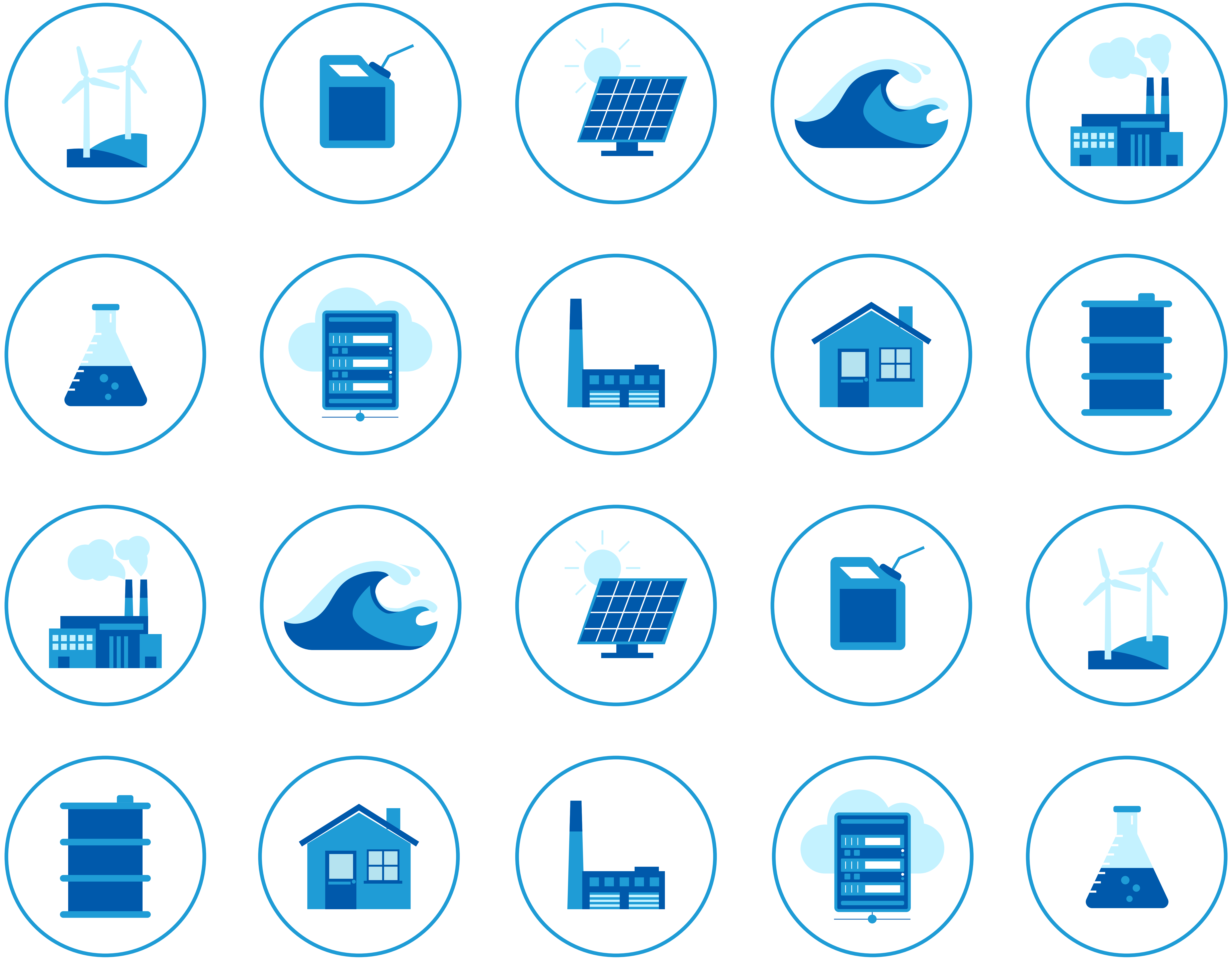
ARUP

Small Modular Reactors and their potential

A five-minute guide



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What are Small Modular Reactors?

SMRs are compact nuclear reactors designed for flexible, cost-effective energy generation. They can be manufactured off-site and installed in diverse locations, making them suitable for both electric power and non-electric energy applications, while addressing deployment challenges associated with traditional nuclear plants. This 5-minute guide will explain at a high-level, some of the many and varied opportunities that could be unlocked with SMRs, as well as the key benefits and deployment challenges.

What are Small Modular Reactors (SMR)?

Small

SMRs are smaller in both size and power output than "conventional" nuclear reactors. SMR power outputs range from 1-500MWe (Megawatts electric), but they are typically less than 300MWe which is ~1/3 the output of a conventional nuclear reactor. Their smaller sizes may allow them to be sited at non-traditional locations opening up opportunities to directly meet the energy needs of a greater range of end users, ranging from industrial applications to both national and decentralised grids.

Modular

SMRs are typically designed as modular units, manufactured in factories and then transported for assembly at the generation site. This method reduces delivery and cost risks by using a standardized design, benefiting from manufacturing efficiencies that ensure consistent and predictable construction timelines.

Reactors

SMRs use proven and controllable nuclear fission. Nuclear fission does not emit greenhouse gases during reactor operation and is a safe and secure means of energy production. The reactors work by generating heat when heavy elements are split, which can then be used directly or converted into electricity. The heat generated by SMRs can be at a sufficiently high temperature such that it can also be used by industrial users with high-heat requirements (such as for water desalination, chemical manufacturing or green hydrogen production for example).

	SMR	Conventional nuclear plant
Power output	1-500MW	1000MW+
Power efficiency	1.2-6MW/acre	0.66MW/ acre
Area requirement	50 acres	1500 acres
Cost	$800m-3bn	$5-9bn
Lead time	2-3 years (estimated)	8 years

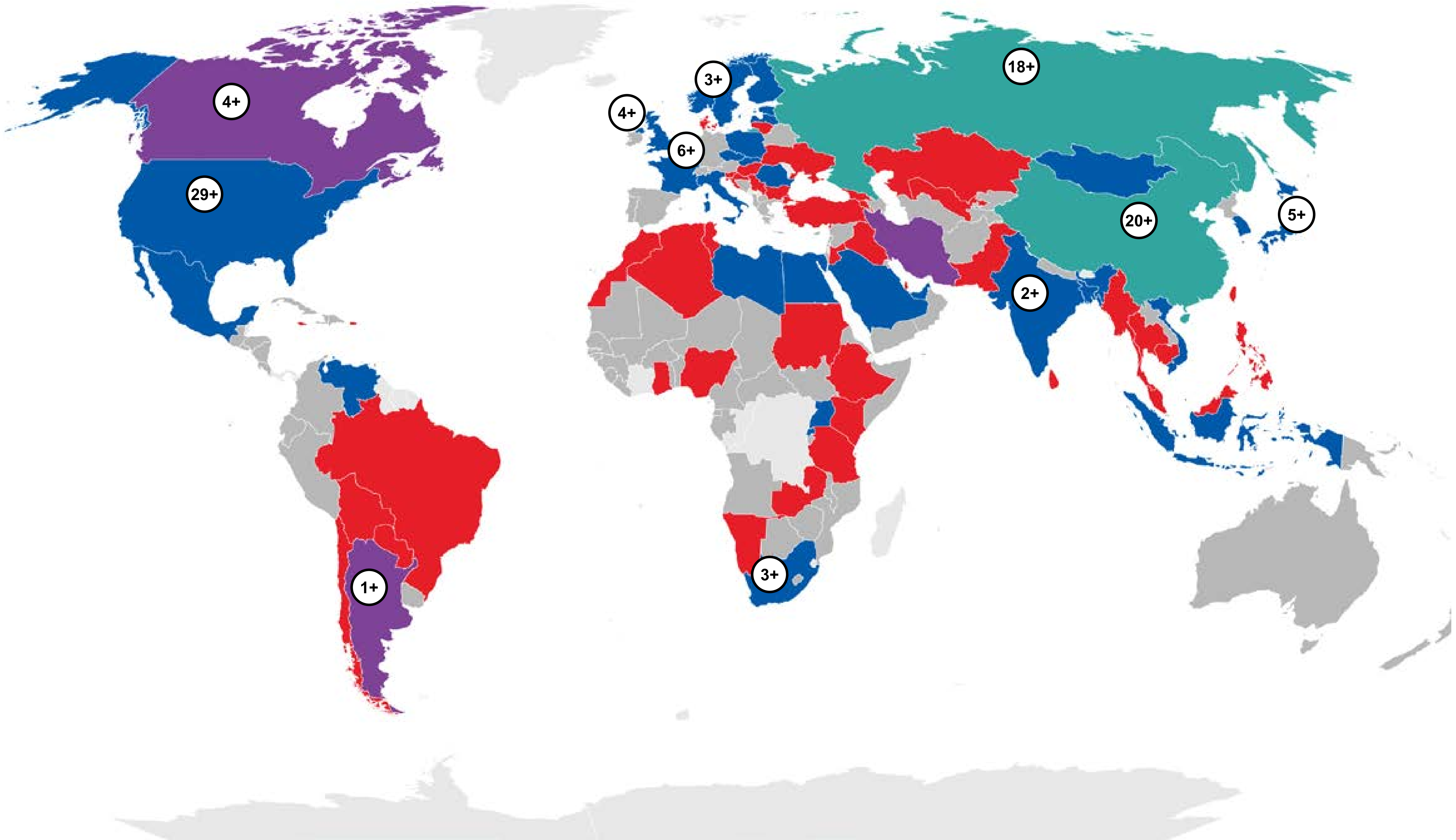
Idaho National Lab, Cleantech Group, SustainableViews

Small Modular Reactor deployment: Global Market

The numbers given on the map indicate the parts of the world where SMRs are already operating, in development, or under consideration. Many nations are actively considering or pursuing nuclear technology, including SMRs, as part of their decarbonisation strategy to achieve net zero.

Nuclear power remains a sensitive topic at regional, national, and international levels, with supporters and critics worldwide. This global overview categorizes nations based on their nuclear development status and long-term plans, from those with no plans or a moratorium on nuclear power to those actively pursuing a fleet of SMRs.

- **No data**
- **No plans/moratorium on nuclear**
- **Considering SMR deployment**
- **SMR Construction begun**
- **Designs and/or Site development**
- **SMR Operating**



World Nuclear Association, IAEA, World Nuclear News, Science Direct

The SMR spectrum

Nuclear reactors have evolved in generations, each improving safety, efficiency, and sustainability. Generation I reactors are typically being decommissioned, while Generation II reactors form the core of most national nuclear fleets. Newer Generation III/III+ water-cooled reactors and Generation IV non-water-cooled systems are in various stages of global development.

SMRs fall into two types, those based on modern "Generation-III/III+" technologies or the emerging "Generation-IV" reactors that use novel coolants. Each generation comes with their own benefits suited to certain applications. Gen-III reactors build upon the global operational experience of existing nuclear technologies. The innovative Gen-IV SMRs have less operational experience, but the fundamental features of the technology have been proven and have wider potential applications.

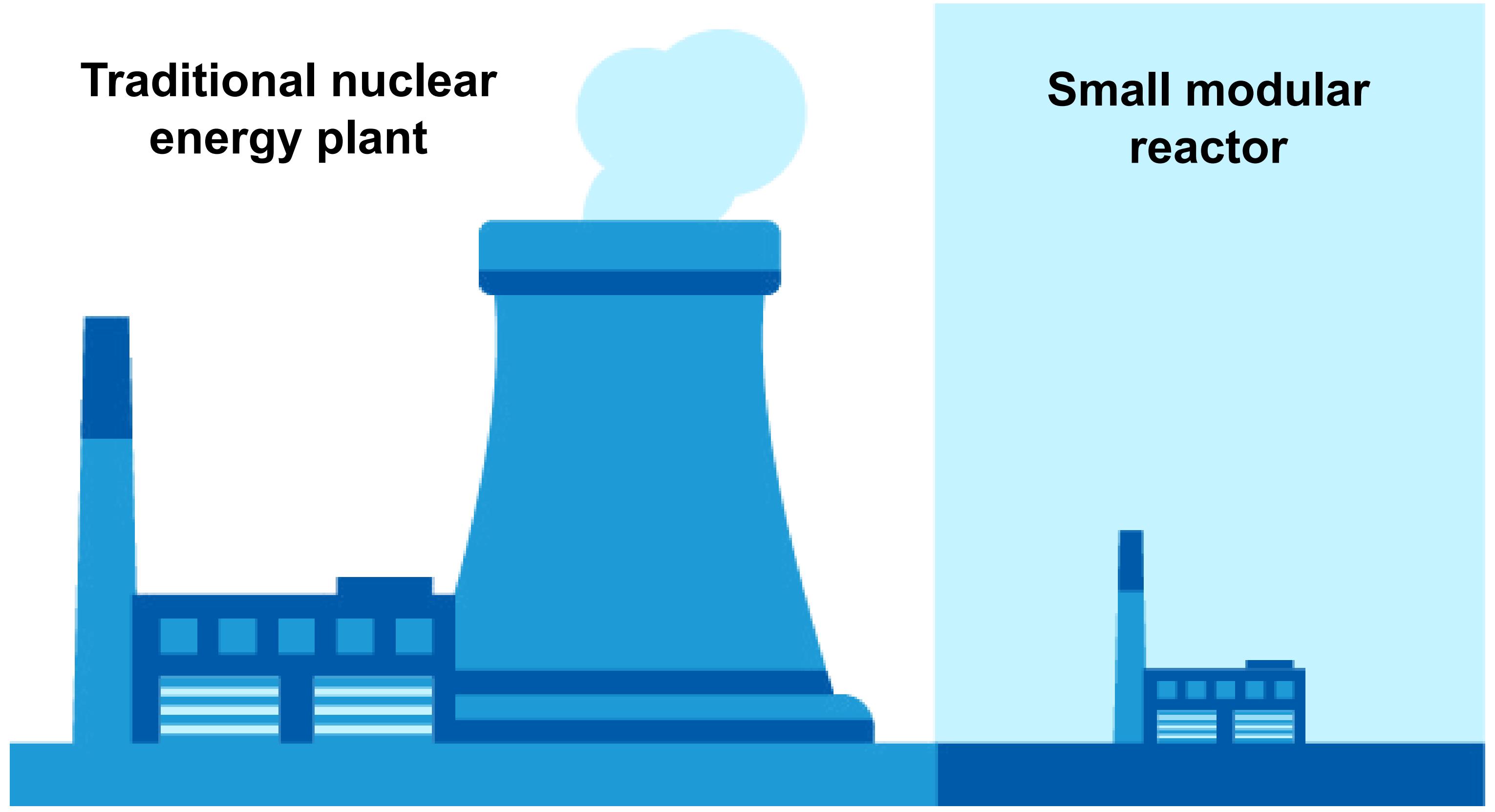


Image showing the scale of an SMR compared with a traditional reactor

Gen-III: Water cooled reactor (WCR)

– Most common technology (96% of the globally operating nuclear power plants are of this type)

– Output heat at temperatures ~300ºC

Gen-IV: High temperature gas-cooled reactor (HTGR)

– One commercial system of this type in China but strong history of GEN-II advanced gas-cooled reactors

– High thermal efficiency and inherent safety features

– Output heat at temperatures > 750ºC

Gen-IV: Fast neutron spectrum reactor (FNR)

– Approx. 20 have operated or are currently operating

– Can increase the sustainability of the nuclear fuel cycle and reduce the volume of waste generated.

– Output heat at temperatures > 500ºC

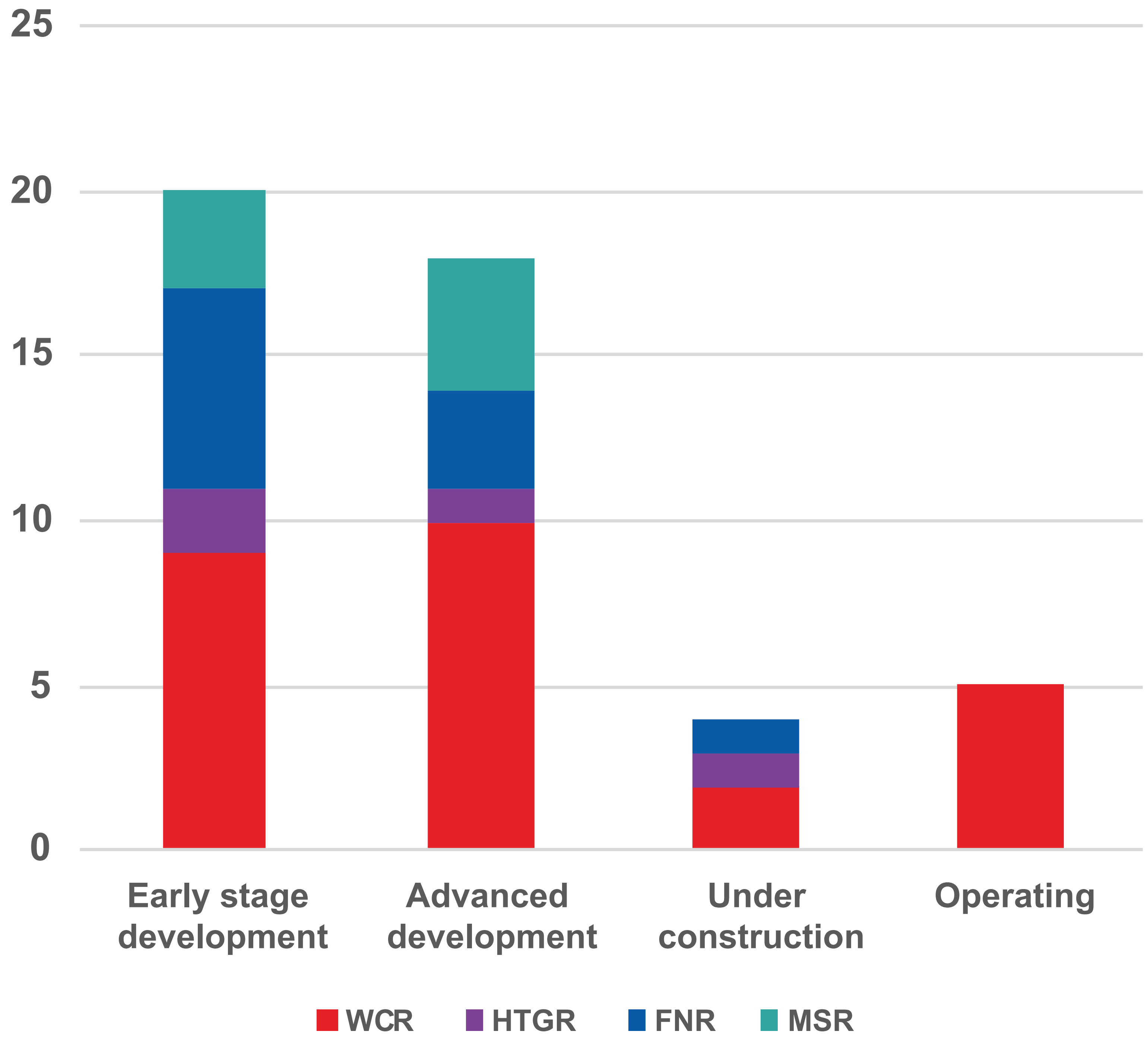
Gen-IV: Molten salt reactor (MSR)

– Only two briefly operated systems

– High thermal efficiency and inherent safety features

– Output heat at temperatures > 500ºC

All can be coupled to traditional turbine technology to generate electricity



SMR development by type (World Nuclear Association 2024)

Benefits and challenges of SMRs

Benefits to achieve

Configurability
Standard designs can be integrated with other applications / users depending on needs and the infrastructure in the location.

Modularity
Designed to be factory manufactured and then transported to site for final assembly and operation.

Financial
Reduced capital costs due to smaller size and standardized designs result in shorter construction times and lower financial risks

Flexibility
Can be deployed in various locations and can operate in conjunction with renewable energy sources for enhanced grid stability.

Reliability
Can produce continuous low carbon energy 24/7, supplementing renewable energy sources for enhanced grid stability.

Footprint
Requires less land than traditional reactors, making it suitable for space-constrained sites.

Adaptability
Readily able to integrate with other low-carbon energy generating technologies. Modular design allows for easy scaling of power output.

Safety
Many are designed with passive safety systems that require no external power or human intervention, reducing accident risks.

Challenges to overcome

FOAK deployment
Initial deployments needed to establish supply chains and build demand.

Demonstrate safety benefits
SMRs must have their safety benefits validated to support deployment and subsequent co-location with industry.

Supply chain maturity
Significant upskilling of the nuclear supply chain is needed. Supply chain for specialized components may not be fully developed.

Licensing
SMRs (like all nuclear plants) must progress through and meet established regulatory and licensing approvals.

Technology development
Some SMRs use innovative coolants or fuels that require research & development to reach technological readiness for deployment.

Economics
SMRs will need to deploy at scale to realise their economic potential.

Public acceptance
To support widespread deployments, greater understanding and awareness of technologies will be required.

International collaboration
Collaboration is key to development, deployment and licensing of technologies but can be complex due to differing interests and regulation.

What needs to be in place for an SMR programme?

Milestones for success

The IAEA (International Atomic Energy Agency) Milestones Approach is designed to support countries developing nuclear infrastructure by structuring the process into three progressive phases, each marked by a major milestone. Arup believes this milestones approach will be equally applicable to the development of SMR infrastructure.

The IAEA identify 19 'Nuclear Infrastructure Issues' which provide a comprehensive framework, detailing what needs to be addressed at each phase to ensure the program's success.

Each infrastructure issue interacts with the milestones by specifying detailed goals and actions for each project phase. This provides a clear, step-by-step approach to establishing a safe, sustainable nuclear power program. The issues are all considered to be of equal importance.

19 IAEA Nuclear Infrastructure Issues:

- National position
- Regulatory framework
- Funding & financing
- Legal framework
- Nuclear safety
- Management
- Safeguards
- Radiation protection
- Electrical grid
- HR development
- Stakeholder involvement
- Site & supporting facilities
- Environmental protection
- Emergency planning
- Nuclear security
- Nuclear fuel cycle
- Radioactive waste management
- Industrial involvement
- Procurement

Phase 1

Considerations before a decision to launch a nuclear programme is taken.

Milestone 1

Ready to make a knowledgeable commitment to a nuclear power programme.

Phase 2

Preparatory work for the contracting and construction of a nuclear power plant.

Milestone 2

Ready to invite bids / negotiate a contract for the first nuclear power plant.

Phase 3

Activities to implement the first nuclear power plant.

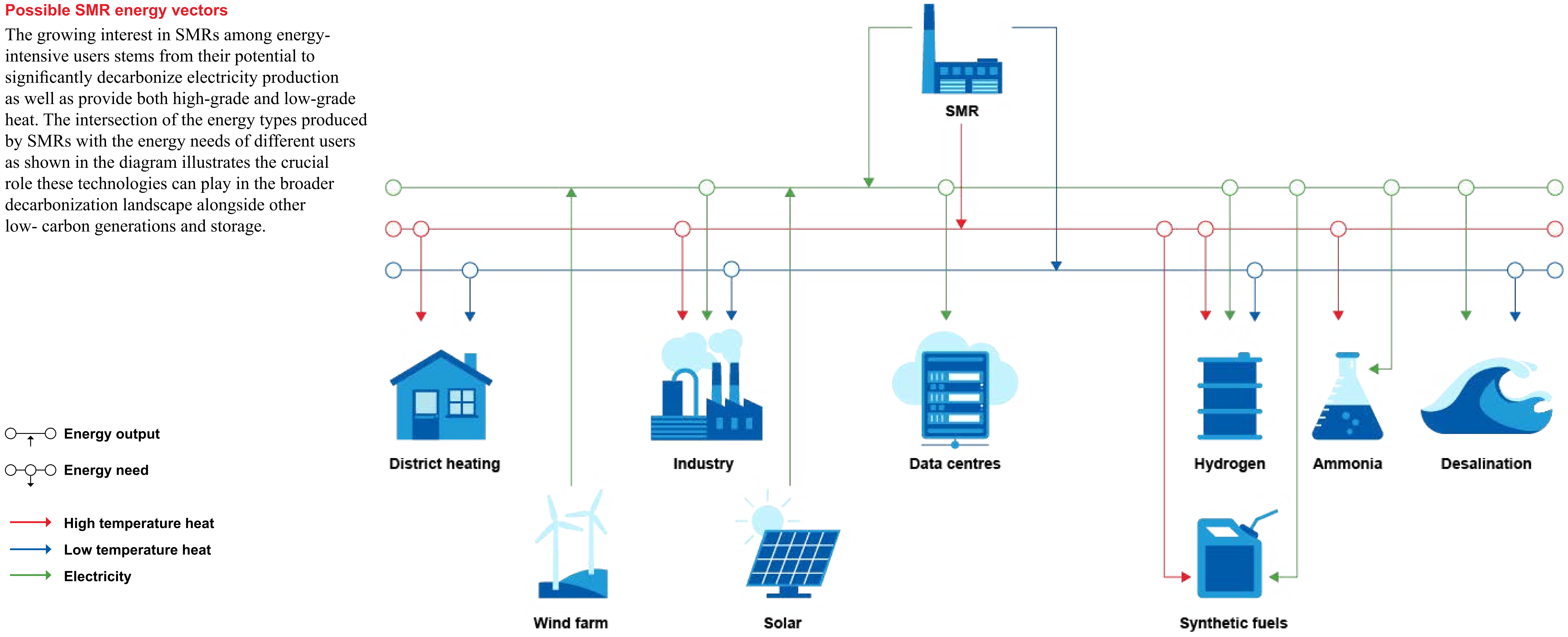
Milestone 3

Ready to commission and operate the first nuclear power plant.

Cogeneration potential of SMRs

Possible SMR energy vectors

The growing interest in SMRs among energy-intensive users stems from their potential to significantly decarbonize electricity production as well as provide both high-grade and low-grade heat. The intersection of the energy types produced by SMRs with the energy needs of different users as shown in the diagram illustrates the crucial role these technologies can play in the broader decarbonization landscape alongside other low- carbon generations and storage.



Data Centres + SMR

Data centres are large facilities responsible for the storage, processing or distribution of data and are currently responsible for circa 3% of global electricity consumption. This is predicted to increase in the coming years. Currently, data centres mainly rely on fossil fuels for their energy supply.

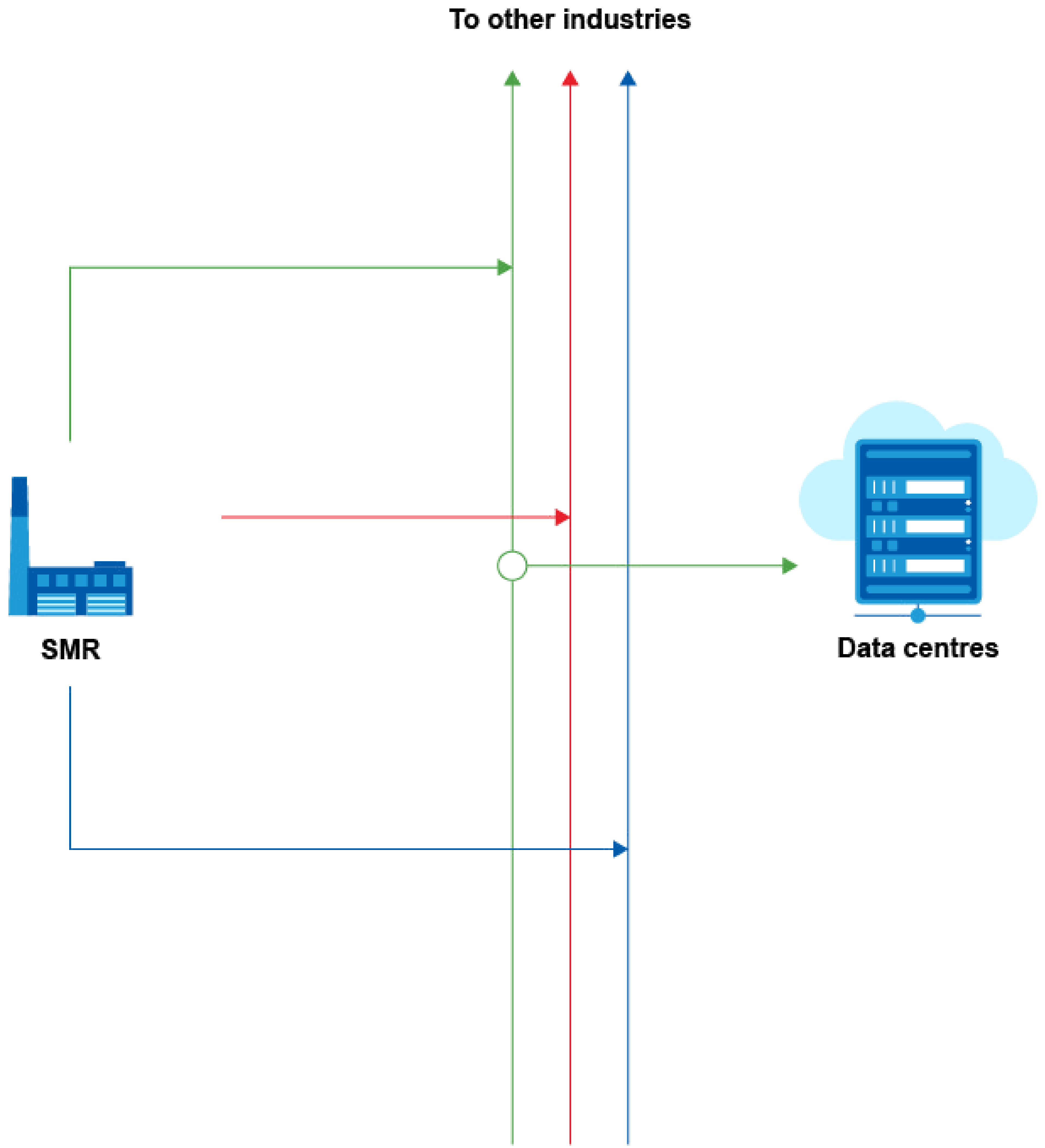
SMRs could be an ideal option to power data centres because:

– SMRs offer a reliable, continuous and low carbon energy supply.

– SMRs have a power output that would meet data centre needs.
Large data centres require ~100 MW of power which could be wholly provided by a single SMR.

– SMRs are modular and so additional SMRs could be added to a site if the energy needs are increased.

Data Centre Needs	How SMR Can Address These Needs
Reliable power	Continuous, dependable power minimizes data centre downtime.
Low carbon footprint	SMRs produce minimal emissions, aiding sustainability goals.
Scalability	Modular design allows phased expansion based on demand growth.
Cost stability	Long-term, stable costs due to predictable fuel and efficiency.
High energy density	Compact footprint ideal for on-site power at data centres.
24/7 availability	SMRs provide constant energy, unlike intermittent renewables.
Cooling system synergies	SMRs and Data Centres have common requirements for cooling, representing an opportunity for the sharing of cooling system plant and infrastructure.

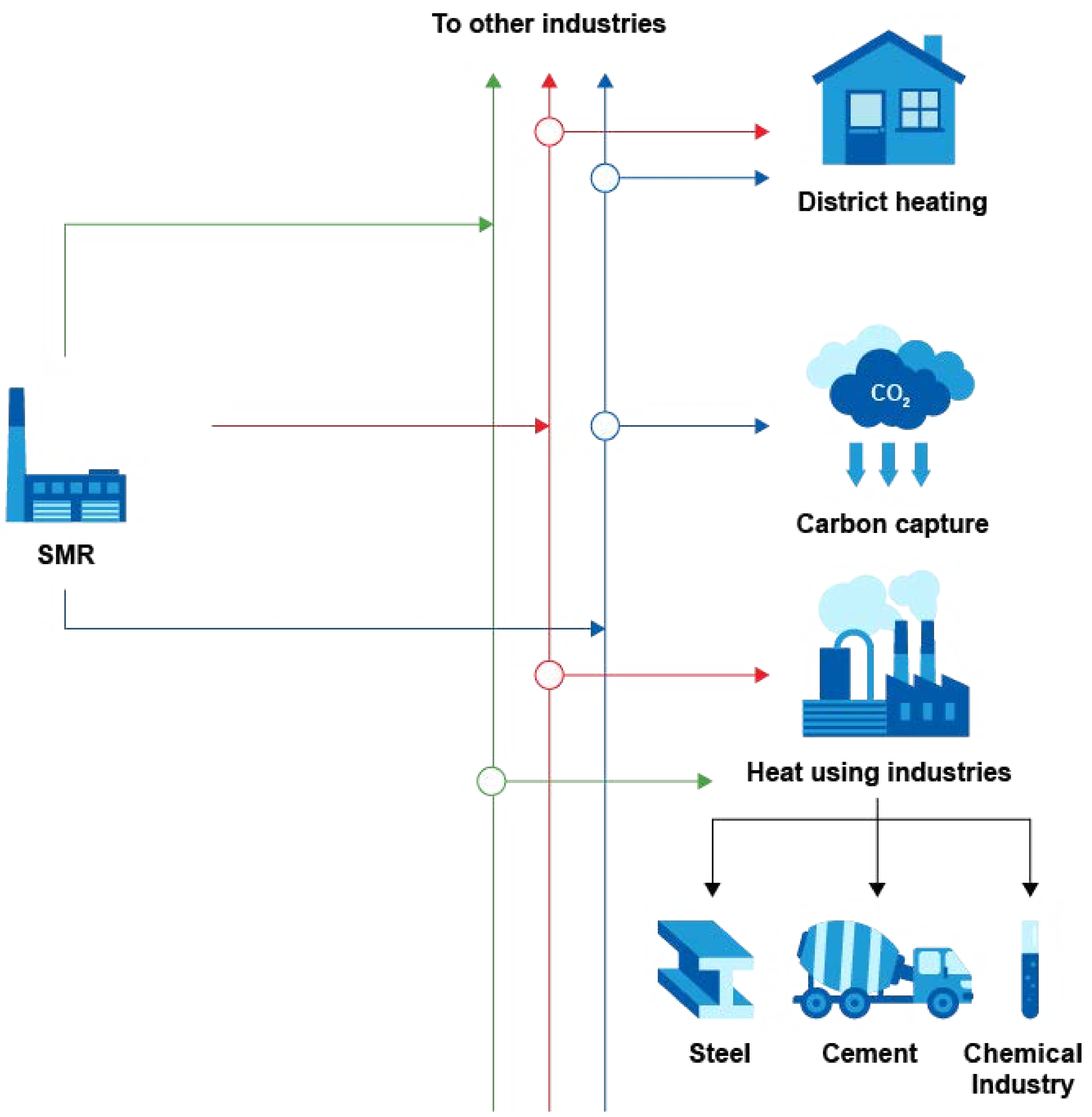


Industrial Heat Production + SMR

SMRs have the capacity to produce both low and high temperature heat (above 400ºC). Through their application to heat systems, SMRs could replace fossil fuels in heat production, support district heating for homes, and supply the high temperatures needed for industrial processes.

By enabling cogeneration, SMRs also maximize efficiency by using waste heat from electricity production for applications like carbon capture and storage. This dual-purpose capacity makes SMRs a powerful tool for reducing emissions and supporting sustainable energy, with a long history of providing heat for both industrial and domestic networks.

Industrial Heat Needs	How SMR Can Address These Needs
High-grade heat	SMRs can produce high temperatures (up to ~750°C).
Low Carbon Emissions	SMRs provide low to zero carbon energy, aiding decarbonization efforts.
Reliable, Continuous Supply	SMRs offer constant energy output, crucial for uninterrupted industrial processes.
Scalability	Modular SMR designs allow flexible scaling to match varying heat demands.
Cost Stability	Predictable nuclear fuel costs lead to long-term energy cost stability.
On-Site Energy Generation	Compact SMR design enables on-site installation, reducing reliance on external energy sources.
Integration with Existing Systems	SMRs can operate alongside or replace fossil-fuel boilers, fitting into current infrastructures.

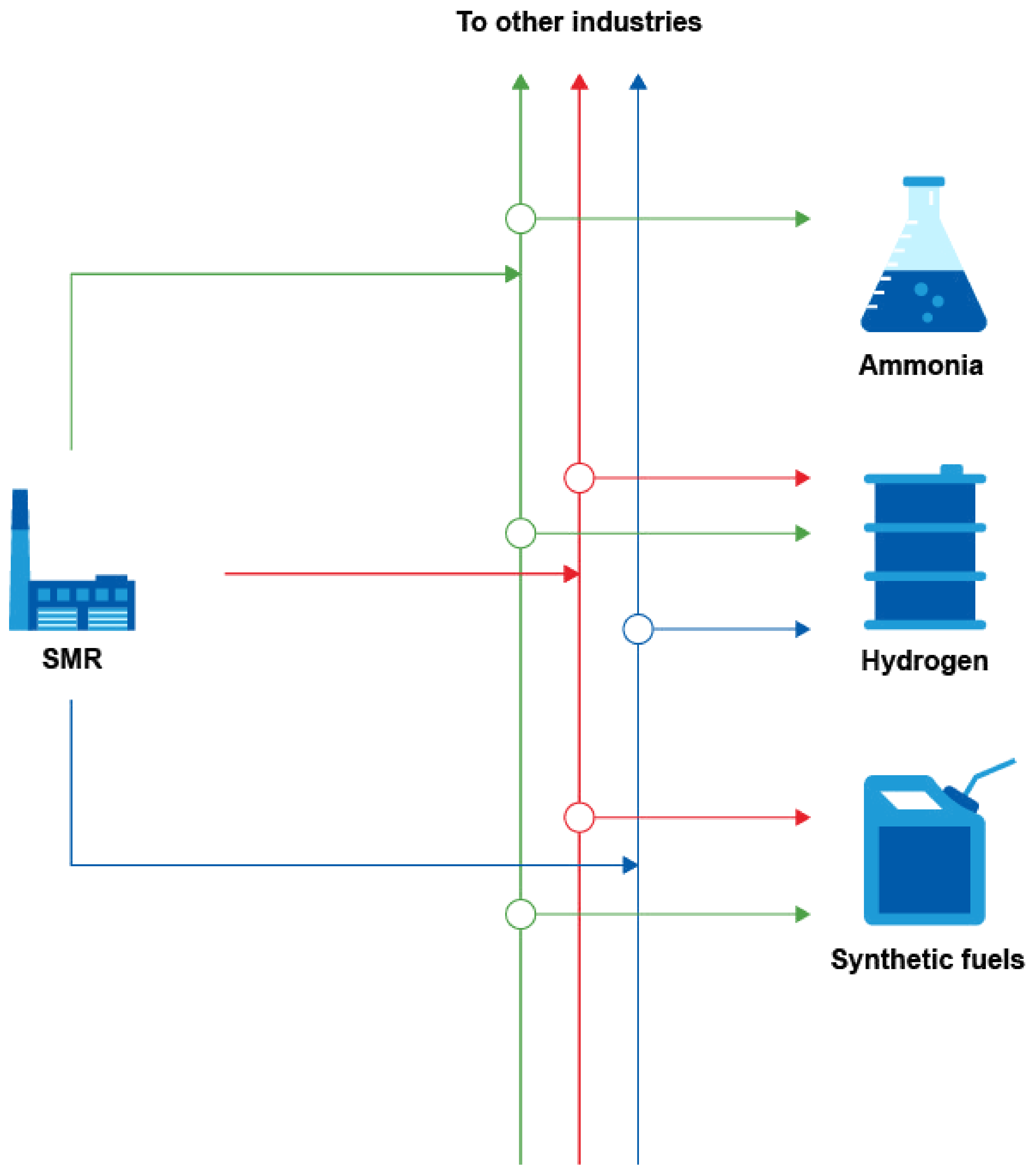


Hydrogen & Synthetic Fuels + SMR

Small Modular Reactors (SMRs) could supply the electricity and heat essential for hydrogen production, supporting the growing interest in hydrogen as an energy carrier and a component in synthetic fuel production. Hydrogen derived from renewable or low-carbon sources, like SMRs, is considered sustainable because it does not emit CO_2 when used.

Additionally, synthetic fuels produced from hydrogen can mimic the performance of fossil fuels, making them a promising alternative for carbon-intensive sectors. The aviation industry, which accounts for a significant share of global transport emissions, sees synthetic fuels as a pathway to achieving net-zero targets, positioning SMR-supported hydrogen as a key resource in this transition.

Hydrogen & Synthetic Fuel Needs	How SMR Can Address These Needs
High-Temperature Heat	SMRs generate high heat (above 400ºC) required for efficient hydrogen production and fuel synthesis.
Low Carbon Energy Source	SMRs offer a near-zero emissions energy source, reducing the carbon footprint of hydrogen and synthetic fuel production.
Reliable, Continuous Power	SMRs provide a stable, 24/7 energy supply crucial for uninterrupted fuel synthesis processes.
Cost-Effective Operation	Predictable nuclear fuel costs make SMRs cost-effective for long-term hydrogen and synthetic fuel production.
On-Site Generation Flexibility	SMRs can be located close to production facilities, minimizing transmission losses and improving overall efficiency.

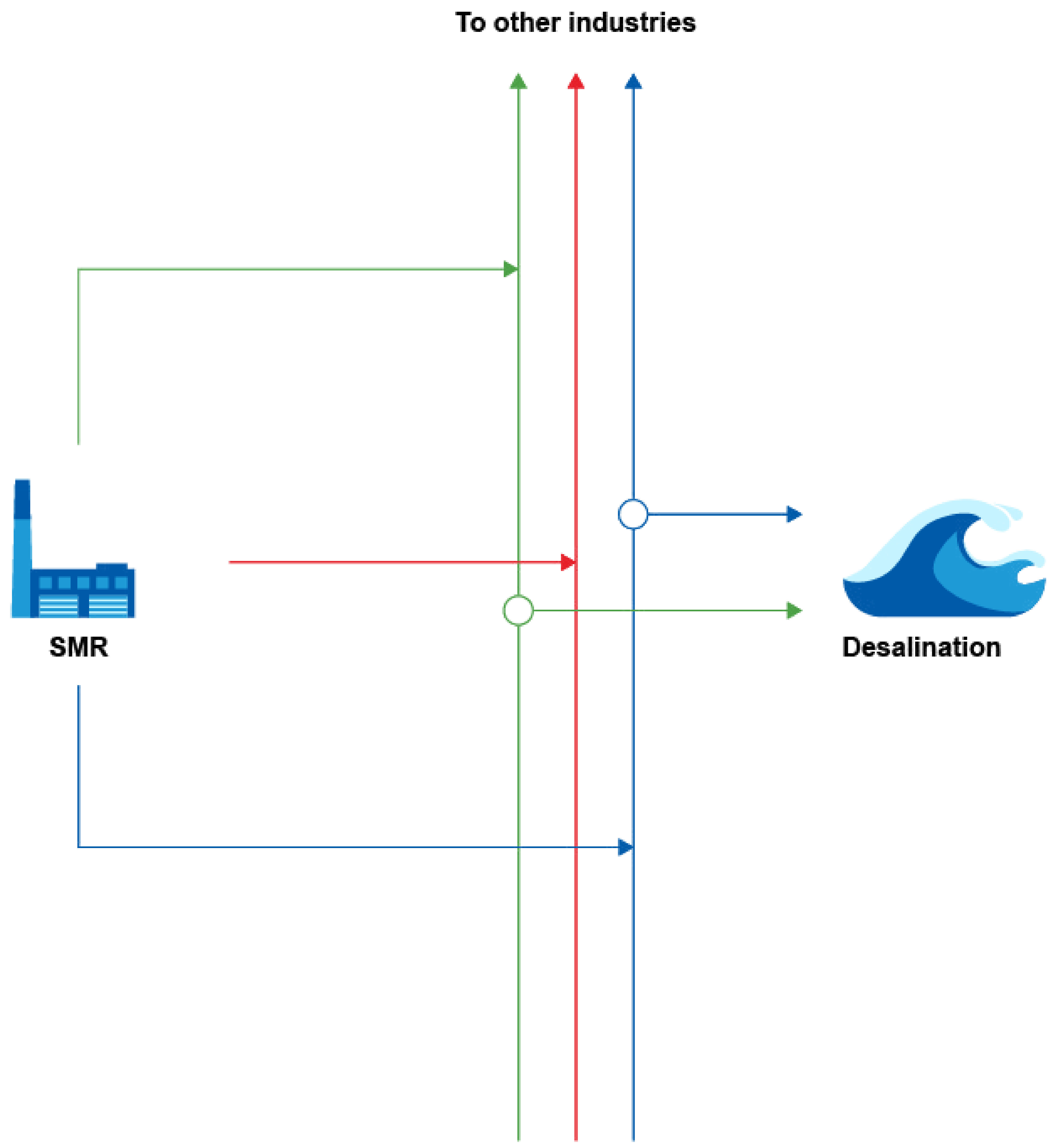


Desalination + SMR

The growing demand for freshwater reserves has made desalination an increasingly viable solution, enabling the conversion of seawater into potable water. Currently, over 300 million people worldwide depend on desalination plants, and this number continues to rise annually.

Traditionally, fossil fuels have powered these energy-intensive facilities, leading to significant CO_2 emissions. To mitigate the environmental impact of desalination, SMRs present a low-carbon alternative by providing both electricity and heat necessary for the process. By integrating SMRs into desalination efforts, it is possible to enhance water sustainability while reducing carbon footprints, making this approach a promising solution for addressing global freshwater needs.

Desalination Needs	How SMR Can Address These Needs
Continuous Power Supply	SMRs provide reliable, 24/7 power, ensuring consistent desalination operations.
High-Temperature Heat	SMRs offer the necessary heat for thermal desalination processes, such as multi-stage flash (MSF) and multi-effect distillation (MED).
Low Carbon Emissions	SMRs produce low-carbon energy, reducing the environmental impact of desalination compared to fossil fuels.
Scalability	Modular design allows SMRs to scale with desalination needs, accommodating demand in both small and large communities.
On-Site Installation	SMRs can be located near desalination facilities, minimizing transmission losses and enhancing efficiency.

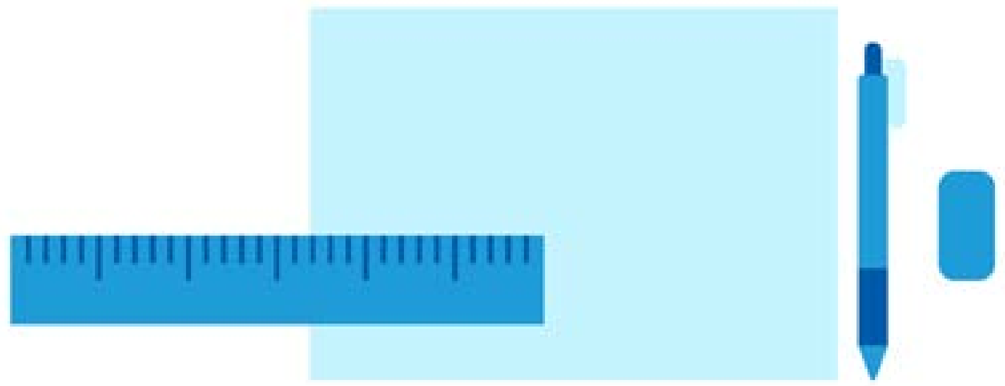


Deployment speed: From development to operation

The stages below describe what is required to take an SMR from design development to its operational life.

The process described here would be expected to take between 8 to 10 years. However, once a design has been granted regulatory approval, the whole process would not need to be repeated for future deployments, significantly reducing the time to operation.

Given the governmental support SMRs have been receiving it is Arup's view that SMR fleet deployments should be expected in the early-mid 2030s.

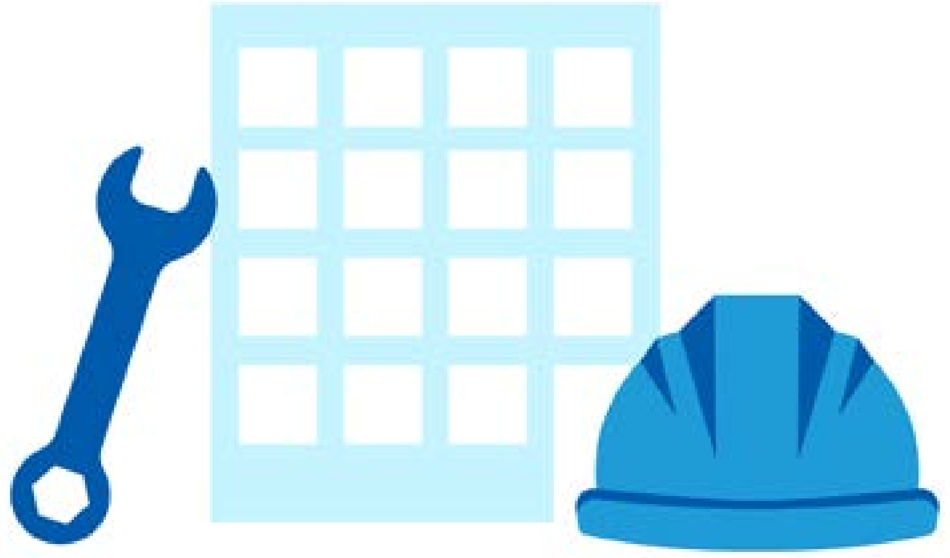


Design and site selection

- Development of the reactor design such that it is technically, economically and environmentally feasible.
- Ensure site selected is suitable for constructing and operating a nuclear site.
- Consider natural hazard risk, proximity to communities, ground condition for foundations and other such aspects.

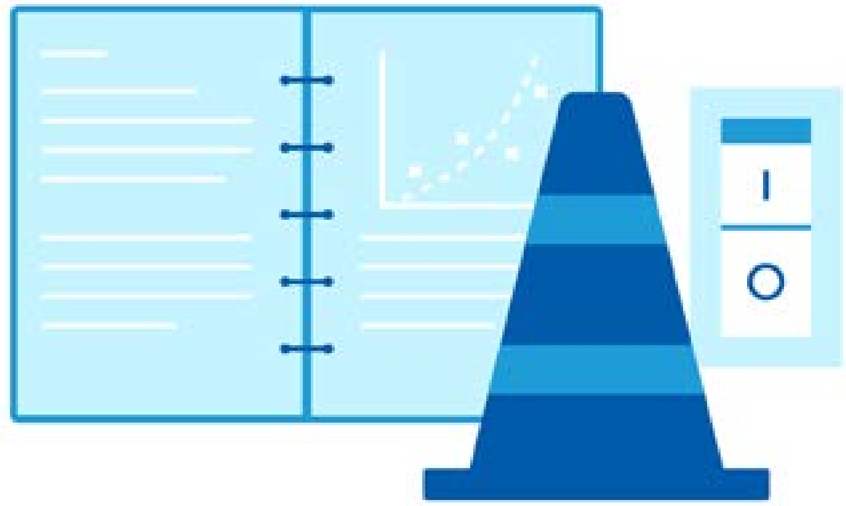
Finance, licensing and planning

- Finance the design and site so that the regulatory and licensing process can begin.
- Obtain the relevant licenses, permits and consents to proceed to construction, commissioning and operations.
- During the relevant regulatory processes, the proposed SMR and site will be assessed to ensure safety, security, safeguards and environmental impacts have been sufficiently developed and considered.



Manufacturing, procurement and construction

- Key systems and components constructed once relevant licenses, permits and consents are in place.
- Much of the manufacturing and construction can be done offsite if the SMR is being built modularly.
- Contracts for key services for operations and waste management are entered into. This may require international collaboration if the operating country does not have its own nuclear waste or fuel infrastructure.



Operations

- Once the site is constructed there will be a period of commissioning and testing while the performance of key components and systems is verified.
- Site can then begin operation.

Summary: Small modular reactors and their great potential

SMRs offer opportunity for scalable, localised, and reliable low-carbon energy supply within a timeframe that can play a meaningful role in the transition towards a low-carbon and energy-secure future.

Secure and stable

SMRs are compact and modular nuclear fission reactors that build on the extensive operational knowledge gained from existing and previous generations of GW-scale nuclear plant. As the most dependable form of low-carbon energy, nuclear power can operate nearly continuously at full capacity.

Low-carbon baseload electric

SMRs can seamlessly integrate with other low-carbon energy sources like solar and wind and can be implemented in regions with limited infrastructure. This capability ensures a resilient low-carbon baseload power supply, essential for continuous energy availability.

International market

There has been significant investment in SMR development programs from various countries, including Canada, China, Poland, France, the UK, and the US. SMRs offer considerable export potential to deliver low-carbon energy to developing countries, where traditional nuclear reactors may not be practical or suitable.

Non-electric applications

SMRs are capable of operating in cogeneration modes, which support industrial applications that require nuclear heat. Different designs of SMRs are being developed to cater to diverse end-user needs.

Some of the more advanced designs feature innovative capabilities that could facilitate deeper decarbonization by providing high-temperature heat or enabling additional siting options. Potential applications include powering data centres, producing green hydrogen, supporting chemical and cement production, desalination, steel manufacturing, and district heating.

Challenges and opportunities

The primary advantages of SMRs over conventional nuclear systems lie in their smaller footprint and modular design, which help to lower initial capital costs, reduce risks associated with deployment, and provide flexibility in siting.

However, for successful SMR deployment, it is crucial to address challenges such as licensing and regulatory issues, gaining public support, ensuring adequate demand, and managing spent fuel effectively. Overcoming these challenges will be essential for SMRs to contribute significantly to a low-carbon energy landscape.