in SMR/AMR**, along with other solutions such as high-capacity nuclear power, geothermal energy, carbon capture, carbon-free hydrogen, and long-term storage.

2 Decarbonizing heat consumption in large industrial sites and district heating networks is a major challenge that will require a combination of solutions

2.1 Industrial heat is mostly fossil-fuel based today

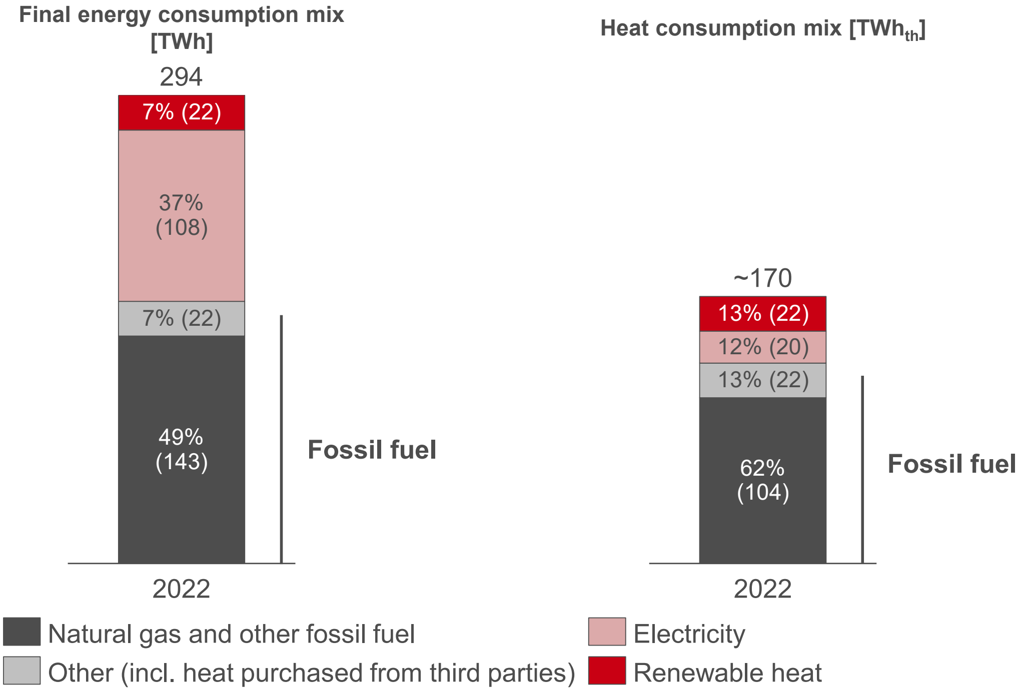


Figure 1: Final energy consumption mix in industry in 2022, and estimated heat consumption mix by energy source[6][7]

Final industrial energy consumption in France amounted to around 294 TWh$_{th}$ in 2022, of which more than half in the form of heat. Fossil fuels account for over 50% of this consumption, with natural gas playing a predominant role across nearly all industrial sectors, mainly for heat production. Coal, coke, and petroleum products are used mostly in specific activities – such as metallurgy and chemicals – where they often also serve as feedstock.

Electricity accounted for about 37% of industrial energy consumption in 2022 and benefits from a very low carbon intensity thanks to France's nuclear capacity. Out of ~108 TWh of electricity, around 20 TWh are used for heat production[8]. Renewable heat accounts for less than 7% of final industrial energy consumption, and about 13% of final industrial heat consumption.

---

[6] Heat purchased from third parties is produced by an entity (such as a CHP plant, industrial boiler, or heating network) and sold to third parties. It is currently mostly of fossil origin.

[7] Actual 2022 data not adjusted for climate (excluding waste heat recovery) from France's 2023 Energy Balance Sheet - Provisional data (SDES). Heat mix estimate is based on INSEE data - *Energy consumption in industry in 2022*.

[8] Estimate based on thermal uses (electric arcs, resistors, etc.), assessed at 18% of electricity consumption (ADEME 2014)

Decarbonization of heat applies is limited in most industrial sectors, with specificities in certain sectors. For example, the pulp and paper sector uses biomass by-products generated during pulp production. These are commonly used in CHP plants, leading to a more decarbonized heat mix than in other industrial sectors.

2.2 Conversely, district heating networks are already mostly decarbonized

Around 950 district heating networks operate in France with a total thermal power of ~24 GW_{th}. Generally set up by local authorities, these infrastructures are unevenly distributed across the country, with the Paris region accounting for 10 GW_{th} of thermal capacity (i.e., ~40% of the total).

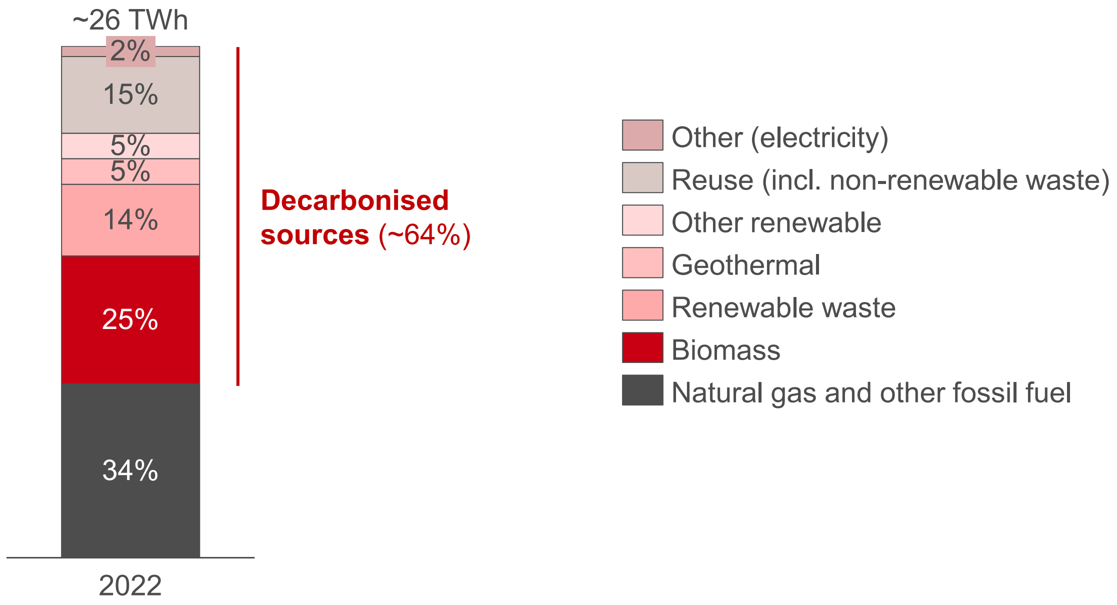


Figure 2: Final energy consumption mix of district heating networks in 2022[9]

In 2022, district heating networks delivered 26 TWh_{th} of heat to consumers, 64% of which came from renewable energy sources or reuse. The majority (~55%) came from biomass and waste-to-energy plants (both renewable and non-renewable waste), while geothermal and other renewable sources accounted for ~9%. Natural gas accounted for just over 30% of the mix.

2.3 Achieving carbon neutrality for industrial heat and district heating by 2050 will require a combination of solutions

France has committed to achieving carbon neutrality by 2050, with interim targets for both industry and district heating networks.

[9] Data from France's Energy Balance for 2022, May 2024.

For industry, this translates into a targeted 81% reduction in greenhouse gas (GHG) emissions by 2050 compared with 2015 levels. This target, set out in the National Low-Carbon Strategy (SNBC), is differentiated for six major industrial sectors. At the government's request, these industries – which together account for ~85% of industrial emissions – have drawn up decarbonization roadmaps. These roadmaps set sector-specific emission reduction targets, ranging from -80% by 2050 for cement production to -100% (i.e. full carbon neutrality) for steelmaking. The strategies rely on several key levers: electrification of processes, greater use of low-carbon thermal energy, integration of low-carbon hydrogen, deployment of carbon capture technologies, and improved energy efficiency.

For district heating networks, the 2015 Energy Transition for Green Growth Act calls for a fivefold increase in the supply of renewable and recovered heat and cold by 2030, with continuous growth through to 2050 in order to achieve carbon neutrality.

The combination of heat supply solutions that will be chosen by stakeholders to achieve these ambitious targets will largely depend on the economic competitiveness of the solutions available and suited to their temperature requirements. The pace of this decarbonization of heat will be linked in particular to changes in the price of carbon allowances on the ETS market[10] .

[10] Emission Trading Scheme

3 SMRs/AMRs are one of the possible sources of decarbonized heat and electricity for industry and district heating networks

3.1 SMRs/AMRs encompass several technological families, with varying technical characteristics and levels of maturity

SMRs/AMRs (Small Modular Reactors, Advanced Modular Reactors) are standardized, industrialized nuclear reactors that are partly manufactured off site and assembled on site. They are designed to limit construction times and secure construction costs.

There is strong interest in SMRs/AMRs: in 2023, the IAEA identified more than 60 SMR/AMR designs under development[11] by various types of players, from large industrial groups such as EDF, General Electric Hitachi, and Rolls-Royce to research centers and small innovative companies. Some are based on technologies that have already been deployed industrially and commercially (Generation III pressurized water reactors, sodium-cooled fast neutron reactors), while others are based on technologies that underwent initial testing in the 1960s and 1970s but were not followed by commercial deployment, mainly due to a general decline in interest in the nuclear industry as of the 1980s (e.g., Generation IV molten salt reactors).

To support this momentum, France has established a dedicated support framework, notably through the "Innovative Nuclear Reactors" call for projects, managed by Bpifrance with support from the CEA. This program aims to foster the development of next-generation nuclear reactors, with a focus on technological innovation, competitiveness, and optimizing both the fuel cycle and waste management. The first round, closed in June 2023, resulted in €130 million in state funding[12] being awarded to 11 selected projects.

Most of the projects supported by France 2030 involve CHP (i.e., production of both heat and electricity): only Calogena is strictly on heat only[13]. These projects span a wide range of technologies, which can be grouped into five main categories depending on coolant, fuel, and moderator type.

---

[11] Advances in Small Modular Reactor Technology Developments, IAEA, 2024 (68 designs in "active" development, and 83 designs identified in total in the 2022 version of the report)
[12] €102.21 million to support the first 8 winning projects and €27.8 million for the 3 new projects announced in March 2024
[13] In addition to Calogena, the French ARCHEOS project developed by the CEA is also exclusively focused on heat

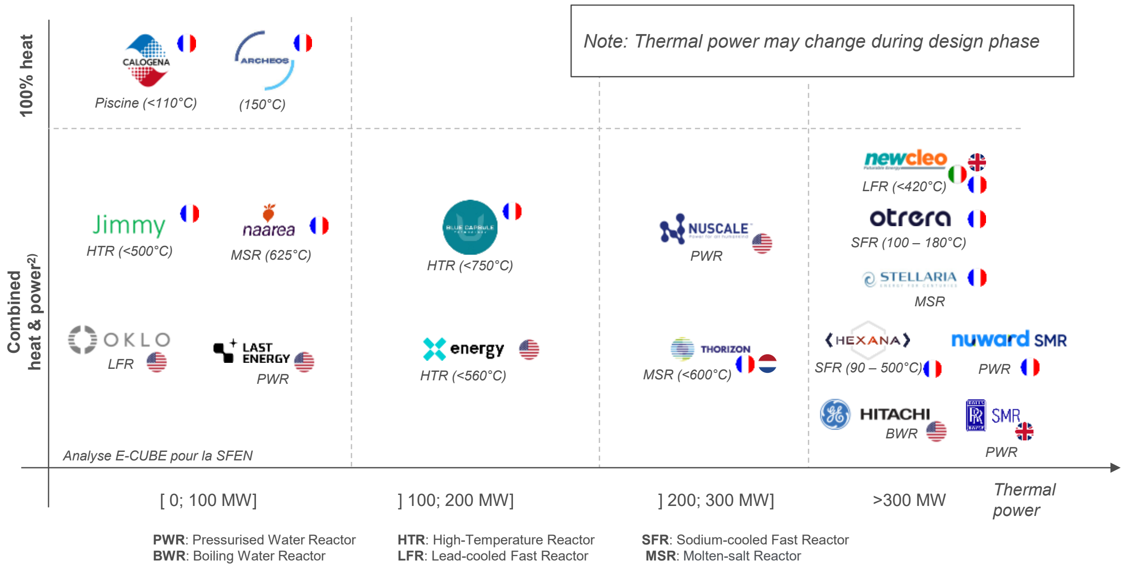


Figure 3: Selection of CHP or purely heat producing SMRs/AMRs (including 10 companies supported by France 2030, ARCHEOS, and a sample of international players)[14]

3.1.1 Pressurized water reactors

General description of the technology

Pressurized Water Reactors (PWRs) use fuel enriched to 3–5% uranium-235 and ordinary water under high pressure, which serves both as moderator and coolant. The reactor core heats the water, kept in liquid form under high pressure in a primary circuit. The heat is then transferred to a secondary circuit that produces steam, which can be directed to a turbine to produce electricity and/or heat.

Maturity and development status

This technology accounts for ~60% of nuclear power plants worldwide and all commercial reactors operated by EDF in France. Several companies have launched “small-scale” versions, including France’s Nuward (EDF Group), NuScale, and Rolls-Royce. Of the 25 designs listed by the IAEA in 2023, two are currently under construction in Argentina and China. The others range from conceptual design to detailed design, with several projects targeting deployment around 2030.

Technical characteristics (thermal)

The size of these reactors could range from under 100 MW_{th} (Last Energy, ~80 MW_{th}) to over 1000 MW_{th} (RR-SMR, ~1350 MW_{th}).

They can produce heat at temperatures between 150 and 250–300°C.

Illustration – Nuward

[14] The "cogeneration" category includes all SMRs/AMRs for which cogeneration has been announced or is being studied, even if the possible heat/electricity split is not yet known

The NUWARD project, led by the EDF Group, is a French solution for a small modular pressurized water nuclear reactor. With an electrical power output of around 400 MW_e, this reactor is intended for CHP generation and initially sized for up to ~100 MW_{th}.

At the end of 2024, the NUWARD teams reviewed their design to optimize their performance and competitiveness objectives. The goal now is to finalize the conceptual design by mid-2026.

3.1.2 Boiling water reactors and swimming pool reactors

General description of the technology

These reactors also use "light" water as a moderator and coolant. However, they differ from pressurized water reactors in that the water is heated directly in the reactor. Like PWRs, they use low-enriched uranium fuel.

There are two types:

- Boiling water reactors (BWRs), in which steam is generated directly in the reactor
- Open pool reactors, in which water is heated in the reactor without reaching the boiling point

Maturity and development status

Initially developed in the United States (first commercial unit at Humboldt Bay in 1963), low-pressure light water reactors are now the second most common type of reactor in the world, with reactors in operation in the United States, Japan, Germany, and Russia, among others.

To date, several SMR developers have opted for "low-pressure" light water reactor technologies: this is notably the case for Calogena's open pool reactor (30 MW_{th}) and GE Hitachi's boiling water reactor (870 MW_{th}).

Technical characteristics (thermal)

Thermal power ranges from a few dozen MW_{th} (Calogena) to several hundred (GE Hitachi). Most REBs operate at a pressure of 70 to 80 bar and produce steam at temperatures of up to 250-300°C. Pool reactors operate at lower pressure (5 bar for Calogena) and produce low-temperature heat (around 100°C).

Illustration – Calogena

Created in 2021 as a spin-off from the industrial group Gorgé, Calogena is dedicated to the development, construction, and operation of modular nuclear heat-only reactors with a capacity of around 30 MW_{th}, designed to supply low-carbon heat to district heating networks. The outlet temperature is expected to range between 70 and 110°C. In November 2024, Calogena submitted its safety authorization application (DOS) to the safety authority ASNR, marking a critical milestone toward licensing of the Cal-30 reactor.

3.1.3 High-temperature and very high-temperature reactors

General description of the technology

High-temperature reactors (HTRs) use helium as a coolant and graphite as a moderator. They operate with enriched uranium, for example in TRISO (TriStructural Isotropic) form, consisting of microbeads of medium-grade uranium (High-Assay Low-Enriched Uranium) with an enrichment level varying between 5 and 20%.

Maturity and development status

The development of HTR reactors began in the 1950s as part of research projects in the United States, Germany, and the United Kingdom. These early reactors had power ratings between 40 and 150 MW_{th} and could reach temperatures close to 1000°C. These initial projects laid the foundations for modern HTR technologies, which are currently under development in China, the United States, and France.

In China, the HTR-PM built in Shidaowan entered service in December 2023. This demonstrator consists of two reactors, each with a capacity of 250 MW_{th}/105 MW_e, using fuel enriched to 8.5% and capable of producing steam at 750°C.

Technical characteristics (thermal)

Modern HTR reactors vary in power from a few MW (Jimmy, 10 to 20 MW_{th}) to several hundred MW (Chinese HTR-PM, 250 MW_{th} per reactor). Their technology allows them to reach higher temperatures than pressurized water reactors, which can exceed 500°C.

Illustrations – Jimmy and Blue Capsule

In France, the startup **Jimmy** is developing a 10 to 20 MW_{th} reactor targeting the industrial sector, for heat consumption up to 500°C. In 2024, it announced that it had submitted an application to the Ministry of Ecological Transition for authorization to create a thermal generator project aimed at producing heat at the industrial site of Cristal Union, a major European player in the sugar sector, located in Bazancourt. In addition, in early 2025, Jimmy obtained a building permit for a first industrial building in Le Creusot Montceau, which will initially house a test loop and will eventually be used to store, test, and pre-assemble equipment delivered by suppliers.

Also a winner of the France 2030 call for proposals, **Blue Capsule** relies on a combination of two technologies: TRISO fuel for HTR reactors and the heat transport system and certain other components of sodium-cooled fast neutron reactors. This reactor is designed to provide up to 150 MW_{th}, with an outlet temperature of 700 to 750°C.

3.1.4 Sodium- or lead-cooled fast neutron reactors

General description of the technology

Fast neutron reactors (FNRs) differ from conventional reactors in that they use high-speed neutrons (approximately 20,000 km/s), which increases the efficiency of fission reactions (in thermal reactors, neutrons are slowed down to approximately 2 km/s). Several fluids can be used to transfer the heat generated by fission, mainly sodium (FNR-Na) or lead (FNR-Pb). These reactors operate without a moderator, allowing the neutrons to retain high kinetic energy. Fast neutron reactors are distinguished by their ability to use not only uranium-235, but also uranium-238 or plutonium-239 as fuel, while recovering materials from the reprocessing of spent fuel. This feature allows them to maximize the use of nuclear resources by achieving "breeding," i.e., producing more fissile isotopes than they consume, and significantly reducing the long-lived radioactive waste from spent fuel in light water reactors.

Maturity and development status

Among the different variants of FNRs, only sodium-cooled reactors (FNR-Na) have reached an advanced level of technological maturity. Demonstrators (first generating heat and then power), experimental reactors (Phénix in France, Joyo in Japan) and industrial reactors (Superphénix, with 1,200 MW of electrical power; BN800 in Russia) have been operated or are still in operation in several countries.

Technical characteristics (thermal)

Although the temperature produced by FNRs varies depending on the design, it is generally between 400 and 600°C. FNRs come in a wide range of sizes, from reactors of a few megawatts (Oklo Aurora, ~50 MW_{th}) to several hundred megawatts (HEXANA, 2x400 MW_{th}).

Illustration – HEXANA, Otrera, Newcleo

HEXANA is developing a fast neutron reactor CHP system with integrated sodium coolant, comprised of two modular reactors of 400 MW_{th} each (capable of supplying heat at 500°C) and the equivalent of 300 MW of electricity. These reactors are unique in that they are combined with a heat storage device (molten salt tanks) that separates the continuous reactor operation from the distribution of energy, which is flexible and adapts to load curve of customers.

The **Otrera New Energy** reactor also uses sodium as a heat transfer fluid. The OTRERA 300 is a sodium-cooled loop reactor that can provide 2x110 MW_e and 2x180 MW_{th} at 100-180°C.

Newcleo is developing a fast neutron reactor based on technology that uses lead as a heat transfer fluid in two configurations: 90 MW_{th} for the LFR-AS-30 and 480 MW_{th} for the LFR-AS-200. The latter can be deployed in multi-reactor power plants comprising 2, 4, or even 6 units, depending on requirements, and is capable of supplying heat at 500°C (R&D activities are underway to achieve temperatures above 550°C).

3.1.5 Molten salt reactors

General description of the technology

Molten Salt Reactors (MSRs) are characterized by the integration of fissile fuel directly into the coolant – a molten salt – circulating continuously through the reactor core. They are designed to operate at atmospheric pressure and can be configured for either thermal or fast neutron spectra. Their technology enables partial closure of the fuel cycle, recycling certain actinides and reducing the volume of radioactive waste.

Maturity and development status

The first experimental molten salt reactor was developed in the 1960s by Oak Ridge National Laboratory (7 MW_{th}). Around ten MSR reactor designs are currently being studied worldwide, most of which are currently in the *pre-licensing* phase, although some have progressed beyond this stage[15]. The Natura Resources research alliance, a consortium including three other universities, recently obtained a construction permit for its new molten salt reactor, the Natura MSR-1, on the campus of Abilene Christian University (ACU).

Technical characteristics (thermal)

[15] TerraPower began construction of the non-nuclear parts of its MCRE SMR in Wyoming in June 2024, and its construction license is currently being reviewed by the NRC

Molten salt reactors operate at temperatures between 500 and 700°C, opening up possibilities for industrial thermal applications.

Illustration – Naarea, Thorizon, Stellaria

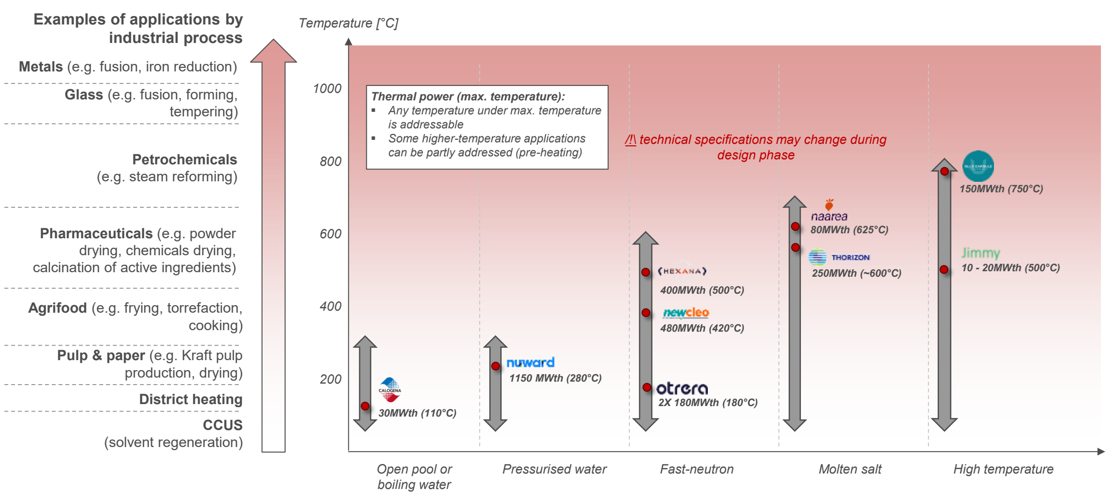
In France, the XAMR reactor being developed **by Naarea** is an example of a small fast-spectrum molten salt reactor with a thermal power of 80 MW, capable of producing both heat and electricity, with a maximum operating temperature of 625°C. Naarea plans to commission its first XAMR reactor in 2030.

Thorizon is developing a modular molten salt reactor designed to produce 250 MW_{th} using interchangeable fuel cartridges. Scheduled for initial deployment in 2032, the project began a *joint preparatory review* with the French and Dutch authorities in 2024.

Founded in 2023, **Stellaria** is an offshoot of the CEA. It aims to design innovative fast neutron nuclear reactors using molten salts. These reactors, with a capacity of approximately 500 MW_{th} or 250 MWe each, are intended to produce both electricity and heat for large industrial users and for injection into public networks.

3.2 Each SMR/AMR concept can serve specific heat decarbonization use cases, depending on secondary circuit temperature and pressure

The applications suitable for each reactor depend on the proposed power level (see following chapters) and the temperature and pressure range at the secondary circuit outlet.



Note: even if the temperature of a process is higher than the outlet temperature of an, of the heat demand can be covered by the SMR-AMR (e.g. to pre-heat up to 250°C or 500°C), while another heat source provides the complementary energy to reach a higher temperature

Figure 4: Temperature ranges by SMRs/AMRs technology

In France, ~50% of industrial heat consumption is used in processes requiring temperatures below 250°C. In this range, heat is mainly used in the form of steam. This mainly concerns the agrifood industry, where steam is used for cooking, pasteurization, and sterilization processes, and the paper industry, where steam is mainly used in the production and drying phases of paper pulp. Other industrial sectors require these temperatures for certain production stages, such as the textile industry, where steam is used for washing, dyeing, and drying fibers, and the chemical industry, which consumes steam for certain low-temperature reactions.

Certain carbon capture technologies, including absorption, adsorption, and membrane separation, consume heat generally below 150°C for the solvent or membrane regeneration stages.

In addition to industry, district heating networks also require heat supply in the 60–300°C range. Most of the market lies below 200°C, with the exception of a few networks in the Paris region.

These use cases are therefore accessible to the majority of SMR/AMR technologies. They are the core target for boiling water and pressurized water reactors, whose temperature range is limited to 250–300°C.

Conversely, some industries such as petrochemicals, pharmaceuticals, and metallurgy have heat requirements well above 250°C. In these cases, steam is less commonly used as the primary heat transfer medium, with gases and other thermal fluids playing a greater role. For applications reaching up to 750°C, high-temperature reactors or fast reactors (cooled with lead, sodium, or molten salts) can provide decarbonization solutions. In addition, these sectors may turn to hybrid technological setups, where an SMR/AMR provides part of the temperature rise – such as the preheating stage (e.g., up to 250°C or 500°C) – and another technology supplies the additional heat needed to reach higher temperatures (for instance, electric resistance heating, which could itself be powered by an SMR/AMR). As an illustration, steam reforming in the petrochemical industry requires temperatures above 800°C. However, a significant share of energy is consumed below 250°C, notably for naphtha vaporization (latent heat required for the phase change). Similarly, high-temperature electrolysis involves an initial vaporization phase (around 150°C), at much lower temperatures than the electrolysis phase itself (500–900°C).

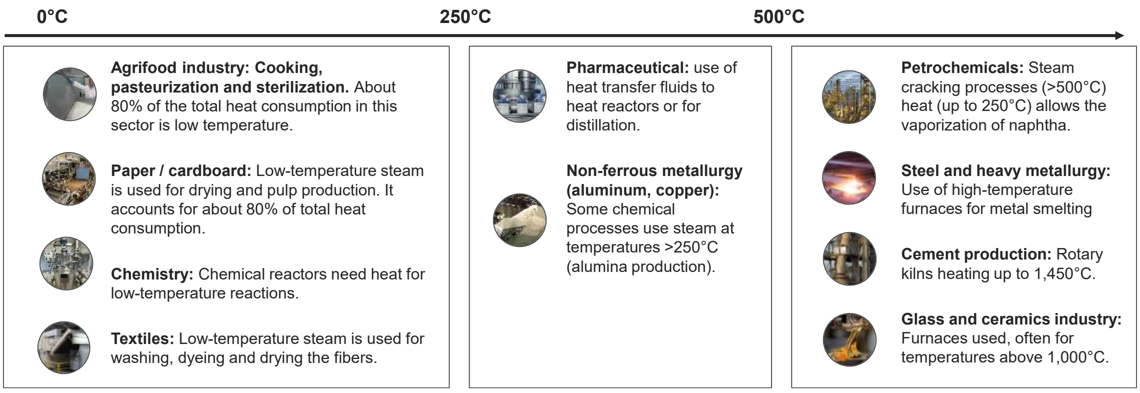


Figure 5: Examples of industrial processes by temperature class

3.3 The geographical distribution of SMR/AMR will be partly driven by local demand, and constrained by technical limitations and local acceptance

3.3.1 Local heat and electricity demand will be among the drivers for the location of SMRs/AMRs

For heat production, **the siting of SMRs/AMRs will primarily be driven by local demand** and constrained by technical limitations and local acceptance. Indeed, **heat is currently only transported over a few kilometers** (currently ~1 km to ~25 km, depending on the temperature of the heat delivered)[16].

The location of **SMRs/AMRs for electricity generation is less driven by closeness to consumer sites,** because the national transmission grid connects generation and demand efficiently. In general, SMR/AMR sites could include sites that sit**es that have already hosted electricity generation** (e.g. former thermal generation plants) or **that have hosted nuclear operations.** To address local specificities (self-consumption, grid capacity constraints, SMR/AMR operating in CHP mode), SMRs/AMRs could also be located on or **near industrial sites or data centers**.

These drivers are summarized below:

Energy carrier	Main drivers of SMR/AMR location
Heat	▪ Individual demand of industrial sites for: - Current industrial processes - Carbon capture - Electrolysis for carbon-free hydrogen production ▪ Demand of urban (or industrial) heating networks ▪ Opportunities to pooling industrial and/or district heating network demand
Electricity	Injection into the national grid: particularly sites that have already been used for electricity generation (e.g. former thermal power plants) or that have already hosted nuclear operations. Local opportunities: ▪ Constraints on connection capacity to the transmission grid, in particular due to - New industrial demand - Electrification of processes on existing industrial sites - New data centers ▪ Opportunities for self-consumption (consumers seeking a low-carbon, constant electricity supply at a stable price over the long term) ▪ SMR/AMR operating in CHP mode

3.3.2 Technical constraints may limit the possible locations for each technology

On a local scale, several technical constraints may limit possible locations. The nature and extent of these constraints depend on the SMR/AMR technology:

[16] Transport over longer distances is technically feasible, but transport costs and losses can significantly impact project economics depending on the temperature of the steam delivered

Nature of the constraint	Details on the constraint
Available land	Availability of land to build the **plant** (including security perimeter) and set up a **construction perimeter**, while complying with soil artificialisation rules: detailed criteria are ▪ **Distance between plant location and energy consumption location** ▪ Availability of **large enough land tracts** (e.g. brownfield industrial site) to secure the site (security perimeter, guards etc)
Accessible transmission / distribution grid connection capacity	**Feasibility of a connection to the medium or high voltage grid:** ▪ **Distance to the grid** ▪ **Grid congestion risk** ▪ In certain cases: **redundancy** (separate feeders on several transformers)
Water supply (depends on SMR/AMR technology)	Access to water supply that fits the safety requirements and cooling needs of the reactor ▪ **Distance between plant location and water source (sea, lake, river, canal, water table…)** ▪ **Minimum flow** *Note: certain SMR/AMR technologies use cooling systems that do not require access to a water sources (ex: closed-loop cooling). In addition, for technologies that do require it, the constraint is all the smaller as the % of energy used to generate electricity is lower (as opposed to generating heat).*
Other: seismic activity, submersion risk…	Criteria pertaining to site security

Table 1: Main technical constraints on the deployment of SMRs/AMRs[17]

3.3.3 Acceptance and industrial safety will also play a key role in SMR/AMR deployment

Local acceptance and compliance with the Technological Risk Prevention Plan (PPRT in France) will influence the actual development of SMR/AMR projects. Regarding local acceptance, a recent study conducted by OpinionWay for SFEN highlighted the need to establish stakeholder dialogue structures such as Local Information Commissions (CLIs).

Given their project-specific nature, these aspects are not addressed in this document.

4 The heat demand that SMRs/AMRs could technically address is over 100 TWh_{th} by 2050

Caveat: this section is based on an assessment of heat demand with current processes, but certain industrial processes may evolve, particularly as decarbonization and electrification projects are implemented. The opportunity to adapt processes will depend on the decarbonization solutions that are available to industrial players – among which SMRs could play a role.

4.1 Industry is the primary potential market for SMRs/AMRs, with ~70 TWh_{th} of heat demand technically addressable by these technologies

[17] SMR/AMR projects will have to undergo site-specific geological and seismic analyses. Thus, although seismic risk is unevenly distributed across France, it is not possible to determine whether sites are compatible with this criterion.

Out ff the 170 TWh_{th}/year of industrial heat consumed in France, modular nuclear reactors as a whole could "technically" address ~70 TWh_{th}/year: this is the technically addressable market. In reality, the economically and commercially addressable market are smaller due to other constraints (in particular competition from other decarbonized heat technologies). These 70 TWh_{th}/year are spread across approximately sixty *clusters* in France.

Depending on their specific characteristics, each technology will only be able to address part of this ~70 TWh_{th}/year. In particular, technical properties, economic competitiveness, as well as development timelines will all reduce the addressable market for each SMR or AMR. These impacts are detailed below.

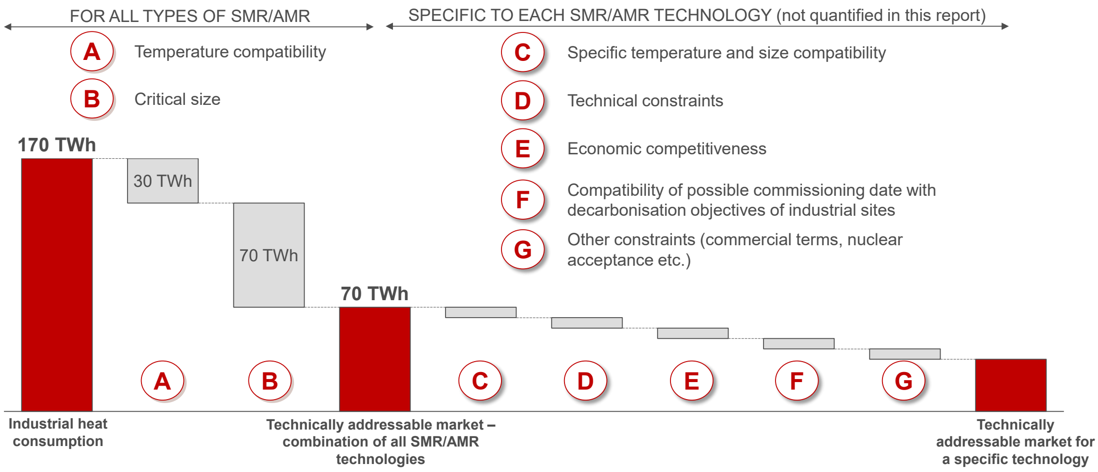


Figure 6: Waterfall of the addressable market for SMRs in the industrial heat market[18]

4.1.1 ~80% of the energy consumed in industrial heat processes is technically addressable by nuclear reactors

As detailed in **Error! Reference source not found.**, each type of modular nuclear reactor (SMR/AMR) is designed to provide heat within a specific temperature range. Pressurized water reactors (PWR) and boiling water reactors (BWR) can address needs up to 250-300°C, while high-temperature reactors (HTR) or fast neutron reactors (FNR) can deliver temperatures around 700°C. Each technology is therefore compatible with some of the needs of industrial sites, whose heat consumption profiles vary greatly.

By combining the temperature ranges covered by different SMR/AMR technologies (including preheating), around 140 TWh_{th}/year are technically addressable by at least one SMR/AMR technology – representing 80% of industrial heat demand. Conversely, certain specific processes,

[18] The market presented here is that of heat consumption in 2022 in TWh_{th}: possible variations over the coming decades (deindustrialization/reindustrialization, energy efficiency) are not taken into account.

such as those requiring very high-temperature furnaces (glass industry, metallurgy), are not addressable with steam from SMR/AMRs.

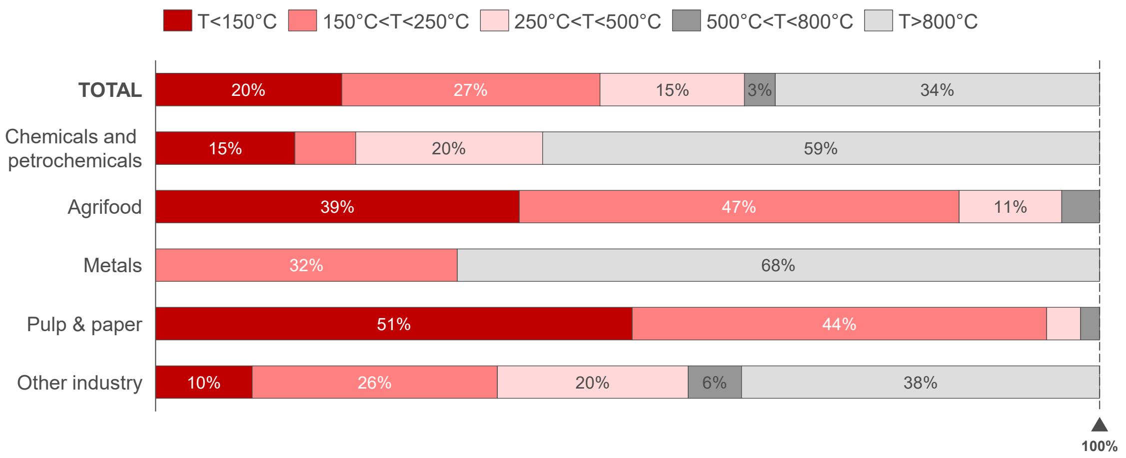


Figure 7: Estimated industrial heat consumption in France by process temperature [% of energy consumption in the form of heat by segment][19]

4.1.2 ~70 TWh_{th}/year of heat consumption is concentrated in *clusters*[20] with sufficient demand to justify SMR/AMR deployment

The economics of heat-generating SMR/AMR generally require a high utilization rate to amortize the significant initial investment over the largest possible heat consumption. However, CHP can cover more variable heat needs over time, as energy not consumed in the form of heat can be turned into electricity.

In both cases, given that heat is difficult and costly to transport, heat-generating SMR/AMRs will need to be installed in geographical areas where local heat offtake is sufficient.

To assess the addressable market, E-CUBE analyzed the location and heat consumption of industrial heat users. While some large industrial sites alone consume more than certain reactors, SMRs/AMRs could also supply several sites located within a limited radius (industrial cluster[21]). For the purpose of this study, we assume a maximum distance of 20 km between two sites supplied by the same SMR/AMR.

The thermal power of reactors under development ranges from a few megawatts (MW) to several hundred MW per unit. In addition, some reactors can modulate heat production, allowing them to adapt to varying consumption. Indeed, many industries do not consume heat in a stable and continuous way throughout the year. Below are three typical heat consumption modulation profiles: "intraday," "2x8," and "seasonal."

[19] Estimates based on heat consumption distributions by temperature class per industry from ARENA (Renewable energy options for industrial process heat, 2019), the IEA (IEA Decarbonizing industrial process heat: the role of biomass) and The European Heat Pump Association

[20] An industrial *cluster* corresponds to the aggregation of heat consumption from several industrial sites within a 20 km radius. See the methodology for creating *clusters* in Appendix

[21] See the methodology to group sites into clusters in Appendix

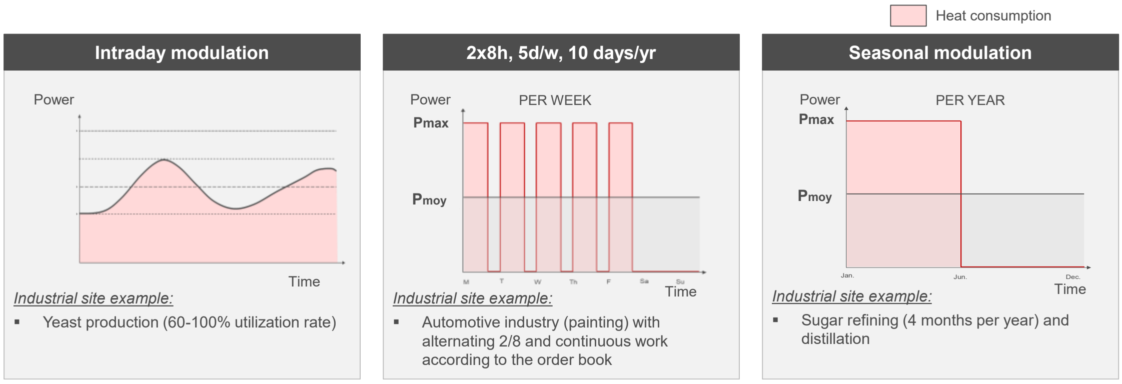
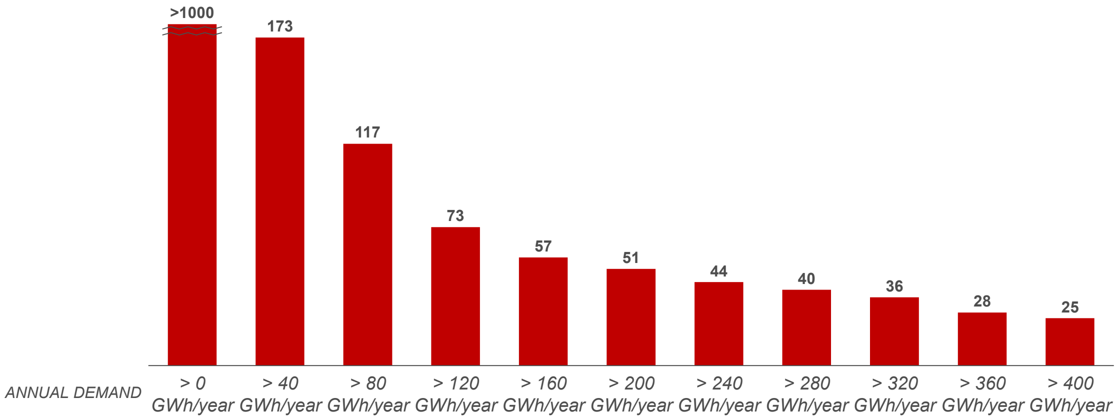


Figure 8: Example of industrial heat consumption profile

E-CUBE therefore set a minimum heat consumption threshold of **~160 GWh_{th}/year**, which corresponds to 20 MW_{th} thermal power baseload (with 90% availability). By applying the 160 GWh/year threshold, more seasonal uses are also included, where the SMR/AMR would operate at > 20 MW_{th} threshold for part of the year.



Reading note: there are 57 clusters in France with consumption exceeding 160 GWh_{th}/year.

Figure 9: Number of industrial clusters by annual heat consumption addressable by an SMR/AMR (2022)[22]

E-CUBE has identified 57 industrial clusters whose heat consumption exceeds 160 GWh_{th}/year. Heat demand located in these clusters[20] that can be addressed by an SMR/AMR is estimated at ~70 TWh_{th}/year.

Note: only heat currently supplied by natural gas or biomass is considered substitutable by nuclear reactor heat. Heat produced from SRF (solid recovered fuel) or solid mineral fuels (coal, coke, etc.) is assumed to have limited substitution potential, since it is used either to eliminate on-site waste or to serve both as a feedstock and as a heat source.

[22] Figures based on the reprocessing of consumption data by energy delivery points at address level – 2022 (SDES)

4.1.3 The industrial heat market that is technically accessible by SMR/AMR as a whole is comprised of ~60 *clusters*, mainly in Northern and Eastern France

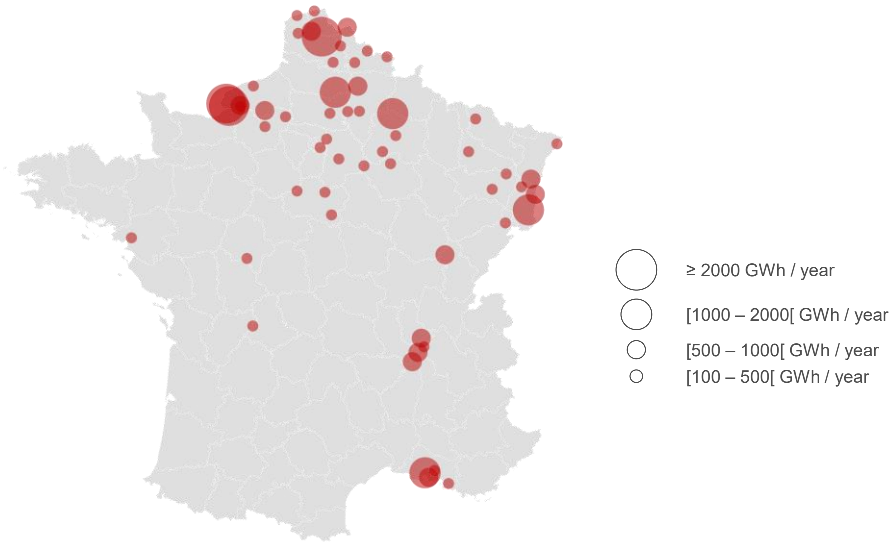


Figure 10: Map of industrial *clusters* that are technically addressable by SMR/AMR

4.1.4 However, SMRs/AMRs will only capture part of the technically addressable market, due to technical, economic, and decarbonization timeline constraints

(C) Temperature and size constraints specific to each technology

Maximum temperature and minimum power constraints will depend on the technology. For example, boiling water reactors and pressurized water reactors will only be able to access the demand in their temperature range, i.e. below ~250-300°C.

(D) Technical criteria specific to each technology

Each reactor design comes with specific technical constraints that may limit its deployment potential. Depending on the case, these may include land to host the reactor, proximity to a water source with adequate flow to supply the cooling circuit, or availability of a high-voltage grid connection – particularly for CHP. The criteria are listed in section 3.3.2.

(E) *Economic competitiveness criteria*

On sites where an SMR/AMR can technically be deployed, they will face competition from other low-carbon heat sources. Industrial players are likely to choose solutions that are available and mature, that operationally match their needs (temperature range, available thermal output), and that are cost-effective. The five main competing solutions are biomass, biomethane, solar thermal, high-temperature heat pumps, and solid recovered fuels.

- **Biomass** is currently the most developed renewable heat production solution. Biomass boilers for industry have been developed through the BCIAT[23] calls for projects created in 2009 and financed by the Fonds Chaleur (*Heat Fund*), France Relance, and France 2030. Between 2009 and 2022, 245 projects amounting to 16 TWh_{th}/year of production were supported. The majority of biomass boilers were developed in the agrifood industry, as well as in the wood, pulp & paper, and chemical industries.
- **Biomethane** is produced through the anaerobic digestion of organic matter. It can be self-consumed as heat or electricity, or purified and injected into the natural gas grid as biomethane. From the EU-ETS perspective, a gas consumer consuming from the grid can certify the renewable origin of the gas used (e.g., in a boiler) by signing a long-term Biomethane Purchase Agreement (BPA) with a biomethane producer. Other frameworks such as the GHG Protocol may soon recognize this option as well. In 2023, 11.8 TWh_{th}/year of biomethane production capacity was connected to the gas grid[24], and this capacity is expected to continue growing.
- **Solar thermal** energy only accounted for 0.2% of final heat consumption in France in 2022[25]. It is divided into two categories: low-temperature (up to ~150°C) and concentrating solar (which can produce heat between 250 and 1000°C). In industry, the former is mainly suited to preheating and drying processes – for example, the 13 MW_{th} plant commissioned in 2023 at Lactalis's whey production facility. Concentrating solar technologies are less developed in France. While traditionally used for electricity generation, they are increasingly being considered as an industrial heat solution.
- While **air-sourced heat pumps** are now widespread in homes, high-temperature heat pump (HTHP) technology for industrial applications is only emerging. A few players positioned along the industrial HTHP value chain and have begun installing demonstrators – for example Transpac (developed by Dalkia) has been in operation since April 2023 at Wepa Greenfield's paper mill. These heat pumps can recover waste heat in the 60–90°C range and upgrade it to 140°C. Potential applications include the paper, agri-food, and textile industries.
- **Solid recovered fuels** (SRF) are non-recyclable waste materials such as wood, plastics, rubber, paper, cardboard, and fabric. They offer an alternative to landfill and SRF boilers enable industrial companies to decarbonize their heat mix simply by replacing gas boilers. The FNADE estimates that by 2050, the SRF market could reach 5 mt, of which 1 mt would be used to decarbonize the cement industry[26] . This represents a potential heat production of ~12.5 TWh_{th}.

Other, less mature technological options also exist, such as equipping a gas boiler with carbon capture technology or using hydrogen as a fuel. These could nevertheless become credible alternatives by the 2050 horizon, although their development will depend on the establishment of dedicated CO_2 or H_2 logistical chains.

---

[23] Biomass Heat for Industry, Agriculture, and the Tertiary Sector
[24] Overview of renewable gases in 2023, SER
[25] Overview of renewable heat in 2022, ADEME
[26] Contribution of the waste sector to the French energy mix, FNADE, December 2023

Electric boilers (e-boilers) may also be used: although structurally more expensive than heat pumps, they can reach higher temperature levels. Their operation is mainly considered as a complement to other systems to seize low/negative wholesale electricity price opportunities[27].

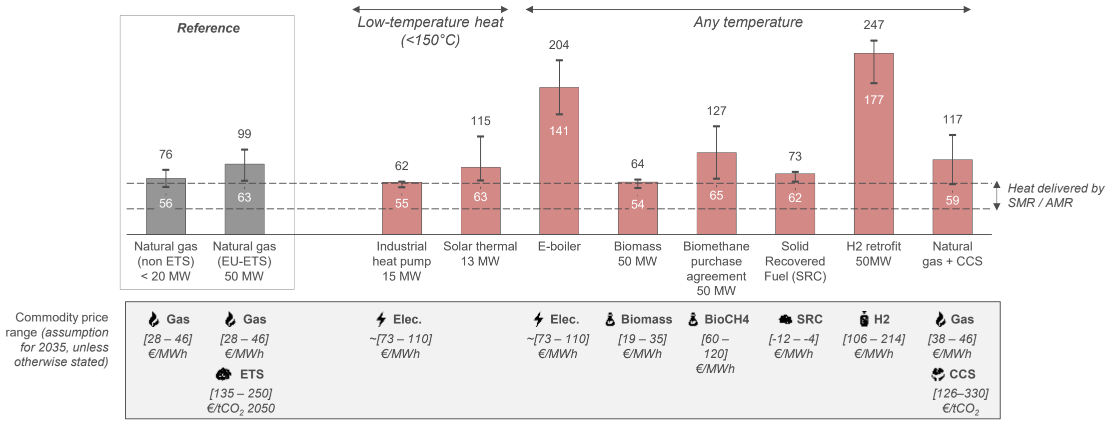


Figure 11: Levelized cost of heat by technology [€/MWh$_{th}$]

Assumptions: E-CUBE calculations based on a literature review of CAPEX/OPEX assumptions, 10% discount rate (third-party financing assumed), 2% annual inflation, 20-year asset life, and project start in 2035. Costs do not include the allocation of free EU ETS allowances. CCS estimates include CO_2 transport and storage but do not include heat distribution. For heat pumps and electric boilers, costs are estimated without electricity or heat storage.

The public data available to estimate the cost of heat produced by SMR/AMR is limited: players only communicate orders of magnitude. Calogena has announced a cost target of ~€60/MWh$_{th}$[28], while Steady Energy, in collaboration with Tractebel, is aiming for less than €40/MWh$_{th}$[29] (some developers mention even lower costs).

The development of SMR/AMR will heavily depend on the price they can offer. For low-temperature applications, heat pumps (HP) appear to be the main competition, but their performance depends on the availability of a waste heat source. Furthermore, heat pumps and solar thermal energy are limited in terms of power (currently ~15 MW$_{th}$) and temperature (140°C)[30]. It should be noted that these values correspond to the technologies available today and they are likely to evolve in the future: several projects mention heat pumps capable of exceeding 30 MW$_{th}$ of power and prototypes reaching temperatures above 140°C. Our analysis takes into account the current limitations of industrialized and commercially available technologies: in this context, high temperature concentrating solar thermal is not included.

For high-temperature applications, biomass boilers are a potential alternative, but their deployment may be limited by fuel availability – particularly wood – and by the constraints of sustainable forest resource management. ADEME[31] projects between 47 and 68 TWh$_{th}$/year of biomass heat production for industry, district heating, and commercial buildings by 2050, of which 25 to 45 TWh$_{th}$/year would be for industry. This represents only a moderate increase compared with the ~20 TWh$_{th}$ of biomass heat already consumed by industry. In addition, biomass heat

[27] The full cost shown in Figure 12 for the electric boiler corresponds to baseload use

[28] Calogena, Decarbonizing Urban Heating, 2024

[29] Revolutionizing energy production. The future of clean heat is here, 2024

[30] However, the temperature and pressure of the steam can be increased by mechanical compression

[31] *Biomass: a strategic issue for ecological transition,* ADEME, February 2024

production could face competition from other uses or run up against the imperative of sustainable resource management.

(F) *Alignment with decarbonization timelines*

Pressure – regulatory, stakeholder-driven, and economic –shapes the decarbonization timelines of industrial players.

- **Regulatory pressure**: Measures such as the EU ETS and the French Climate and Resilience Law set ambitious 2030 and 2040 targets. Under the latest EU ETS revision, the emissions cap for covered industries is expected to reach zero around 2040, following the gradual reduction of allowances. For many sites, major industrial upgrades occur during large maintenance shutdowns every 6–8 years, requiring years of preparation – meaning strategies to meet the 2040 target must be defined during the 2030s.
- **Stakeholder pressure**: Clients, consumers, and shareholders are stepping up their requirements, reinforced by the EU taxonomy and CSRD.
- **Economic pressure**: Rising costs of emissions and volatility in fossil fuel prices are pushing industry to accelerate the transition.

In this context, the effective availability date of SMRs/AMRs will directly influence the market they can address: the later they arrive, the more alternative decarbonization solutions will already have been implemented. However, since most of these alternatives (solar thermal, heat pumps, biomass or SRF boilers) have an asset life of ~20 years, SMRs/AMRs could also target a "second wave" when these investments come up for renewal.

Industry	Regulatory pressure	Pressure from counterparties	Economic pressure

Wood and paper industries
Glass, ceramics and concrete industries
Heavy industries (refinery, chemicals, pharmaceuticals, metallurgy)
	▪ Industries subject to the ETS
	▪ The most emitting sub-sectors have been forced to publish a decarbonization roadmap, with the approval of the government (or are in the process of drawing it up), with a target of reducing emissions in 2030 compared to 2015:
	  ▪ Mining and metallurgy: -31%
	  ▪ Chemicals: -26% to -33% target, depending on technology readiness
	  ▪ Concrete: -24% target
	  ▪ Paper: -39% target
	▪ In addition, the 25 most emitting sites are required to build their own roadmap
		▪ Few requirements from stakeholders except in specific sectors (e.g. metallurgy manufacturers must meet the demand of car manufacturers for low-carbon steel)
		▪ Shareholder pressure is expected to increase with the entry into force of the European taxonomy
			▪ Exposure to international competition mitigated by the launch of the CBAM CO2 Border Adjustment Mechanism (Fit for 55)
			▪ Sectors among the largest consumers of energy (~2/3 fossil origin)
			▪ Cost of ETS benefits

Food & Beverage Industries	▪ Industries potentially subject to the ETS according to the size of sites located in Europe ▪ Decarbonization roadmap under construction	▪ Mainly B2C sector with a strong importance of brand image ▪ Presence of "prescriber" actors involved in the RE100 and SBTi ▪ Impact of climate change on agriculture	▪ High variability in the share of energy costs: some sub-sectors have energy-intensive production processes (e.g. malting, milk powder) ▪ Cost of ETS quotas
Other Manufacturing Industries	▪ Industries potentially subject to the ETS according to the size of sites located in Europe	▪ Sub-sectors with high exposure to the B2C market (e.g. car manufacturers) ▪ Shareholder pressure is expected to intensify with the adoption of the green taxonomy	▪ Sectors exposed to competition from outside Europe with strong pressure to reduce costs ▪ Competition mitigated by the launch of the CBAM – CO2 Border Adjustment Mechanism (Fit for 55)

Figure 12: Illustrations of decarbonization pressure in selected industrial sectors

(G) *Other constraints impacting the commercially addressable market*

The deployment of SMR/AMR solutions could be limited by several commercial factors. Among these, counterparty risk, both on the side of the SMR solution developer – who may be considered insufficiently financially robust – and on the side of the heat consumer, whose long-term business continuity over the reactor's lifetime may be uncertain. Indeed, nuclear solutions are amortized over a long period (at least 20 to 30 years) and therefore require long-term commitments. This need for visibility over time could restrict the number of addressable clients, particularly in

industries with shorter investment horizons or business models that do not allow for long-term commitments. Another factor is the risk of delays in deployment and the limited ability to commit to long-term heat volumes.
Furthermore, although nuclear energy can raise concerns, this argument appears to have limited impact among French industrial players, where public opposition to nuclear was estimated at around 12% in 2022 (compared with 46% favorable and 40% undecided), according to ASNR. It is also plausible that acceptance will be higher near certain existing nuclear sites.
Some French industrial companies already consider SMRs a viable decarbonized solution for their heat demand: for example, Cristal Union has launched a feasibility study for the installation of a Jimmy Energy reactor to supply heat to its distillery and sugar plant in Bazancourt (Marne).

4.2 With temperature requirements between 60 and 300°C, district heating networks represent a technically addressable market estimated at between 12 TWh_{th} and 33 TWh_{th}/year for heat supply from SMRs/AMRs

The technically addressable market for district heating networks in France, for SMR/AMR, is estimated between 12 TWh_{th} /year – based on current demand – and 33 TWh_{th} , taking into account future network development. Since temperature ranges from 60 to 300°C, all district heating demand can be addressed by SMR/AMR technologies. As with industrial applications, the addressable market will significantly depend on the technology, due to economic competitiveness and other commercial criteria.

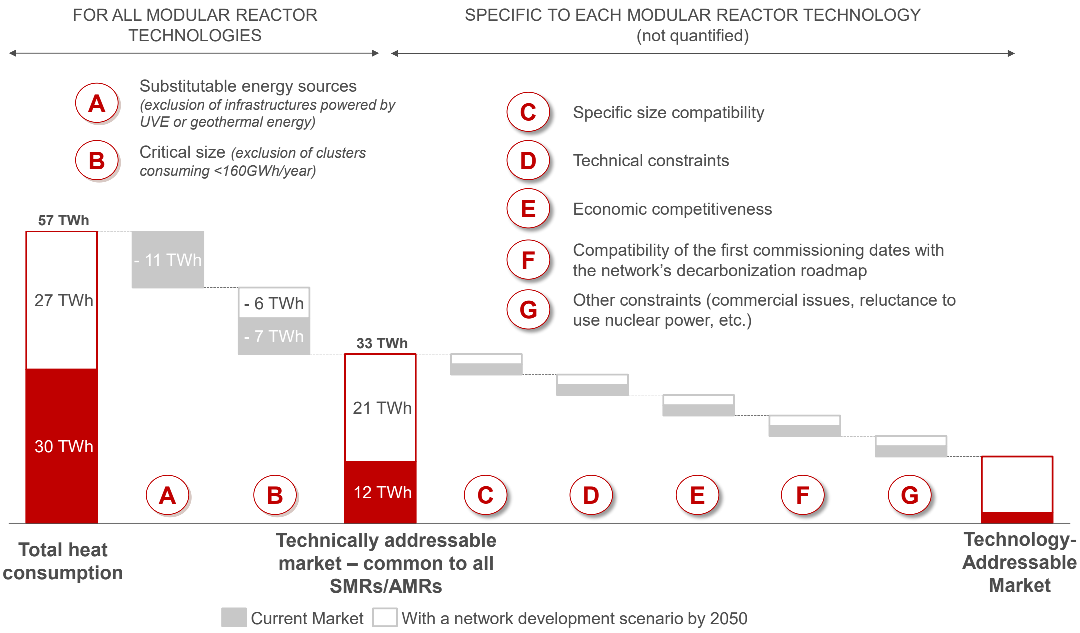


Figure 13: Waterfall of the addressable market for SMRs/AMRs in the district heating network market[32]

[32] Difference from data in part 2.2 related to climate correction. Estimates based on SDES data

4.2.1 Networks supplied with decarbonized heat sources that are likely to still be in use by 2050 are not considered technically addressable by SMRs/AMRs

In order to estimate the technically addressable market, it is relevant to exclude networks where a significant proportion of the heat already comes from a decarbonized heat source with a long asset life.

The average lifespan of a biomass boiler is around 20 years. We can therefore assume that district heating networks powered by biomass facilities since the 2010s will reassess this technological choice by 2030. These networks are therefore included in the addressable market for SMR/AMR.

Conversely, a significant proportion of district heating networks are currently powered by waste-to-energy (WtE) plants, which recover heat from waste combustion, and are expected to still operate by 2030 or 2050. Although the amount of waste to be incinerated in the future is uncertain due to bio-waste collection and incentives to increase recycling, networks supplied by WtE plants are excluded from the technically addressable market.

Similarly, geothermal facilities, which supply around 40 networks for a total 1.7 TWh_{th}/year, have a lifespan of over 60 years. As these infrastructures are unlikely to be replaced in the short or medium term, they are also removed from the technically addressable market by SMRs/AMRs.

This first filter reduces the addressable market from 30 TWh_{th} to 19 TWh_{th}[33].

4.2.2 The target market for SMRs/AMRs is on "large" heating networks, i.e., those with sufficient demand to justify the construction of a reactor

Many small district heating networks operate in France whose energy demand is insufficient to justify the use of SMRs: around 80% of networks have an installed thermal capacity below 10 MW_{th}. Their heat supply is sized to meet winter peak demand: unlike in industry, heat consumption in district heating is significantly lower in the summer and the annual load factor of networks is generally around 40%. The target market for SMRs/AMRs is therefore considered to be primarily large networks, with installed thermal capacity above 45 MW_{th}[34].

[33] Climate-adjusted heat consumption
[34] Corresponds to an average power consumption of 20 MWth over the year.

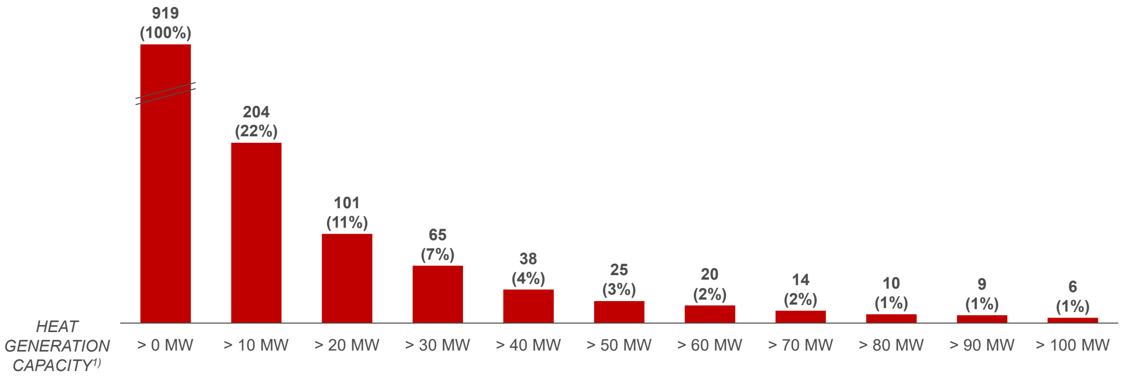


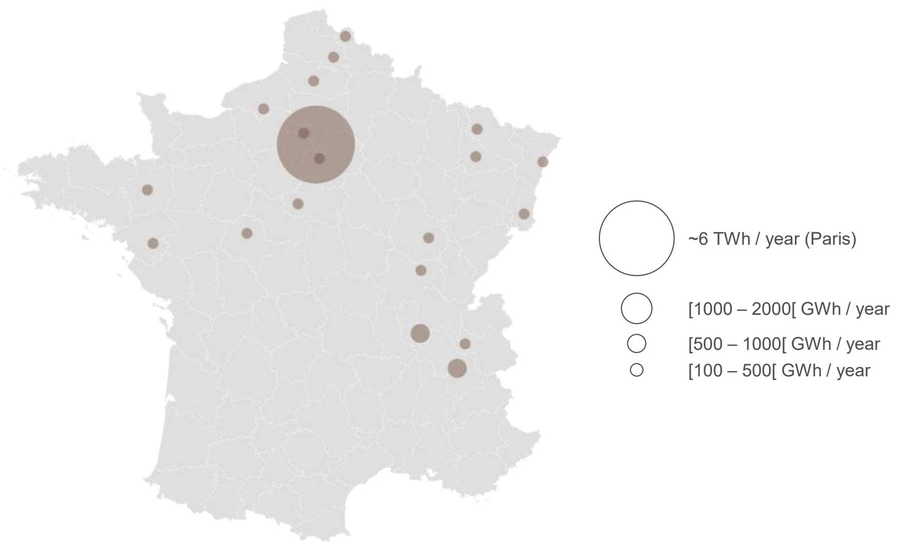
Figure **14**: Number of district heating networks by installed capacity in 2022

1) Installed capacity derived from annual heat consumption with a 40% load factor

Reading note: there are 25 heating networks in France with an installed capacity of over 50 MW_{th}.

SMRs/AMRs can supply heat to several nearby district heating networks that form a cluster[35]. E-CUBE considered only clusters of networks with annual heat consumption above 160 GWh_{th}, i.e., networks with *a minimum* average power of 20 MW_{th} over the year.

This results in a technically addressable market for SMRs/AMRs of ~12 TWh_{th} per year in 20 district heating clusters.



[35] Based max 45km diameter (max. SMR/AMR-district heating network distance: 22.5km), excluding networks with annual consumption <25GWh. For details on the clustering methodology, see Appendix 1.

Figure 15: Map of existing district heating network *clusters* that are technically addressable by SMRs/AMRs

4.2.3 Extensions of existing networks and the development of new networks will increase the technically addressable market by SMRs/AMRs

France has set ambitious targets for the development of district heating networks. The draft PPE 3 currently under consultation targets 90 TWh_{th} of heat delivered through district heating networks by 2035 (compared with 26 TWh_{th} in 2022). E-CUBE adopts a more conservative scenario, assuming 2% annual growth[36] in consumption per network. By 2050, heat demand is expected to increase through the extension of existing networks (+18 TWh_{th}) and the development of new ones (+9 TWh_{th}), raising the total heat delivered by district heating networks from 30 TWh_{th} in 2022 to 57 TWh_{th} in 2050.

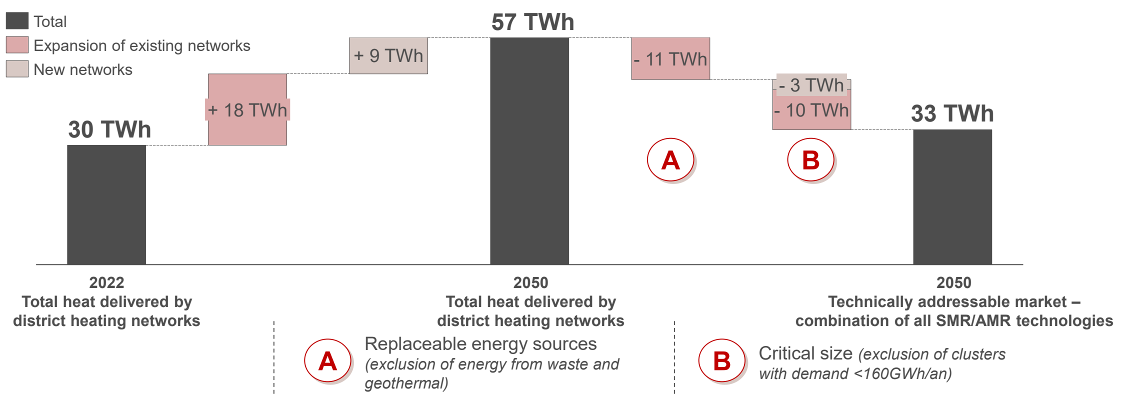


Figure 16: Market for district heating networks technically addressable by SMRs/AMRs in 2050, in TWh_{th}/year of heat delivered

District heating networks are expected to significantly increase in both number and size. This dynamic will substantially expand the addressable market for SMRs/AMRs.

E-CUBE estimates the technically addressable market at ~33 TWh_{th} when accounting for network developments. The extension of existing networks is assumed to be proportionally distributed, allowing some clusters that are currently "too small" to reach the critical size needed to justify the deployment of a nuclear reactor. By 2050, the distribution of heat production by cluster size is assumed to be the same for both existing and new networks.

In addition, growth in district cooling networks could drive higher heat demand to supply absorption chillers (thermal compression using an intermediate fluid such as lithium bromide or water-ammonia). However, these technologies are currently little used compared with compression-based technologies: they account for less than 5% of cooling produced in French urban cooling networks in 2023, according to FEDENE.

[36] Average growth rate of heat network consumption in the ADEME S3 "Transitions 2050" scenario

4.2.4 However, several factors will limit the technically addressable market share captured by SMRs/AMRs

A number of factors will impact the ability of SMR/AMR to capture market share. Technical, economic, and commercial constraints will either support or hinder the deployment of SMRs/AMRs. First, SMR/AMR will face competition from alternative solutions (see section 4.1.4).

In addition, the load profile of district heating networks, which is heavily influenced by seasonal variations, requires SMR/AMR to modulate their heat production. This means

- Either accepting low utilization outside of peak demand periods, which reduces the project's economic viability
- Or undersizing SMRs/AMRs to maximize their utilization, which requires backup production capacity to meet demand during periods of high demand
- Or making production flexible, for example by converting unused heat into electricity

The regulatory framework also plays a key role. The Energy Transition for Green Growth Act (LTECV) sets the target of a fivefold increase in heat production from renewable and recovered energy (EnR&R) by 2030 compared with 2012, which would correspond to 39.5 TWh_{th} in 2030. The PPE, currently under consultation, sets a target 75% share of renewable energy in district heating networks by 2030 and 80% by 2050.

These objectives focus on the penetration of renewable and recovered energy sources, and it remains uncertain whether they will be extended to include low-carbon technologies such as SMRs/AMRs. How these technologies are considered as part of the energy transition will directly influence their deployment potential.

4.3 Current heat demand technically addressable by SMRs/AMRs represents around 18 $MtCO_2eq$ of direct emissions, mainly in industry

4.3.1 The current heat mix of industry and district heating networks resulted in total 2022 emissions estimated at respectively ~26 $MtCO_2eq$ and ~3 $MtCO_2eq$

In 2022, heat demand in industry reached a total 170 TWh_{th} (representing ~58% of final energy consumption by industry). It is estimated that the production of this industrial heat caused ~26 $MtCO_2eq$ per year[37] of direct GHG emissions. These are mainly linked to the combustion of fossil fuels, which account for around 62% of the energy mix used for heat production in industry.

[37] Estimated using the emission factors for different energy sources provided by ADEME for fossil fuels and Amorce for heating networks.

Heat production for district heating networks represented circa 3 $MtCO_2eq$[38] of direct GHG emissions in 2022 (mainly from the combustion of natural gas, which accounts for 30% of the heat mix).

4.3.2 Current heat consumption technically addressable by SMRs/AMRs represents around 16 $MtCO_2eq$ of direct emissions avoided in industry and 2 $MtCO_2eq$ in district heating networks

Of the 170 TWh_{th} of heat consumed by industry, 70 TWh_{th} are considered technically addressable by modular nuclear reactors, representing 16 $MtCO_2eq$ of direct annual emissions.

For district heating networks, the ~12 TWh_{th} technically addressable by SMRs/AMRs correspond to just under 2 $MtCO_2eq$ of direct annual emissions.

In total, across these two technically addressable markets, direct emissions amount to ~18 $MtCO_2e$ – over 60% of the direct emissions from heat consumption in these sectors.

4.4 The emergence of new heat-consuming sectors (carbon-free hydrogen production, CCUS) could represent an opportunity of >10 TWh_{th} /year by 2050

Several industrial processes currently under development could present significant opportunities for SMR/AMR:

- The production of carbon-free hydrogen for various applications, including: refining/petrochemicals, production of ammonia, and synthetic fuel production (*e-fuels*)
- CO_2 capture for reuse or storage
- Seawater desalination

In addition, marine propulsion could be another market for SMR/AMR.

This study focuses solely on hydrogen production and CCUS.

4.4.1 Hydrogen production from high-temperature electrolysis could represent a technically addressable market for SMRs/AMRs between 0.5 and 3 TWh_{th} by 2050

High-temperature electrolysis (HTE) breaks down water molecules into dihydrogen and dioxygen. Unlike standard electrolysis (which is based on alkaline & proton exchange membranes), this technology uses 500-800°C[39] steam to increase process efficiency to >85-90%, vs ~60-70% for

---

[38] Based on LCA data from the Fedene 2022 survey using the emission factors from the tertiary decree (with the exception of a few emission factors, e.g., wood energy considered at 13 gCO2eq/kWh).
[39] Some high-temperature electrolysis systems (e.g., Genvia) are designed so that at steady-state operating point, the system can be fed with steam at only 150°C, with the outlet gases reheating the inlet steam.

standard technologies. Solid oxide electrolysis cells (SOEC) are the main technological component used in this process[40] .

This technology significantly reduce hydrogen production costs in the long term. Several projects are currently under development such as the construction of a SOEC unit *gigafactory* by GENVIA.

The heat requirements of HTE could represent a particularly interesting opportunity for SMRs/AMRs, as these processes consume a significant amount of heat (8 to 10 kWh_{th}/kg of hydrogen produced[41]) at a temperature of between 500 and 800°C[42]; moreover, the heat/electricity mix corresponds to what certain SMR/AMR designs can deliver. In RTE's *Futurs énergétiques 2050* scenarios, hydrogen production from electrolysis in France could reach 1 to 2 mt by 2050[43] . If high-temperature technology accounts for between 10%[44] and 20% of future developments (i.e., developments after 2030), between 45 and 350 kt of hydrogen could be produced from high-temperature electrolysis by 2050. If hydrogen production units are large enough to justify building an SMR/AMR, the technically addressable market by 2050 could be estimated at ~0.5 to 3 TWh_{hth}.

While some SMR/AMR technologies can supply all of the heat for HTE, others may only provide part of it, particularly during the initial vaporization phase, which occurs at around 150°C. In addition, SMR/AMR cogeneration plants are also capable of providing the electrical energy required for the electrolysis reaction.

It is important to note that these estimates do not take into account the regulatory risk associated with the European definition of hydrogen, depending on the source of electrical energy used. Following the adoption in May 2024 of the "Hydrogen and Decarbonized Gas" package, the European Commission is preparing a delegated act[45] defining accounting standards and emission reduction thresholds for low-carbon hydrogen production methods, which will serve as the basis for a future certification system. If nuclear-based production is not recognized as "low-carbon," the development of SMRs/AMRs in this market could be significantly reduced. In addition, this market will face competition from other heat production technologies, as well as from the various market-limiting factors in previous paragraphs.

4.4.2 Carbon capture technologies could represent a 10-15 TWh_{th} technically addressable opportunity by 2050

Carbon Capture, Utilization and Storage (CCUS) technologies enable the capture of CO_2 emissions for use as a feedstock (e.g. to produce renewable fuels) or for permanent storage. CCUS is one of the key levers to achieve global and national carbon neutrality targets, particularly

---

[40] Other technologies under development, such as thermochemical water splitting, may require lower temperatures (e.g., 550°C for the Cu-Cl hybrid cycle).

[41] Solid Oxide Electrolysis (SOEL) Overview of the technology and Current challenges and developments, 2022

[42] Some high-temperature electrolysis systems (e.g., Genvia) are designed so that at steady state, the system can be fed with steam at only 150°C, with the outlet gases reheating the inlet steam.

[43] The RTE N03 scenario projects ~64 TWh PCI of hydrogen produced per year; the RTE M0 scenario projects ~35 TWh PCI of hydrogen produced per year

[44] Global Hydrogen Review 2023, Electrolyzer production capacities by 2030, ~10% will be based on SOEC technology

[45] The draft delegated act submitted for consultation in September 2024 postpones the assessment of nuclear energy until 2028

for “hard-to-abate” emissions such as those from certain non-energy industrial processes (e.g., cement production).

In France, the current national CCUS strategy[46] projects 31.4 to 57.9 mt CO_2 captured annually by 2050. In some sectors, the captured CO_2 is biogenic – i.e. from the combustion or degradation of biomass (as opposed to fossil CO_2) – and can be used to produce synthetic fuels (e-fuels). This is the case in the pulp and paper industry, where CO_2 stored in trees is released as part of cellulose pulp production.

In other sectors, CCUS capacitu will allow for the capture of hard-to-abate emissions. For example, 7–8 $mtCO_2$/year from cement and lime production come from heating limestone to produce clinker. In the chemical industry, CCUS is expected to capture otherwise unavoidable emissions, such as safety flares in steam crackers or the incineration of solvents and hazardous waste. The sector is also relying on CCUS as a faster and more cost-competitive solution than electrolysis for hydrogen decarbonization. In fact, hydrogen produced by steam methane reforming accounted for 2.5 $mtCO_2$/year in 2019.

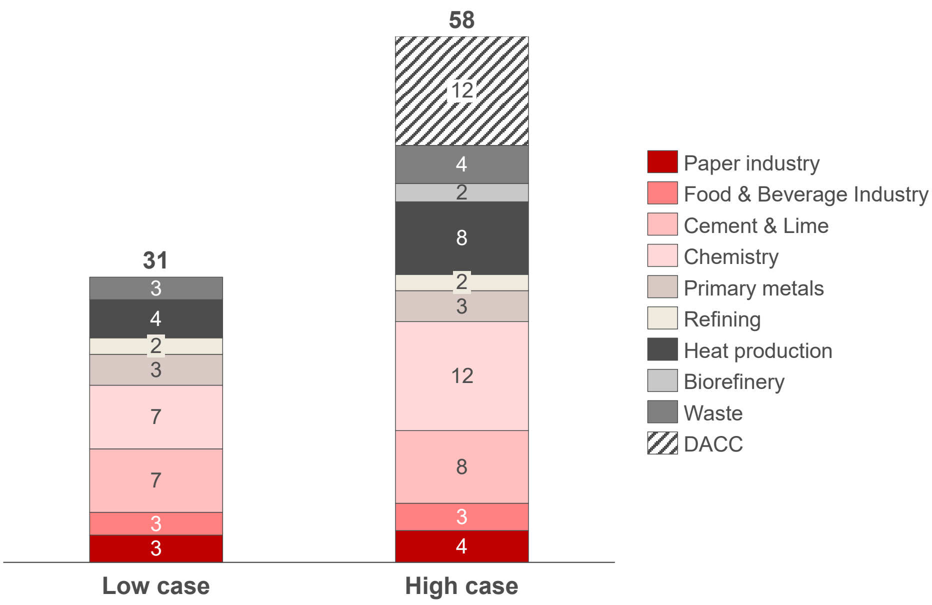


Figure 17: CCUS capacity in 2050 by source according to the national CCUS strategy, in $MtCO_2$/year captured

Several carbon capture technologies are currently under development. Some require heat during the regeneration phase:

- Solvent-based technologies, such as amines, absorb CO_2 in a contactor, which must be heated in order to release the captured CO_2 and allow the solvent to be reused. This step is very energy-intensive and requires temperatures between 120 and 150°C.

[46] CCUS status and outlook, July 2024, Ministry of Economy

- Absorption technologies also require heat to release the captured CO_2, the temperature of which varies depending on the type of sorbent. Note: while the use of a thermal cycle is common, some variants of absorption technologies use a pressure drop.
- Membrane technologies separate CO_2 from waste gases. Once saturated, the membrane is subjected to a temperature increase in order to desorb the CO_2 from the membrane, the solvent, and the outlet, respectively.

By contrast, cryogenic distillation technologies do not require heat as an input: they rely on a phase change, separating CO_2 from the gas by distillation under cryogenic conditions, in liquid (liquefaction) or solid (desublimation) form. Air Liquide has developed a CO_2 capture solution called Cryocap, which it has been operating at a hydrogen production site since 2015.

Technology	Description	Heat requirement	Temperature	Heat consumption	TRL
Absorption	CO2 from flue gases or air is trapped in a solid or liquid solvent	The mixture is then heated to extract the CO2 (some solvents can be reused)	120 – 150°C	[0.5 to 0.8 MWh/tCO$_2$]	9
Adsorption	CO2 deposits are created below the surface of a high-pressure solid adsorbent The surface is regenerated by decreasing the pressure to release CO2	Regeneration is achieved by increasing the temperature of the solid bed (Thermal Swing Adsorption) or by reducing the pressure (Pressure Swing Adsorption)	100-130°C depending on sorbents	Similar to absorption	7 9
Membrane separation	Carbon dioxide is separated from other high-pressure flue gases through a filter	Some membranes function at high temperatures	70 – 100°C	Lower than absorption	7 9
Cryogenic distillation	CO2 is separated from the air or flue gases through its distillation under cryogenic conditions (liquefaction at -57°C or desublimation at -79°C)	*None*	-	-	7
"Carbonate looping"	Carbon is chemically trapped in a redox reaction before being converted into carbon dioxide under a chemical loop	The resulting carbonate is then heated to release the CO2	700 – 950°C	~2 MWh/tCO$_2$	6

The most mature technologies (TRL between 7 and 9) have an average heat demand of 650kWh/tCO2

Figure 18: Overview of carbon capture technologies and their heat requirements[47]

CCUS capacity that will be deployed with technologies requiring heat input will create market opportunities for SMRs/AMRs. However, the penetration of the various capture solutions is highly uncertain by 2050 as many technologies are currently under development, and this strong competition is driving innovation. Assuming heat-consuming solutions account for 50% of the market[48], the market technically addressable by SMRs/AMRs could represent 10-15 TWh_{th}/year.

This estimate does not take into account developments in Direct Air Capture (DAC) processes, which also consume significant amounts of heat (1.47 - 2 MWh_{th}/ton of CO_2 according to the IEA[49]). The high-case scenario of the National Strategy (12 $mtCO_2$ captured/year) would therefore represent a technically addressable heat consumption of ~17 to 24 TWh_{th}.

In this market, SMRs/AMRs will face the same constraints as in other markets. The minimum heat consumption constraint should have a low impact, given that CCUS capacity will only be deployed at the most emissions-intensive sites or industrial areas. In fact, 20 MW_{th} (the lower end of the SMR size range) can meet the needs of a carbon capture facility of around ~250 $ktCO_2$/year, but most of the projects currently under development involve sites well above this emission level.

[47] The absorption data correspond to amine technology, which is the most advanced and least expensive solvent. Oxy-combustion technologies are not studied here.
[48] Assuming that competing cryogenic technology captures most of the market for chemical applications (including hydrogen production) and cement.
[49] Energy requirements for L DAC and S DAC processes – Source: IEA data (2022).

Technical constraints will vary depending on the SMR/AMR technology. They will have a similar impact as on industry, given that CCUS will be developed at the same sites (see section 3.3.2).

Modular reactors will also have to compete with other heat production technologies (see section 4.1.4). For low-temperature technologies such as absorption or membrane separation, economic competitiveness with industrial heat pumps could have a significant impact on the market share of SMRs/AMRs.

5 SMRs/AMRs can address growing electricity demand from large consumers

Although the transmission system operator RTE does not anticipate any development of commercial SMR/AMR power generation in France before 2035[50], it does consider the possibility that they develop alongside EPR2 reactors by 2050 in scenario N03 of the *Futurs Énergétiques 2050* outlook. In this scenario, SMRs/AMRs start deploying in 2035 and reach an annual electricity output of 27 TWh by 2050.

SMR/AMR power generators can offer electricity production:

1. Either **to complement the national electricity mix by injecting electricity into the national grid**, without targeting locations close to high-consumption sites ("national" rationale): some SMRs/AMRs are designed for flexible operation with significant modulation in response to wholesale electricity market price signals, thanks to integrated on-site heat storage.
2. Or **to supply locations or areas with specific needs** (“local” rationale). These needs can be of several kinds, including:
    - Demand for a low-carbon, constant electricity supply at a stable price over the long term (**"economic" rationale**)
    - Grid constraints: limits on available withdrawal capacity or network reinforcement lead times (**"technical" rationale).**

In the first case, SMR/AMR installations could include **sites that have already been used for electricity generation** (e.g., former thermal power plants) or that have already hosted nuclear operations. We do not examine this case in further detail in this report.

The second case could pertain to **industrial sites or data centers of various** sizes, similar to those currently connected to thermal CHP plants (particularly natural gas plants), whose thermal power sometimes reaches several hundred MW.

In the second case, **the "economic" rationale** can be addressed by **PPAs** without SMR/AMR being located near the consumer site. Compared to a PPA, self-consumption can reduce certain costs (network and taxes) to the extent permitted by regulation, but these are relatively limited in France for large consumer sites[51] .

As for the **"technical" rationale**, it is **difficult to precisely identify areas that would be most favorable for the development of SMR/AMR**, as the lead time to reinforce the grid (4 to 5 years between initial studies and commissioning for a 225 kV / 400 kV line[52]) is currently shorter than

---

[50] RTE does not anticipate commercial SMR power generation coming online before 2035 but does not rule out the development of prototypes or experimental reactors.

[51] For consumers > 150 GWh/year, network charges (TURPE) amount to circa €5/MWh (with abatements of 50% to 80% for electricity-intensive companies), and taxes of around €1/MWh.

[52] Deadline presented by RTE for "P2" industrial zones in the SDDR 2025

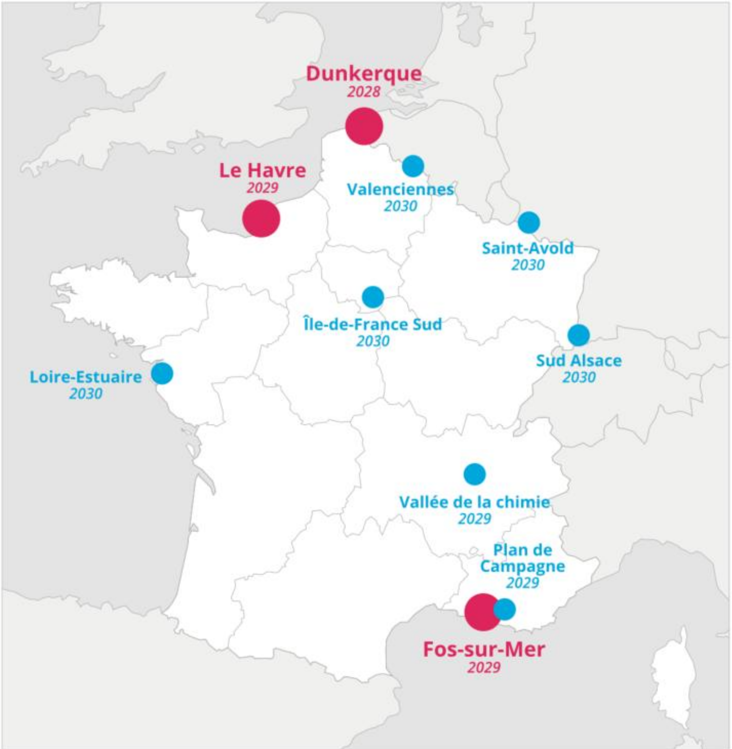
the time before the first commercial commissioning of most of the SMR/AMR power generators selected for the France 2030 program (demonstrators are scheduled to be commissioned in 2030 at the earliest). Consequently, strengthening the grid currently appears to be a "faster" solution than building an SMR/AMR.

However, because of the scale of the work and investment required to upgrade the electricity transmission network in the coming years (renewal of existing assets, connection of offshore wind farms, development of interconnections), **RTE is establishing an order of priority for reinforcement work,** particularly for connecting onshore solar and, wind power generation and new consumer sites.

This prioritization led RTE to define several **priority categories** in the latest SDDR (10-year network development plan) **for areas with high electrification demand,** particularly for industry and data centers:

- Priority 1 (P1): Major industrial ports (Dunkerque, Fos-sur-Mer, Le Havre), reinforcement projects are already well advanced to address strong expected demand growth (at least environmental studies are underway).
- Priority 2 (P2): Seven areas where RTE has initiated administrative procedures, but the actual start of works is conditioned upon the “concrete materialization of the industrial projects that these reinforcements are intended to serve” (unless the State or CRE lifts this condition).
- Priority 3 (P3): Areas where “an increase in electricity consumption is likely to occur in the near future” due to development ambitions of local authorities, and where “financial commitment will be required from the relevant industrial players” to initiate the works.

In addition, RTE will set up an allocation procedure for sites that can be quickly (as early as 2028) supplied with high power (~1 GW).



Target dates are:

- **for P1/P2 zones**: subject to obtaining the necessary administrative authorizations according to the most optimized timeline.
- **for P2 zones**: subject to investment decisions by the relevant industrial players prior to RTE obtaining the necessary administrative authorizations.

Figure 19: P1 and P2 zones (network development for low-carbon industry and/or data centers) of RTE's SDDR 2025 (source: RTE)

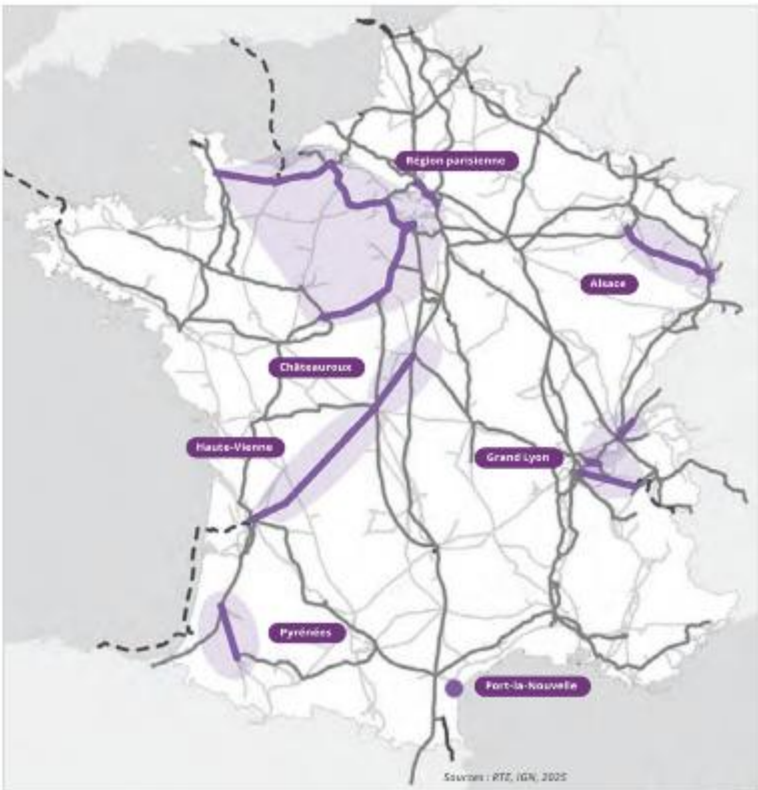


Figure 20: P3 zones and associated strategies for accelerating the very high-voltage development program to accommodate industrial consumption by 2030 from RTE's SDDR 2025 (source: RTE)

It is therefore possible that by 2035, the construction of an SMR/AMR may be considered as an alternative or complement to electricity supply when grid reinforcement is required to accommodate a large consumer site in an area where withdrawal capacity is insufficient. Such projects could arise from initiatives by large consumers or by local authorities, such as those in the "P3" zones of the SDDR.

However, it is important to note that connection of SMRs/AMRs to the public electricity transmission grid will remain necessary:

- At a minimum, to ensure redundancy of supply for consumers in the event of a planned or unplanned outage of the SMR/AMR.
- Depending on the technology, to ensure reactor safety functions (e.g. PWRs): in some cases, this may require several electrical connections with the same voltage level (400 kV) and reliability as consumer sites.
- Potentially, to enable the injection of surplus electricity generation into the grid.

Thus, in most cases SMRs/AMRs could reduce the need for the public grid without fully replacing it.

Power-generating SMRs/AMRs addressing local issues could notably be located:

- **On-site (individual self-consumption):** this option theoretically provides the best guarantee of physical supply security and the lowest infrastructure cost. However, site constraints – particularly available land – may limit feasibility.
- **"Nearby" new consumer sites:** for example, in a draft decision put out for consultation in February 2025, the Irish regulator CRU proposed making the construction of new data centers conditional on adding on-site or "nearby" generation capacity at least equivalent to the data center's grid connection capacity – the implementation details of this proposal remain to be defined.

6 A sharp increase in electricity consumption is expected in the coming years from large industrial sites and data centers

SMRs/AMRs could develop based on supply contracts with large consumer sites, whose consumption is expected to sharply increase in the coming years as a result of:

- The electrification of **industrial processes** (direct and indirect)
- The development of **data centers**

Other specific applications (e.g. remote sites in extractive industries) could represent commercial targets for SMRs/AMRs, but they are not discussed in this report.

6.1 The electrification of industrial processes, combined with increased use of low-carbon hydrogen, is expected to drive strong growth in electricity demand in major existing industrial areas

Electricity demand is expected to significantly increase at certain industrial sites due to decarbonization. It can be:

- **Direct**: for example, replacing fuel-fired boilers with industrial heat pumps to produce low-temperature heat in sectors such as agrifood or paper and cardboard manufacturing, or replacing gas furnaces with electric furnaces in the glass industry. According to RTE estimates, this increase in industrial consumption could reach between 10 and 50 TWh_e by 2050 compared to 2019[53] .
- **Indirect**: replacing fossil fuels with carbon-free hydrogen from water electrolysis. In its "reference" scenario (*Futurs Énergétiques 2050*) RTE projects 1-2 mt/year hydrogen production from electrolysis by 2050[54]. This production will require significant amounts of electricity: approximately 50 kWh_e per kilogram of hydrogen produced for low-temperature electrolysis (~65% efficiency) and approximately 35 kWh_e for high-temperature electrolysis (up to 90% electrical efficiency), which also requires heat input. Thus, hydrogen production from electrolysis could mobilize between 9.5 and 21 GW_e of installed electrical capacity in 2050, representing an annual consumption of ~50 to ~100 TWh_e of electricity.

6.2 Data center operators are increasingly interested in nuclear power

[53]Source: RTE Energy Futures 2050, additional electricity consumption from industry in the "electrification+" and "reindustrialization" scenarios (excluding hydrogen production).
[54]In RTE's "hydrogen+" scenario, hydrogen production from electrolysis in France reaches ~3-4 mt

The electricity consumption of data centers has been growing steadily for several years. This growth is set to accelerate as a result of increased internet traffic, the development of cloud services, and the rise of artificial intelligence models, particularly text and image generation.

Several ownership and operating models exist for data centers: this report focuses only on colocation and dedicated data centers.

Type of data center	Characteristics	Location
Enterprise	Operated and used by a company for its own needs.	On or near the company's site, to maximize control and security.
Colocation	Operated by a hosting provider and used by client companies that rent space and/or servers there. *Examples: Data4, Digital Realty, Equinix, etc.*	**Historically**: close to network infrastructure (submarine cable landing stations, internet interconnection points, etc.) to maximize connection quality, and/or close to centers of economic activity to facilitate technical operations by the operator, its subcontractors, and its customers. **Increasingly for HPC/AI applications (training in particular)/cold storage**: depending on access to energy/land/water resources (cost, availability)
Dedicated	Operated by an IT or telecom service provider (e.g., cloud, AI, internet access, etc.) and used for its own account. *Examples:* ▪ *Cloud or AI service providers: Amazon, Google, Meta, Microsoft, OpenAI* ▪ *Telecom operators: Bouygues, Free, Orange, SFR*, etc.	

6.2.1 Data center operators seek competitive, high-quality, carbon-free electricity that is readily available on a continental or even global scale

For data centers for which latency is not a major constraint (e.g. cold data storage, artificial intelligence model training), the choice of location can be made on a national, continental, or even global scale, as connectivity costs are relatively low.

	Digital resources (storage, computing, interconnection) with location needs			Digital resources without location need
Location rationale	Close to end users (factory, city, vehicle, etc.)	Close to economic activities	Close to key points of the internet network	NA
Types of locations	Cities with 100k+ inhabitants with significant economic activity	Very large cities	Large cities hosting IXPs or submarine telecom cable landings	NA
Examples in France	Rennes, Strasbourg	Paris	Paris, Lyon, Marseille	Anywhere
Types of applications	Telecom networks Edge applications (e.g. AI inference)	Any compute or storage needs		**Latency-free applications:** high-performance computing (scientific computing, AI training), "cold" data storage
Examples of actors	▪ Telecom operators (bouygues, orange) ▪ Colocation hosts specialising in "edge" (nlighten, UltraEdge)	▪ Shared accommodation providers (Data4, Digital Realty, Equinix) ▪ Cloud operators with their own data centers (aws, Google, OVH.com, Microsoft)	▪ Specialized players in network services (e.g. CDNs, IXPs, telecom operators)	

Figure 21: Rationale for data center location

This choice is based on several strategic criteria:

- **Electricity**: low and stable **cost** over several years, **quality** (power supply continuity defined by frequency and outage time, voltage wave quality), **carbon-free or renewable**, **fast** connection
- **Land**
- **Water resources**: liquid cooling is the most efficient and energy-dense (in kW of computing power per standard server rack) and therefore limits electricity and land consumption. This explains why processors (CPUs, GPUs, TPUs) and servers designed for AI are now mostly designed for this cooling method. However, it generally consumes a significant amount of water as it is often associated with evaporative cooling towers.

The growth of cloud services and AI models is leading to an increase in the computing power required and – due to economies of scale – to an increase in the unit size of data centers: *hyperscale* sites (>20 MW), once operated only by GAFAM, are now becoming the norm, and project sizes are now measured in hundreds of MW (e.g. 300 MW for the Sesterce project in Gardanne, intended to offer third parties computing power to train AI models) and some even reach GW scale (e.g. 2 GW for Meta's project in Richland Parish, Louisiana which is intended to train its Llama AI models)[55] .

This context explains why data center developers and operators are particularly interested in sites that already consume large amounts of electricity and water, in cold or temperate climates, and where electricity is carbon-free and abundant (e.g. Google has been operating a data center on the site of a former paper mill in Hamina, Finland, since 2009).

In February 2025, the French government unveiled a list of 35 "ready-to-build" sites specifically identified to host new data centers, representing areas ranging from 18 to more than 150 hectares, which can be quickly connected to the electricity grid and could reach a total of 1 GW by 2027.

6.2.2 Data center consumption in France could reach ~29 TWh$_e$ by 2040, driven by the increase in the number of data centers and growing AI-related needs

According to RTE's ten-year network development plan (SDDR, version submitted for consultation in 2024), the annual consumption of data centers could reach around 29 TWh$_e$ by 2040. According to the CESE, this consumption could reach "50 or even 70" TWh$_e$ by 2050[56] .

Several factors make it difficult to estimate future data center consumption in France:

- International competition between countries to host data centers
- Uncertain balance between demand growth and energy efficiency gains, the latter enabling even stronger growth in demand for storage, computing, and data transport capacity. These efficiency gains are expected at several levels:

[55] At the AI Action Summit in Paris in February 2025, the French Presidency unveiled an investment project led by a Franco-Emirati consortium that could lead to the creation of a 1GW data center

[56] Source: CESE, *"For Artificial Intelligence Serving the Public Interest"*, January 2025

- **Software**: efficiency of AI algorithm training (e.g. players such as Deepseek and MistralAI seek to minimize the computing power used to train their models compared to the market leaders in LLM: in January 2025, DeepSeek announced that they were using around one-tenth of the computing power of Meta's Llama 3.1 model, thanks to more efficient training methods – although the performance of the models is not equivalent).
- **Hardware**:
  - **Cooling** technology (e.g. switching from air cooling to liquid cooling)
  - Processor/chip/server **design** (e.g. Google claims 67% energy savings with its sixth-generation TPU compared to the previous generation[57])
  - Computing **technology** (e.g. developments in optical data processing)

6.2.3 SMRs/AMRs are an attractive solution for data center operators who set ambitious targets for energy supply and carbon neutrality

Major operators in the sector are adopting ambitious strategies to limit their environmental impact. These strategies particularly focus energy efficiency and electricity supply.

The objectives are multiple:

- To reinforce the **right to operate** data centers
- To facilitate project **development** by limiting the resources required
- To secure **electricity supply** (cost, quality, carbon-free or renewable nature, quick availability)

Historically, securing electricity supply mainly involved **purchasing renewable electricity through PPAs**, which made it possible to claim that the electricity used was renewable while securing part of the supply in the long term (depending on the source of supply and the type of PPA): Google, for example, signed their first PPA with a wind farm in 2010 and report having contracted a total of 14 GW of renewable capacity between 2010 and 2023. Some also use self-consumption projects by integrating renewable assets on site, such as Echelon in Ireland (1 GW wind project) or Google in Belgium (2.8 MW of photovoltaics), but the power of these projects is limited compared to the consumption of data centers.

For several years now, some players such as Google and Microsoft have been combining this strategy with a goal to **match carbon-free production with consumption at a short time step** (whereas the matching based on guarantees of origin associated with PPAs is at a monthly time step in Europe), known as "**24/7 *carbon-free energy matching***." However, the approaches of other players (Amazon, Meta) differ, and this search for matching is less prevalent in France, where the electricity mix is already largely decarbonized due to the large nuclear generation capacity[58] .

[57] TPU: Tensor Processing Unit, an integrated circuit developed by Google for tensor computation, one of whose applications is *machine learning* algorithms

[58] According to RTE, "95% of the electricity produced in France in 2024 was carbon-free."

In recent years, data center operators have been exploring different options to secure significant dispatchable power generation capacity near data centers, for two main reasons:

- current or anticipated strong growth in electricity use in certain regions limits connection capacity
- rapid growth of solar and wind generation increases intra-day price spreads and reduces the economic attractiveness of “as-produced” renewable PPAs (particularly solar) to cover the nearly constant (baseload) consumption of data centers.

Solutions include large-scale nuclear, geothermal, carbon capture, low-carbon hydrogen, and long-duration storage. SMRs offer the advantage of a certain replicability of projects from one site to another, as well as modularity compared with large nuclear power plants for self-consumption (with additional reactors enabling capacity to scale in line with data center growth, which may extend over several years).

Several recent announcements illustrate this interest, mainly in the US (seeFigure 22 below).

Data Center Operator	Nuclear operating partner	Partnership details
Studsvik	Kärnfull Next	**Sept. 2023: Project to develop an SMR campus on the Nyköping site to supply data centers** Launch of a feasibility study in May and commissioning planned for 2030
amazon	TALEN ENERGY	**March 2024:** Announcement of the **acquisition of the 960 MW data center**, directly powered by the Susquehanna Steam Electric Station (2GW) nuclear power plant, from Talen Energy by AWS (an Amazon subsidiary) and a long-term nuclear power purchase agreement (up to 480MW). **Nov. 2024: Authorities reject the request** for increased supply by the nuclear power plant, citing fears for the local grid.
EQUINIX	OKLO	**Apr. 2024: Signing of a pre-agreement between Equinix and Oklo for the supply of up to 500 MW of nuclear power.** The agreement follows a letter of intent signed in February and Equinix's completion of a $25 million prepayment to Oklo, entitling Equinix to an option on shares of the company or on a preferential electricity supply.
Microsoft	Constellation. An Exelon Company	**Sept. 2024: Signing of a 20-year PPA between Microsoft and Constellation,** starting in 2028, backed by the restart of Unit 1 of the Three Mile Island nuclear power plant (835 MW) in Pennsylvania, closed since 2019, in order to provide electricity to its datacenters.
ORACLE	*NC*	**Sept. 2024: Announcement of the construction of a 1 GW datacenter by Oracle, powered by 3 SMRs (building permits obtained).** Chosen technology and SMR developers not communicated to date.
Google	Kairos Power	**Oct. 2024: Signing of a Master Plant Development Agreement for the construction of nuclear power plants** (500 MW spread over 6 to 7 small modular reactors) by 2035 between Kairos Power and Google. Development, construction and operation carried out by Kairos and sale of energy via a PPA with Google. The first reactor is planned for 2030 to supply data centers.
amazon	X energy	**Oct. 2024: Amazon invests in the X Energy company** to fund the design and licensing processes of the modular nuclear reactor developer. **Development target of 5 GW by 2039,** and first deployment of 4 AMR units totalling 320 MW to power its data centers, as part of its carbon neutrality strategy.
switch datacenters	OKLO	**Dec. 2024: Signing of a non-binding Master Power Agreement for up to 12 GW of capacity by 2044** Provides for Oklo to develop, build and operate its Aurora Powerhouse nuclear reactors under power purchase agreements (PPAs)
Meta	*NC*	**Dec. 2024: Launch of a call for proposals to identify potential nuclear energy developers to support the development of 1.4 GW of new nuclear generation capacity in the United States** Meta will prioritize developers who can handle the entire lifecycle of power plants.
Endeavour Energy	DEEP FISSION	**Jan. 2025: Joint commitment to co-develop 2 GW of nuclear power to power Endeavour's expanding data center portfolio.** The first reactors are scheduled to be commissioned by 2029.
Data4 SMART & SCALABLE DATA CENTERS	Westinghouse	**March 2025: Signing of an agreement (MoU) to study the use of Westinghouse's AP300 SMR to power future Data4 data centers in Europe.** As part of the agreement, Data4 plans to use the AP300 SMR as a reference technology to evaluate its deployment at one of its future data centers in Europe.

Figure 22: Examples of recent announcements by
data centers relating to nuclear power generation (non-exhaustive list)

7 All markets combined, SMR/AMR developments would mostly target large industrial areas and large district heating networks

The identified potential for SMR/AMR deployment is mainly concentrated around large industrial areas and large heating networks.

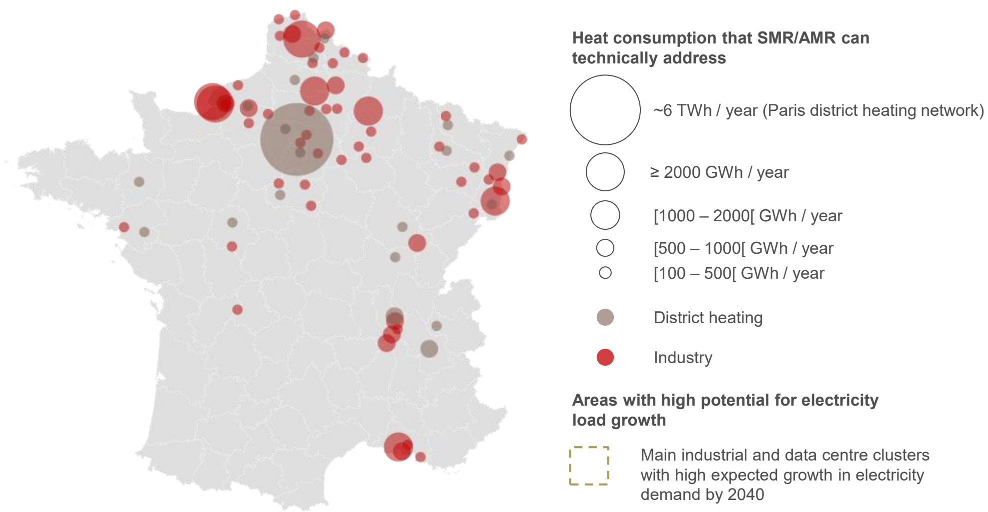


Figure 23: Map of existing industrial clusters and heating networks that are technically addressable by SMRs/AMRs, and areas with strong potential for growth in electricity consumption

In terms of industrial areas, these include:

- **The Le Havre area**, which includes numerous chemical and petrochemical industry sites;
- **Industrial areas close to Germany (Chalampé, Biesheim),** which are home to several chemical manufacturers;
- The **industrial areas of Dunkirk, Fos-Sur-Mer/Lavéra/Berre, and Saint-Nazaire,** which are home to major chemical, metallurgical, and agrifood industry sites
- The **northern industrial zone,** which includes agrifood industrial sites producing sugar and starch products;

- The **chemicals valley**, near Lyon.

These industrial basins combine several potential uses: carbon-free heat and carbon-free electricity for industrial processes, and potentially new uses such as carbon capture (CCUS) and hydrogen production.

In addition to industrial demand, district heating networks also offer significant potential for SMR/AMR. The Paris region is the main center of consumption in volume; it is also identified as an area with significant growth prospects in terms of data center electricity consumption. The networks around Lyon and Grenoble are secondary areas in terms of potential. More diffusely, the other main consumption centers are mainly located in the northern half of the country.

Appendix 1 – Cluster construction methodology

Industrial clusterization methodology

1. *Application of a **minimum size filter** (selection of **industrial sites consuming at least 25 GWh/year**)*
2. *Retrieving of site coordinates (longitudes/latitudes) from their addresses via geocoding API*
3. *Formation of clusters under the constraint: **"The maximum distance between two sites within the same cluster is < 20 km."***
4. *Retention of clusters that exceed a certain heat consumption threshold*

Cluster example

The Gonfreville-L'Orcher cluster pools 7 industrial companies together, with a maximum distance of 9 km between the 2 most distant sites and corresponds to a total heat consumption of 1.7 TWh th.

Appendix 2 – List of clusters

Industry

Annonay
Arques
Artenay
Benheim
Berre l'Etang
Biesheim
Boiry Sainte Rictrude
Calais
Cambrai
Chalampé
Chevrieres
Clairefontaine
Compiègne
Connantre - Haussimont
Corbeilles
Descartes - Les Ormes
Dunkerque
Epinal
Etrépagny
Fontaine le Fun
Fos-Sur-Mer (including Lavéra)
Gien
Gonfreville-l'Orcher

Kaysersberg
Lens - Douai
Lille and surrounding area
Louviers
Maisons-Alfort
Marckolsheim
East Marseille
Matouges - Isse
Maubeuge
Mormant - Nangis
Nancy
Nesle - Roye
Nogent-sur-Seine
Origny Saint Benoite
Port Jérôme Sur Seine
Donges Refinery
Harfleur Refinery
Martigues Refinery
Port-Jérome-Sur-Seine Refinery
Reims
Rety
Rouen South
Roussillon
Saillat sur Vienne
Saint-Agathe (Florange)
Saint-Fons (Southeast Lyon)
Saint-Venant
Sochaux
Soissons
Tavaux (South Dijon)
Valenciennes
Vaujourd - Saint Soupplets
Vienne
Villette sur Aube

District heating networks

Amiens
Chambéry/Annecy/Albertville
Dijon
Grenoble
Le Creusot
Lille
Lyon
Metz

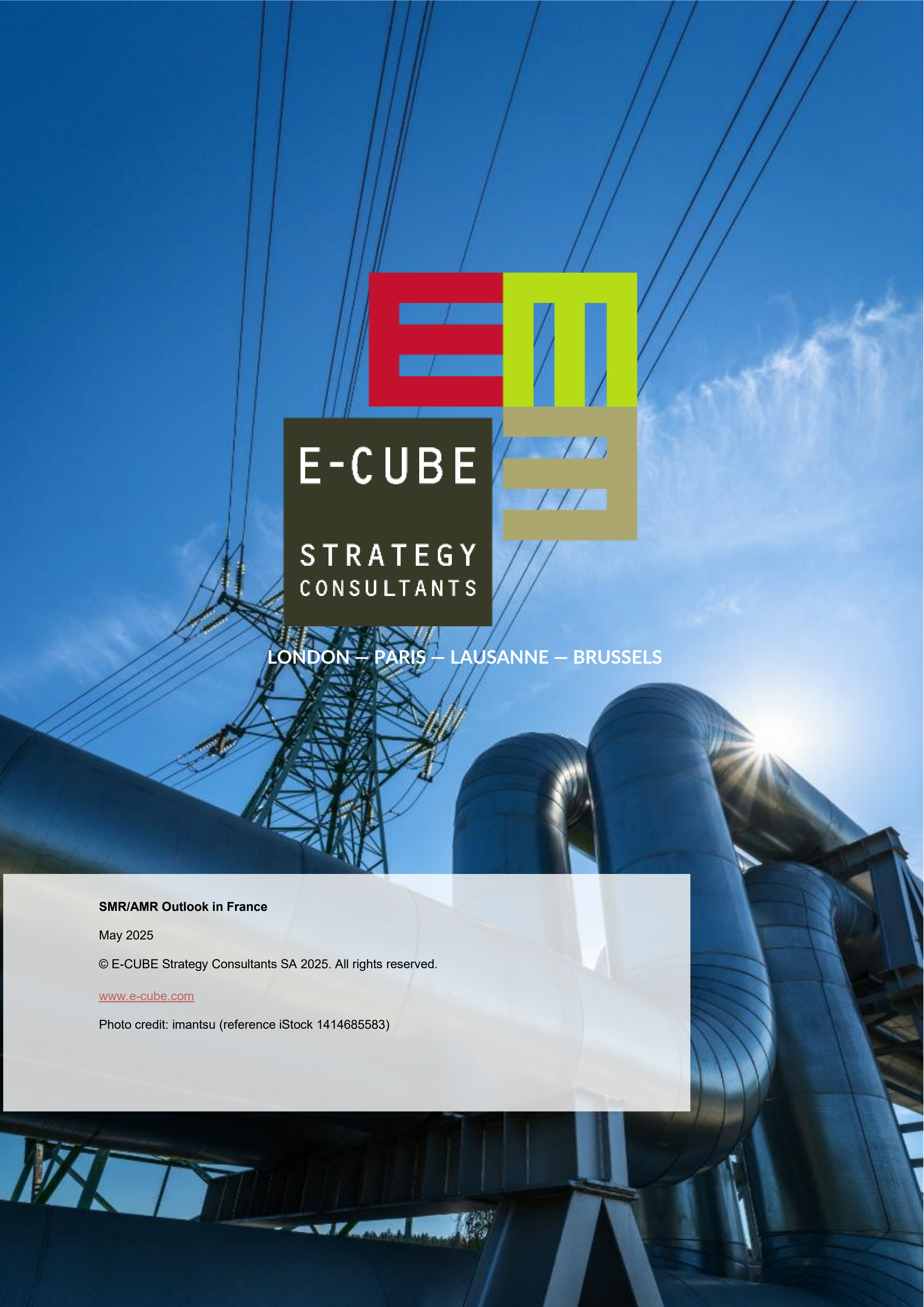
Mulhouse
Nancy
Nantes
Northwest Paris (Cergy)
Orléans
Paris
Southeast Paris
Rennes
Rouen
Strasbourg
Southwest Lille (Arras, Douai, Lens, Béthune)
Tours

E-CUBE Strategy Consultants is a strategy consulting firm specializing in the energy, environment, infrastructure, and decarbonization sectors. We are recognized in the consulting market for the quality of our expertise, the high level of skill of our teams, and our flexibility and responsiveness.

Our work covers all aspects of C-level issues: strategic analysis, decarbonization strategy and impact of climate change on business models, energy supply strategies, regulatory and techno-economic studies, organizational change or operational performance improvement, data analysis and modeling, sell-side and buy-side due diligence.

Our work is organized around three verticals:

- **Energy and Environment**: supporting players in the energy value chain in anticipating and taking into account changes in their market, and their regulatory, competitive, and technological environment. Assisting private and public players in reassessing their strategy to integrate the challenges and opportunities of a "new deal" in energy and environment.
- **Mobility**: supporting players in the automotive, rail, air transport, shipping, and logistics sectors in their strategic (corporate, M&A), regulatory, and operational projects. Supporting industry leaders in reassessing their strategy to incorporate the challenges of digitalization and the energy transition.
- **Decarbonization**: helping industrial and service sector players understand the impact of the energy and environmental transition on their activities and business models, supporting and challenging their decarbonization strategy, and helping them redesign their energy supply and logistics strategies.



SMR/AMR Outlook in France

May 2025

www.e-cube.com

Photo credit: imantsu (reference iStock 1414685583)