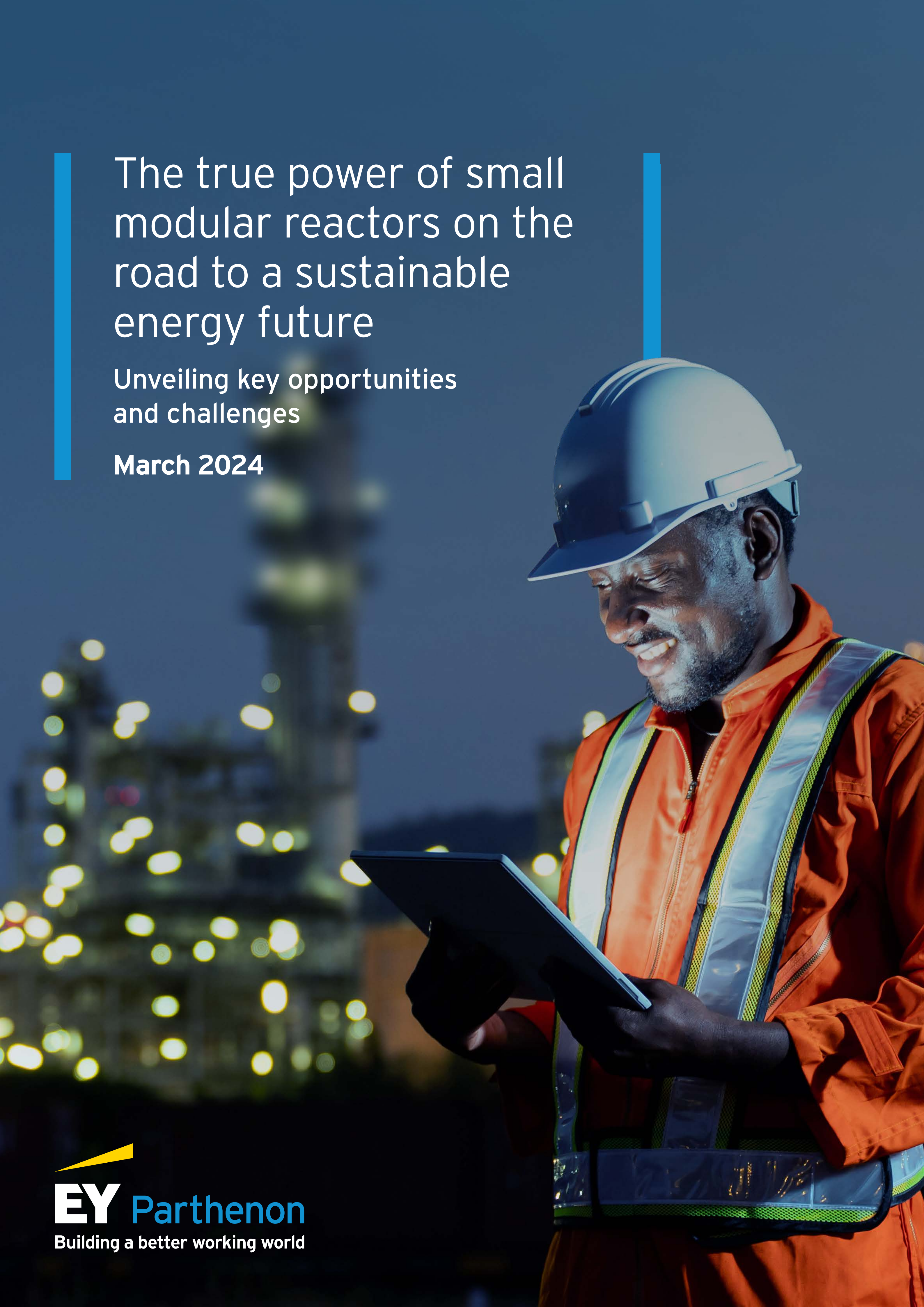
The true power of small modular reactors on the road to a sustainable energy future

Unveiling key opportunities and challenges

March 2024



EY Parthenon
Building a better working world

Contents

Foreword

As we navigate to a sustainable energy future, **small modular reactors (SMRs) emerge as another potential flexible and reliable low-carbon solution.** There has been a strong momentum in SMRs in recent years, with several designs and projects developed globally. Some advanced-stage examples are attracting the attention of the broader industry and investor community which are looking at demonstrators and first-of-a-kind to prove SMR technical feasibility, economic viability and business potential.

With the support of favorable policies and relevant infrastructure, the first demonstrators are expected to be commissioned by 2030 at a US$15k-US$20k/kWe overnight CAPEX. The cost is expected to decline as the industry moves from first of a kind (US$8k-US$13k/kWe) to nth of a kind (US$5k-US$7k/kWe). **Modularization, co-siting, learning and standardization are expected to be the key drivers to optimize SMR costs** in a more efficient and tangible way than for large reactors thanks to series effect.

We anticipate the first demonstrators to be commissioned around 2030, with **a real acceleration in deployment starting in the 2040s** with the emergence of Gen. IV, which can respond to wider applications. Under realistic and accelerated scenarios, we predict 400-700 SMRs (150MWe unit) to be deployed by 2050 (c.60-100 GWe). In 2050, we predict that c.50% of SMRs will be deployed for industry (with hydrogen, steel and aluminum as the main segments), c.40% for the grid and c.10% for district heating. We also anticipate that in 2050, c.50% of SMRs will be located in Asia-Pacific, (driven by China), 17% in Europe and 16% in North America.

However, certain **enabling factors are on the critical path to ensure the successful deployment of SMRs,** such as government sponsorship, regulatory capacity, supply chain consolidation, and Ecosystem coordination. While the private sector is driving the effort on research and development, governments are expected to play a key role in establishing the ground for favorable policy making, licensing framework, and providing long-term support packages to ensure the economic viability of SMR investment.

Collaborative approach from industry players is also required to augment nuclear adoption by providing the required supply chain support. Certain other enabling factors are standardizing the reactor design, obtaining ESG approvals at the beginning of projects, and streamlining the licensing regulatory process to ensure the SMRs development timeline stays on track.

Issam Taleb
EY Advisory France
Partner, EY-Parthenon France
Strategy and Transactions
France Energy Leader

Jeremie Haddad
EY Advisory France
Partner, EY Consulting France
Europe West
Power & Utilities Leader

Mile Milisavljevic
Principal EY-Parthenon
Strategy and Transactions
Ernst & Young LLP US

Introduction

The world is **transitioning toward low-carbon energy,** phasing down fossil fuels and shifting to more electric applications.

While variable renewable energy plays a pivotal role in this transformation, **the energy mix transition cannot fully rely on renewable sources** and requires additional means of balancing supply and demand for power.

Adding nuclear power capacity to national grids is critical to ensure reliable electricity generation and complementary to increasing penetration of variable renewable power generation. Moreover, thanks to continuously rising safety baselines over 60 years, nuclear is now demonstrably safe and affordable when delivered at scale (i.e., large reactor fleet deployment in US, France, Korea and China between 1970-2010s).

Recent years have seen a **resurgence of nuclear power.** During COP28, recently held in Dubai, nuclear was a new key player on a flagship event for the energy industry, that has traditionally showcased renewables.

On that occasion, more than 20 countries from four continents signed a joint declaration to triple nuclear energy capacity by 2050, recognizing the critical role of nuclear energy in reaching net zero.
Moreover, in November 2023, the European Commission formally announced the creation of an Industrial Alliance dedicated to SMRs to accelerate the deployment of these technologies and to ensure a strong EU supply chain.

However, for the past 20 years, nuclear capacity and market share have flattened, and more units in the OECD have been disconnected from the grid than connected.
SMRs represent the industry's promise of becoming a mainstream primary energy source.
This report seeks to address this once-in-a-generation opportunity for the nuclear industry to find its groove and shift back into growth mode.

In this context, can nuclear shake its "too expensive and too slow" reputation to make a difference in the race to a net-zero planet?

What we mean by small modular reactor (SMR) and advanced modular reactor (AMR)

ⓘ For readability, in this report the word SMR refers to both Gen. III/III+ and IV reactors, including SMR and AMR.

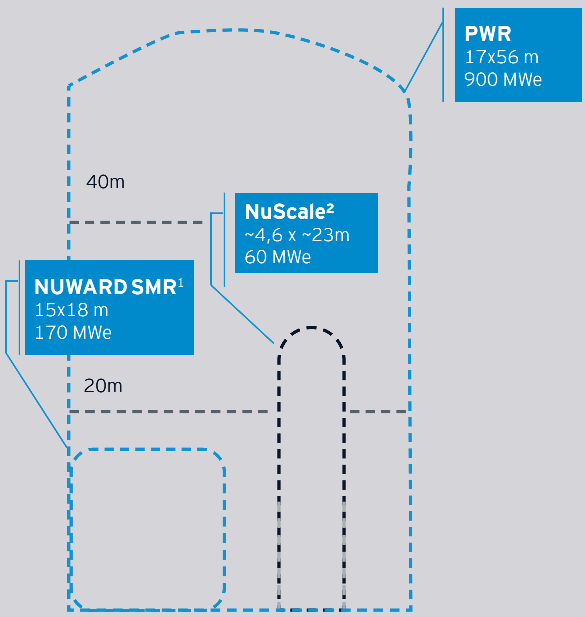
What are SMRs?

Small modular reactors (SMRs) are advanced nuclear reactors that have a power capacity of up to 300 MWe per unit, which is about one-third of the generating capacity of large-scale nuclear power reactors.

SMRs are:

- **Small -** with a power from 2 to 300 MWe;
- **Modular -** making it possible for systems and components to be factory-assembled and transported as a unit to a location for installation;
- **Reactors -** harnessing nuclear fission to generate heat to produce energy.

Conventional Pressurized Water Reactor (PWR) and SMR designs relative sizes



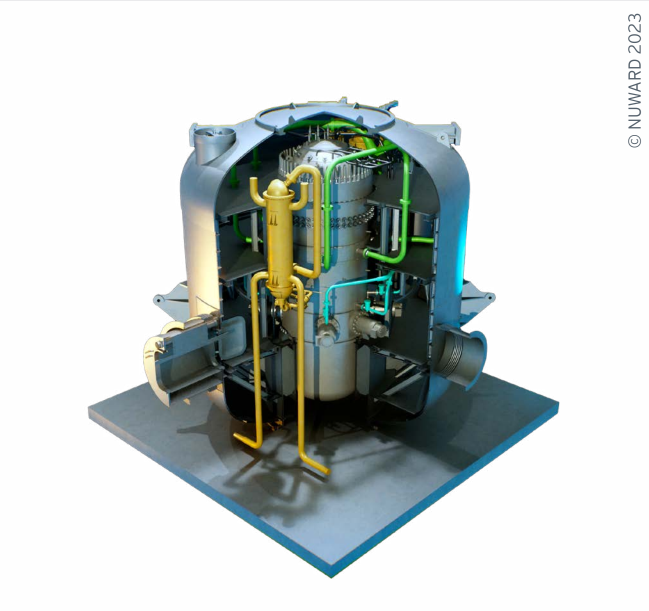
For what uses?

Small modular reactors are intended to supplement the nuclear supply in order to participate in the decarbonization of the economy. Where "large" nuclear reactors are generally only electrogenerating, that is to say dedicated to the production of very large quantities of electricity for the national network, **SMRs aim to meet specific and local needs for heat and /or electricity.** Thanks to their low power, they can more easily be integrated into small electrical or heat networks, close to industries and isolated sites.

What is the status of SMRs?

More than 80 commercial SMR designs are being developed around the world and some SMRs are operational in Russia, China and Argentina.

Globally, SMRs are expected to be deployed from 2030, while AMRs are anticipated to arrive from 2040.



▲ NUWARD digital model, Source: EDF, NUWARD

SMR versus AMR?

- Two types of water reactors exist:
  - **Gen. III:** traditional water reactors;
  - **Gen. III+:** traditional water reactors with enhanced safety features.
- **Small modular reactors** can be traditional water reactors, with lower power ranges compared to large NPPs;
- **Advanced Modular Reactors** (Gen. IV) bring together various technologies that aim to improve the fuel cycle and the safety.

[1] NUWARD, is a French company and an EDF subsidiary, developing a x2 170MWe reactor. Represented: NUWARD metallic enclosure.

[2] NuScale is an American company developing a 50-77 MWe SMR. Represented: NuScale module.

From promises to real value proposition

With the **increasing electricity needs of the energy transition, SMRs provide simple, scalable and reliable low-carbon power.** SMRs complement renewables and address several benefits, such as grid stabilization, cogeneration, reduced land use and decentralization.

Moreover, SMR design intends to bypass some of the financial, timing, centralization, safety and waste management issues that hinder the widespread adoption of conventional reactors. For instance, **several Gen. IV and Gen. III+ technologies** will include passive safety **features** and will use nuclear waste from large Nuclear Power Plants (NPP) to close the fuel cycle.

While SMRs include both Gen. III/III+ and Gen. IV in this report, we distinguish between Gen. III/III+ (also refered as SMRs), which are **miniaturized versions of existing power plants and are already mature, and Gen. IV (AMRs), which hold significant technological promises.** Gen. IV reactor types offer various value propositions, including higher heat applications, enhanced safety, fuel cycle closing but they are at a lower level of technological maturity.

One of the key **strengths of SMRs is their versatility, encompassing both on-grid and off-grid applications.** Thanks to cogeneration, power flexibility and high temperatures, SMRs can provide power to the grid, district heating, industries and remote areas.

Two main business models will likely emerge from the applications and client needs. Firstly, a **manufacturer model** mainly based on design and licensing (which can also include component manufacturing and NPP construction), similar to large NPP, and adapted to grid application. Second, an **"energy-as-a-service" model,** providing turnkey solutions to final client and more adapted for off-grid applications.

Finally, SMRs are gaining momentum, with **over 80 projects underway worldwide.** However, it is important to acknowledge that despite the excitement surrounding SMRs, **only a few projects are at an advanced stage and the economic model and feasibility of this market is still to be proven**.

With the increasing electricity needs of the energy transition, SMRs provide simple, scalable and reliable low-carbon power

“

Supporting growing electricity demand will require nuclear, and at the UN’s COP28 climate change summit, GE Hitachi and other leaders signed the Net Zero Nuclear Industry Pledge which commits to a goal of at least tripling nuclear capacity by 2050.

Brad Hartnett
Strategic Marketing Leader,
GE Hitachi Nuclear Energy

1

Baseload capacity

SMRs offer a high amount of reliable, carbon-free baseload power as a substitution of phasing out fossil sources in a context of electrifying uses.

2

Grid stabilization

Variable renewable sources need to be backed by enhanced stability of electricity grids through flexible operation or load following.

3

Cogeneration

SMRs allow for cogeneration of heat and electricity and address growing electricity demand for off-grid applications.

4

Land use

Nuclear has the lowest median land-use intensity at 7.1 ha/TWh/year. In comparison, solar PV has a 2,000 ha/TWh/year land-use intensity.

5

Decentralization

SMRs are an affordable option to 2-300 MWe or even less users and are available for more diverse applications than historical NPPs, including remote locations.

SMR design is intended to bypass some of the financial, timing, centralization, safety and waste management issues that hinder the widespread adoption of conventional reactors

Gen. III/III+

Gen. IV

Large NPP[1] challenges	Benefits from SMR features compared to conventional reactors	
Cost and Construction time	Simple design and standardization	**Standardized designs and mass production** reduce costs through efficient learning rates and delivery of nearly identical components in the project value chain.
	Modularization	SMRs are designed in **large modules to be built and tested in a plant and integrated on-site** shortening schedule and reducing the risk of construction delays.
	Co-siting	**Constructing multiple SMRs in the same NPP** optimizes construction and facility utilization, spreading investments and operating costs.
	Size	Smaller reactors can enable **faster installation** and replacement thanks to lower work requirements (construction schedule is reduced to 3 to 4 years versus 10 years for a large NPP[1]).
Network integration		Distributed generation **reduces transmission losses**, provides **flexible production**, and **meets diverse electricity and heat needs near end-users.**
Nuclear safety	Integrated design	Integrated designs **limit flows, junctions, and leaks** with smaller size improving the surface/volume ratio for controlling fission energy.
	Passive safety	**Passive safety features** for automatic shutdown are included in molten salt and some fast neutron reactors.
Nuclear waste	Fuel cycle closing	**Use of nuclear waste** from large NPPs and other SMRs allows to **close the fuel cycle** in fast neutrons reactors.

[1] Nuclear Power Plant.

Source: IAEA - Advances in SMR Technology Developments 2022, NEA - The NEA SMR Dashboard 2023, Expert interviews, Desk research, EY-Parthenon analysis.

"

Molten salt technology ensures passive reactor safety through geometric construction, and fast neutrons allow part of existing nuclear spent fuel to be reused as fuel.

Jean-Luc Alexandre
CEO, NAAREA

"

Gen. IV technologies, particularly HTGRs, can produce - with intrinsic safety properties - heat under or above 500°C to meet the needs of heavy industries consuming steam and heat, which are difficult to decarbonize.

Antoine Guyot
CEO, Jimmy

"

Thorizon modular core design leverages on fluid characteristics to implement passive safety.

Laure Claquin
COO and Director France, Thorizon

"

One key feature of SMRs is a lower CAPEX per unit compared to large nuclear, which reduces the balance sheet risk for investors, especially in regions where large nuclear suffered from massive cost and schedule overruns.

Brad Hartnett
Strategic Marketing Leader, GE Hitachi Nuclear Energy

"

newcleo's Lead Fast Reactor offering is unique: our design and intrinsic safety features mean our reactors could be sited in a wider range of locations than other technologies. Our use of recycled spent fuel will not only reduce the climate footprint of our own operations, it will also effectively close the fuel cycle and reduce the stock of long lived waste. Finally, the simplicity of our technology means our reactors will be highly cost-competitive.

Stefano Buono
CEO, *newcleo*

Gen. III/III+ SMRs are miniaturized existing nuclear power plants, Gen. IV AMRs present technological promises

Main disadvantage

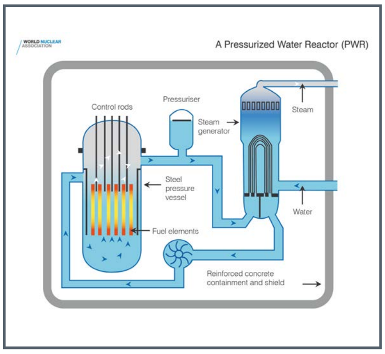
Main advantage

Illustrative examples

Gen. III/III+ SMR

Water-cooled

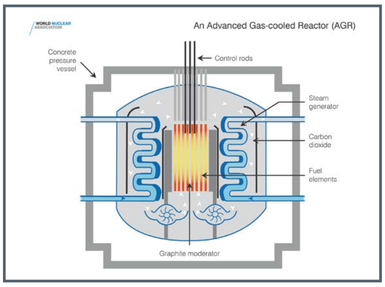
- Historical design of nuclear power plants, using **uranium** to produce **steam** for the turbine in separate steam generators.



Gen. IV - Advanced Reactors AMR

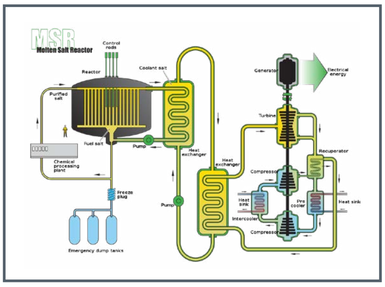
High Temperature Gas-cooled Reactor (HTGR)

- Uses helium or alternative gas like nitrogen. as coolant with fissile material **surrounded** by three **ceramic layers.**



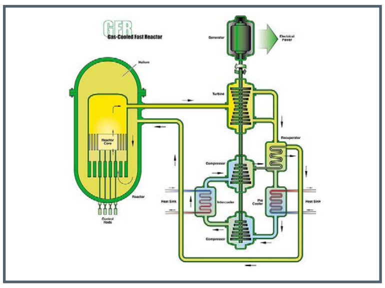
Molten-salt[1]

- A self-regulating critical geometry uses an **enriched molten salt mixture** as coolant and fuel to generate heat.



Liquid metal (Fast neutron spectrum[1,2])

- Uses **fast neutrons capable of carrying more energy** than conventional thermal neutrons, without neutron moderator.



Sources: World Nuclear Association, Idaho National Laboratory

[1] Molten salt and fast neutron technologies can be combined in the same reactor.

[2] Some fast neutron spectrum technologies can also provide increased safety, like LFR (Lead-cooled Fast Reactor).

Differentiating factors

Maturity	Thermal range	Increased safety	Use of waste fuel
3/3	1/3	1/3	1/3

- Most mature technology that can initiate a **decentralized production** system with **electricity and heat uses close to industries.**
- **Heat applications:** Low temperature heat (<300°C) for district heating, desalination, low temperature electrolysis, etc.

Maturity	Thermal range	Increased safety	Use of waste fuel
2/3	3/3	1/3	0/3

- Technology for generating **high-temperature heat** to meet **high industrial requirements.**
- **Heat applications:** Very high temperature (<1,000°C) for petrochemical, coal gasification, steam electrolysis, steam methane reforming, thermochemical processes, steel, etc.

Maturity	Thermal range	Increased safety	Use of waste fuel
1/3	2/3	3/3	1/3

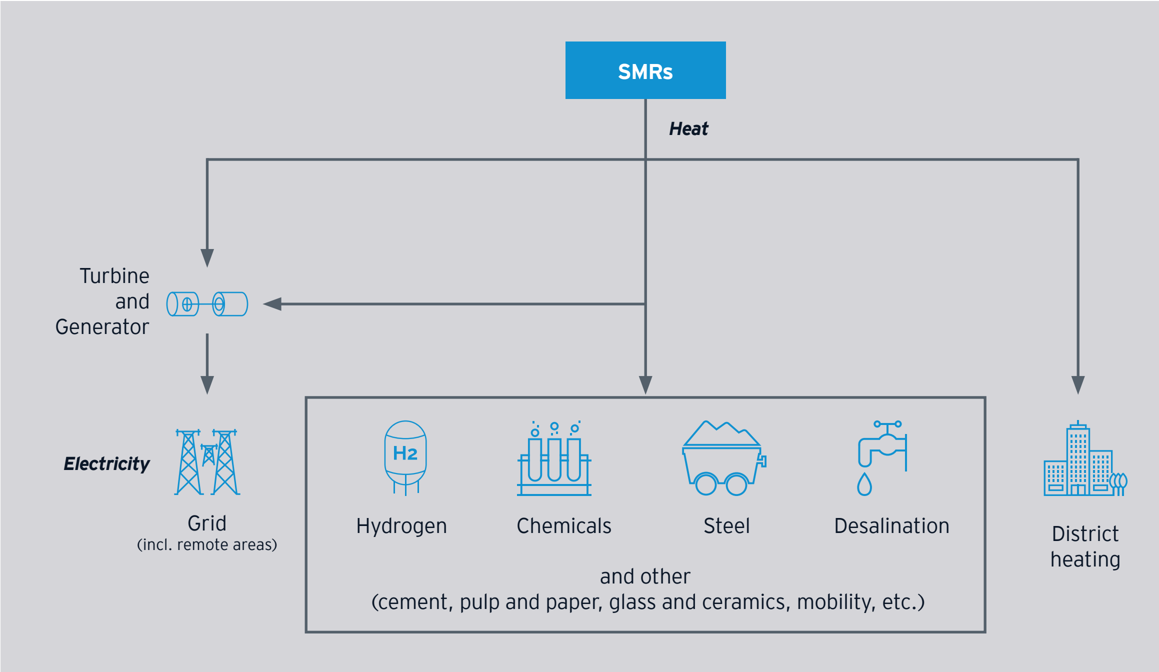
- Technology for implementing **passive safety**, used at **atmospheric pressure** and with **lower water needed.**
- Some molten salt reactors can fall in the **fast neutron** category, allowing to use **nuclear waste** from large NPP and other SMR to **close the fuel cycle.**
- **Heat applications:** High temperature (<800°C) for some petrochemical products, hydrogen production, refining, etc.

Maturity	Thermal range	Increased safety	Use of waste fuel
1/3	2/3	2/3	3/3

- Technology allowing **the use of nuclear waste** from large NPP and other SMR to **close the fuel cycle.**
- **Lead and sodium-cooled reactors** can be operated at pressure levels **close to atmospheric.**
- **Heat applications:** Medium temperature (<600°C) ‡for methanol, petroleum refining, etc.

Sources: IAEA - Advances in SMR Technology Developments 2022, NEA - The NEA SMR Dashboard 2023, Expert interviews, Desk research, EY-Parthenon analysis.

SMRs provide several on-grid and off-grid usage areas thanks to cogeneration (heat/electricity), different ranges of power (from 2 to 300 MWe) and high temperature



Description

- **Grid:** SMRs have the potential to enhance grid reliability and contribute to the resilience of integrated energy systems. SMRs can also provide power to remote areas with limited grid capacity. SMRs address a particular need in smaller countries, where large reactors are less sensible due to grid size and government budget;
- **District heating:** SMRs can be one of the solutions to decarbonize this segment and provide heat at temperature between 160°C and 250°C;
- **Hydrogen:** SMRs can power water electrolysis for green hydrogen production. It is estimated that 65% of hydrogen in 2050 will be produced through water electrolysis. Hydrogen will be used to decarbonize many sectors such as chemicals, steel and mobility;
- **Steel:** With the evolution of BOF[1] production process to DRI-EAF[2], the demand of electricity will significantly increase in this industry and SMRs can provide the electrical and 0-500°C heat needs;
- **Desalination:** SMRs can address the heat/electrical needs of the two production processes for desalination (reverse osmose and distillation);
- **Cement, glass and ceramics:** These segments require high temperature (>1,000°C). SMRs can address the electrical needs and the heat needs in the 0-500°C range;
- **Pulp and paper:** SMRs can provide the necessary heat and electricity to replace gas and other fossil fuels in the production process.

[1] Basic oxygen. Furnace.

[2] Direct Reduced Iron - Electrical Arc Furnace.

Two main business models will likely emerge from the applications and clients needs

Business model | Value chain positioning

- Same business model as for **existing large nuclear reactors;**
- Selling SMR design, which may or may not include components manufacturing and NPP construction, to an operator selling energy;
- **Revenue comes from the sale of the reactors** (one-off sale followed by potential maintenance);
- Prevalent model for **grid application.**

- Providers and vendors of **turnkey solutions to final energy consumer** – design the reactor, operate and maintain it, with or without components manufacturing and plant construction, to direct energy sale;
- Selling **energy as-a-service** (electricity or heat);
- Prevalent model for **industrial applications.**

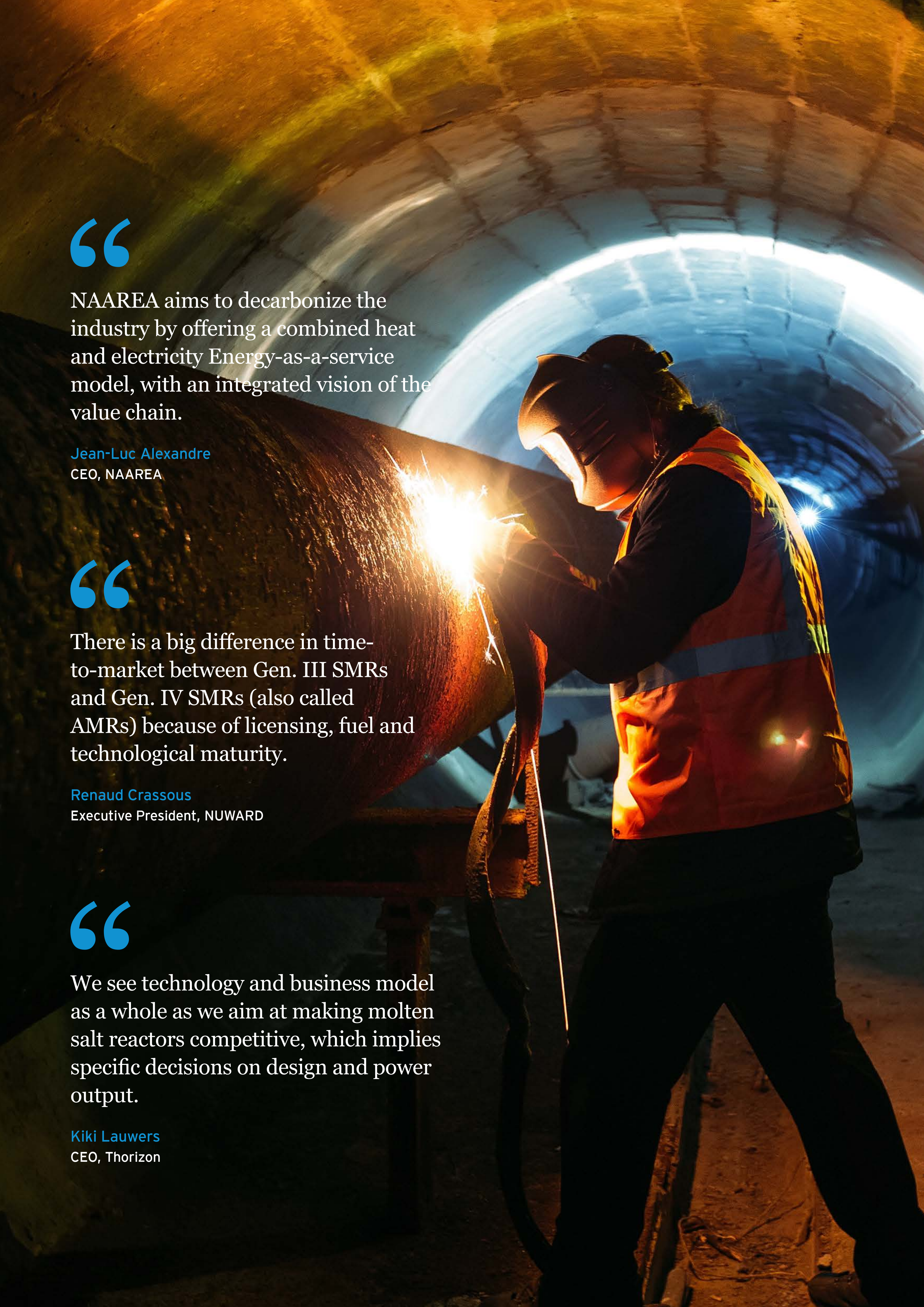
Covered
Potentially covered

Traditional players versus new entrants

SMR industry requires a fundamental **unpacking of the traditional Owner-Operator/Vendor role and relationship.** Emerging SMR deployment models indicate a multitude of key players from the development phase of any project: designer, regulator, site owner, manufacturer, builder, operator and off-taker.

Established companies with existing nuclear footprint benefit from their network and know-how along the value chain, **relying mainly on the large-scale NPP** designs they have already developed to reach the market more quickly.

New players aim to address **a wider range of applications,** including heat, by **reusing as many already lab-proven technologies** as possible.



> NAAREA aims to decarbonize the industry by offering a combined heat and electricity Energy-as-a-service model, with an integrated vision of the value chain.

Jean-Luc Alexandre
CEO, NAAREA

> There is a big difference in time-to-market between Gen. III SMRs and Gen. IV SMRs (also called AMRs) because of licensing, fuel and technological maturity.

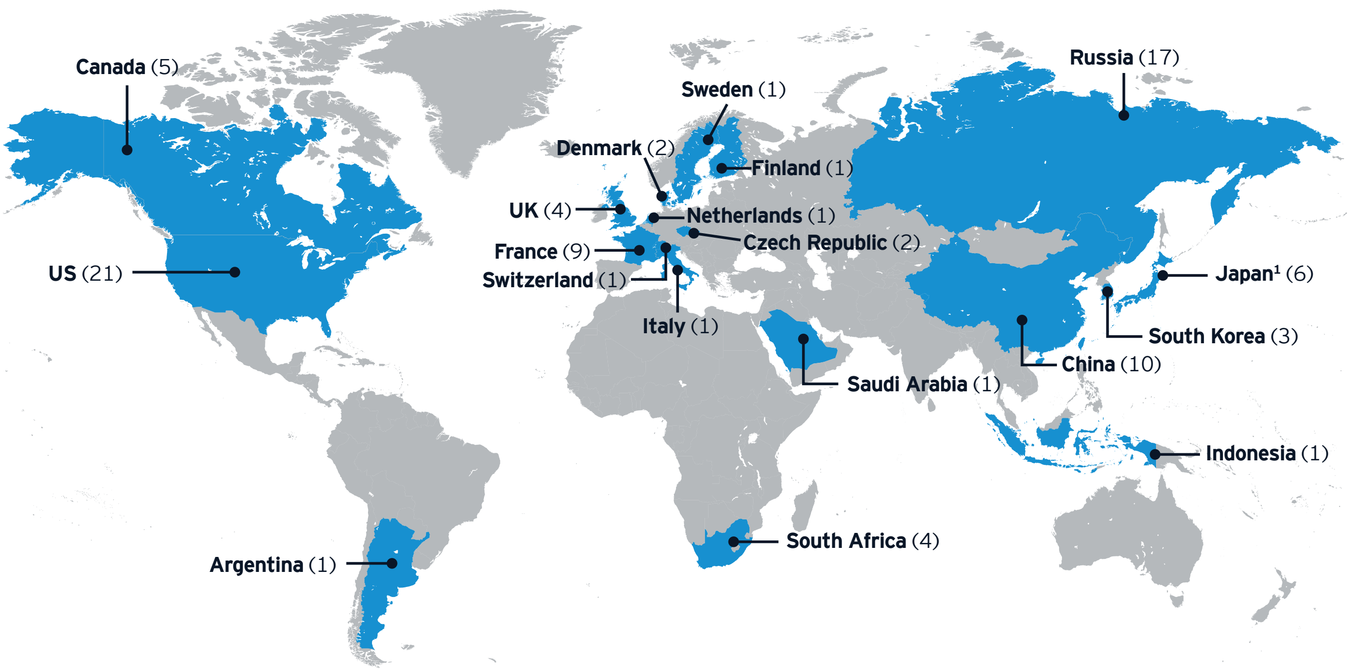
Renaud Crassous
Executive President, NUWARD

> We see technology and business model as a whole as we aim at making molten salt reactors competitive, which implies specific decisions on design and power output.

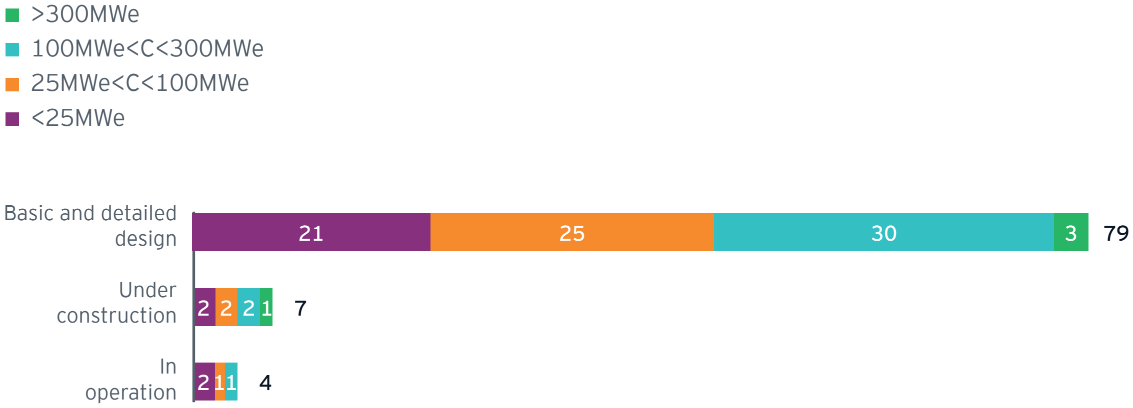
Kiki Lauwers
CEO, Thorizon

SMR projects are already widely spread across the globe although the stages of the projects differ

Countries/regions with SMR's projects

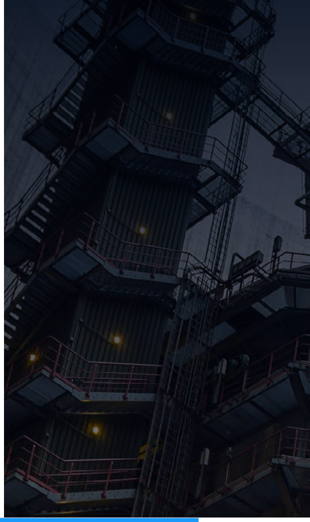


Global number of small modular reactor projects by status of development, 2023



1 Although SMR projects exist in Japan, building new nuclear power plants in new sites may be challenging as political priority is lifetime extension of existing plants. Regarding next generation plants, the Japanese government gives priority to fast reactors and high temperature gas reactors, prioritizing alliance and collaboration with manufacturers from other countries.

Source: IAEA 2022; IHS Markit Global Clean Energy. Technology, November 2021, EY-Parthenon analysis.



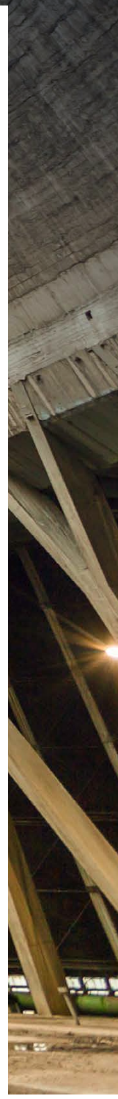
We have identified 20+ projects in different continents, responding to different use cases with varying technologies and maturities

Projects	Companies	Country	Thermal power (MWth)	Technology			
				Gen. III/III+	Gen. IV		
				Water-cooled	HTGR	Molten salt	Fast neut.[1]
ACP100	CNNC	China	c.400	✓			
VOYGR	NuScale	United States	c.200	✓			
CAREM	CNEA	Argentina	c.100	✓			
Rolls-Royce SMR	Rolls-Royce and Part.	United Kingdom	c.1,300	✓			
BWRX-300	GE Hitachi	United States	c.900	✓			
ACPR50S	CGNPC	China	c.200	✓			
NUWARD SMR	NUWARD (EDF Group)	France	c.540	✓			
LDR-50 Heating Plant	Steady Energy	Finland	c.50	✓			
AP300	Westinghouse	United States	c.900	✓			
SMR-160	Holtec International	United States	c.500	✓			
HTTR-30[7]	JAEA	Japan	c.30		✓		
Jimmy	Jimmy Energy	France	c.20		✓		
Xe-100	X-Energy	United States	c.200		✓		
HTR-PM	INET, Tsinghua Univ.	China	c.250		✓		
KP-FHR	Kairos Power	United States	c.320			✓	
Natrium	TerraPower, GE Hitachi	United States	c.840			✓	✓
SSR-W	Moltex Energy	Canada	c.750			✓	✓
XAMR	NAAREA	France	c.80			✓	✓
Thorizon One	Thorizon	France and Netherlands	c.250			✓	✓
Hexana	Hexana	France	c.400				✓
LFR-AS-200	*newcleo*[8]	Italy	c.500				✓
ARC-100	ARC Nuclear Canada	Canada	c.300				✓

Sources: IAEA, NEA - The NEA SMR Dashboard 2023, Expert interviews, Desk research, EY-Parthenon analysis.

✓ Current status or technical choice
Main target
Secondary target or use case partially covered

> “We joined forces with NAAREA in some areas of shared interest to accelerate the development of our respective technologies, to avoid any duplication of work and to provide a more unified voice for the sector.
>
> **Stefano Buono**
> CEO, *newcleo*



Use cases				Geography				Maturity		
Elec. for the grid	Heat used for industries (including cogen.) depending on temperature level :			USA	Europe	China	RoW[5]	Basic/ detailed design	Under manufacturing or construction[6]	In operation
	<200°C[2]	]200-500]°C[3]	>500°C[4]							
									✓	
									✓	
									✓	
								✓		
								✓		
								✓		
								✓		
								✓		
								✓		
								✓		
									✓	
								✓		
										✓
								✓		
								✓		
								✓		
								✓		
								✓		
								✓		
								✓		
								✓		

[1] Fast Neutron Spectrum.
[2] District heating, Seawater desalination, Hydrogen low temperature electrolysis.
[3] Pulp and paper manufacturing, Methanol production, Heavy oil desulfurization, Petroleum refining.
[4] Hydrogen (steam methane reforming, thermochemical), Coal gasification, Blast furnace steel making.
[5] Rest of the world.
[6] Manufacturing covers components or systems. Construction covers site choice, qualification and construction permit, in addition to actual, on-site, works.
[8] *newcleo* and NAAREA announced the creation of a Strategic and Industrial Partnership in January 2024: Press release.
[7] Test Reactor, not for commercial use.


2

Paths towards SMR competitiveness

On average, **SMRs construction should take 8-9 years for the FOAK[1] until the connection to the grid and 4 years for a NOAK[2] in theory,** driven by a strong series effect compared to large scale reactors. Regulatory and licensing support, adequate supply chain and social acceptance are key to drive faster development of SMRs.

To achieve mass adoption of new technologies, **cost competitiveness is key.** The first SMRs built will be demonstrators costing US$15k-US$20k/kWe overnight CAPEX. Industrialized FOAK cost is expected to decline by 20%-40% and then the NOAK even more by 30%-50% to reach US$8k-US$7k/kWe.

Modularization, co-siting, learning and standardization are key aspects to bring the costs down. Modularization alone can reduce costs by 15%-30% as modules are mass-produced in off-site factories and assembled on-site to reduce costs and save time. Multi-module siting at the same site can enable local specificities to be mutualized, resulting in cost savings of 10%-15%. Learning can increase efficiency across the value chain and standardisation allows to deliver (nearly) identical integrated products.

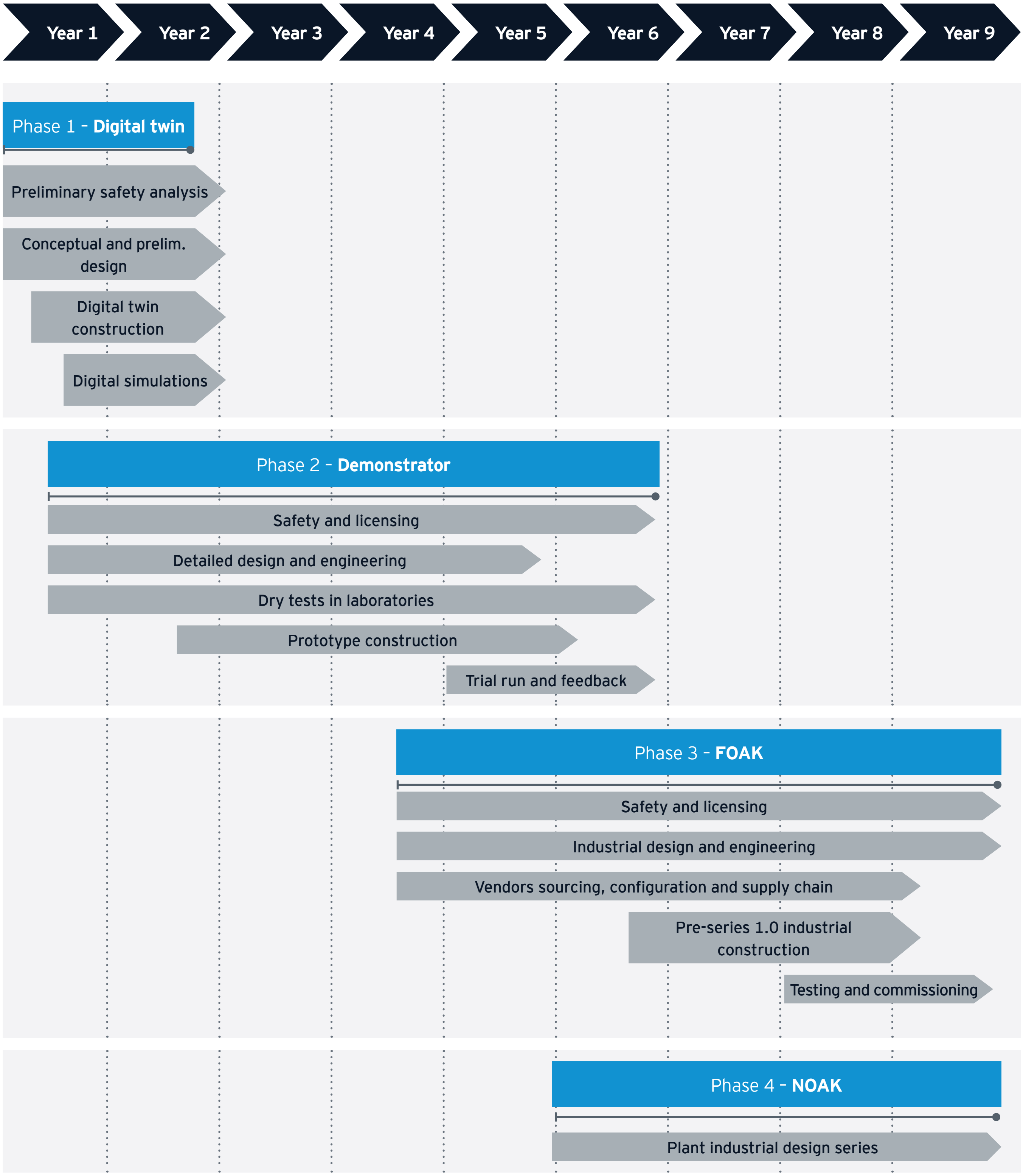
"Nth"-of-a-kind SMR units are therefore expected to be competitive with other clean technologies in the near term. **SMRs have additional benefits of concentrated siting and clustering** (e.g., lower land use, reuse of existing transmission infrastructure), which create economic value. **They can also generate additional revenue streams** such as industrial steam, district heating, DAC[3], H_2 production and desalination in addition to electricity generation.

Additional levers such as investment into R&D and licensing can potentially reduce cost and LCOE[4]. Because of high costs and the risks associated to first-of-a-kind projects, access to capital is key. Once enough SMRs will have been developed, they will be less risky and will be able to benefit from advantageous financing. Gen. IV projects will make it possible to reuse used fuel and can lead to lower fuel costs.

However, SMRs technology may negatively impact some cost inductors such as grid connections and operations. Indeed, if SMRs are dispatched on various territories, diffuse grid connection upgrades may be required. Similarly, dispersing operations across the country lead to increased staffing costs and need for coordination.

[1] First-of-a-kind.
[2] Nth-of-a-kind.
[3] Direct Air Capture.
[4] Levelized Cost of Energy.

On average, it should take 8-9 years to connect a FOAK and 4 years for a NOAK



“

Historically the nuclear industry aimed at increasing plants size to reduce costs. Therefore, the key challenge for SMR is to compensate smaller size with in-factory manufacturing, lower risk and new applications.

Paul Gauthé
CTO and cofounder, HEXANA

“

Gen. IV reactors - such as our modular molten salt reactor intended to work as a waste burner - are key in the energy transition challenge. Therefore, they should become a reality as soon as possible.

Kiki Lauwers
CEO, Thorizon

“

The key success factor for SMRs is to build trust with a FOAK that has the right specs delivered on schedule and on budget.

Brad Hartnett
Strategic Marketing Leader, GE Hitachi Nuclear Energy

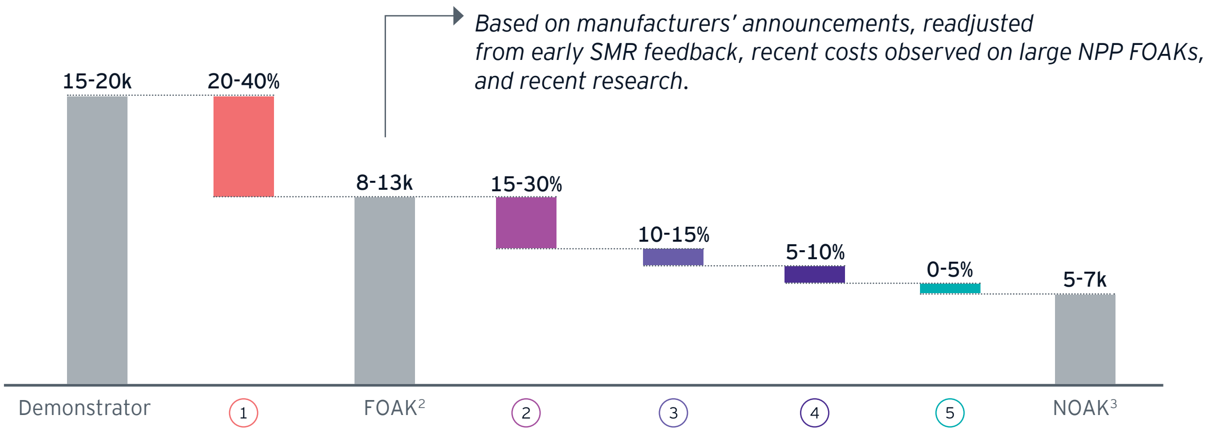
“

Our reactor is built on well-understood, well-established, PWR technology - already operating safely in hundreds of reactors around the world. Where we're innovating is in the delivery of that technology at scale to enable a predictable, repeatable product.

Sam Hounslow
Commercial Director, Rolls-Royce SMR Ltd

The first SMRs to be built will be demonstrators with a cost around US$15k-US$20k/kWe, real industrialized FOAK[2] will be able to reach a 20%-40% cost reduction, and NOAK[3] a further 30%-50% drop in cost through modularization, co-siting, learning and standardization

SMR potential cost reduction breakdown
(US$/kWe, %)[1]



1 **First industrialization**

Implementing **industry best practices** and using **NPP subcontractors skills** will help reduce costs after the demonstrator.

2 **Modularization**

Modules are mass-produced at off-site factories and assembled on-site to **reduce costs and build time.**

3 **Co-siting**

Multi-modules systems located at the same site enable local specificities to be mutualized.

4 **Learning**

Manufaturer, contractor and owner learnings increase efficiency within a **strong value chain.**

5 **Standardization**

Standard design and conception allow for the delivery of (nearly) integrated products.

1 Based on selected projects including GEHitachi, NuScale, Rolls Royce, Holtec, Westinghouse, NUWARD etc.

2 First-of-a-kind.

3 Nth-of-a-kind.

Sources: Carried out by researchers from University of Cambridge, Technische Universität Berlin, German Institute for Economic Research, CopenhaGen.Business School, University of Mannheim etc., IAEA, NEA - The NEA SMR Dashboard 2023, Expert interviews, Desk research, EY-Parthenon analysis.

Focus on FOAK to NOAK breakdown

Modularization

- Modules are **mass-produced in off-site factories** and **assembled on-site** to reduce costs and build time;
- **More compact** factory/manufacturing facilitates the scaling effect;
- Module size is to be **tailored** to the logistical / transport standards of each country;
- **Automation** and **advanced manufacturing techniques**[1] can be implemented in off-site factories.

Co-siting

- Multi-modules systems located at the same site enable to:
  - **Address site-specific characteristics** once for all the modules (e.g., ground / seismic studies etc.);
  - **Mutualize authorizations and public acceptance** processes;
  - **Share facilities, equipment and staff** during both construction and operation phases.

Learning

- **Manufacturer, contractor** and **owner** learning increases efficiency within a strong value chain;
- Global **supplier development** includes learning by doing and joint innovation programs;
- Logistical refinement and time **coordination** to anticipate delays;
- Advanced EPC **contractor development and management tools** to reduce construction time.

Standardization

- **Standard design and conception** allow to deliver (nearly) identical **integrated** products reducing construction **risk and uncertainty;**
- Standard **building blocks allow** to share parts and makes qualification easier;
- Reduced need to adapt to local site conditions and simplified design;
- **Manufacturer scale-up** for expanded future orders;
- Strengthened and operational supply chain.

[1] Including: electron beam welding, diode laser cladding, powder-metallurgy hot isostatic pressing and additive manufacturing.

Source: NEA – Projected Costs of Generating Electricity (2020) and Lloyd (2019), Huntington Ingalls Industries (2017), OECD, Idaho National Laboratory, EY-Parthenon analysis.

> Design decisions must be pragmatic and based on off-the-shelf materials and components as much as possible to optimize licensing time and reduce time to market.

Laure Claquin
COO and Director France, Thorizon

> Several factors help Steady Energy to be competitive: Gen. III technology is mature, the reactor generates heat only so no turbine is needed and the reactor is built underground so no protective dome is needed.

Tommy Nyman
CEO, Steady Energy

> Cost reduction target from FOAK to NOAK is -30%, which is made hard to reach by heterogeneous licensing requirements from one country to another.

Renaud Crassous
Executive President, NUWARD

> Jimmy's approach is to use as many existing, validated and with an existing industrial chain components as possible, to offer an operational and competitive system that can be brought to market quickly.

Antoine Guyot
CEO, Jimmy

Additional levers can have an impact on SMR cost over the long-term depending on how they will be implemented

Additional cost evolution levers and rationale

Potential impact on costs

Grid connection

- As SMR will be dispatched to various territories, **grid connection upgrades will be required.** (Increase potential costs)
- When SMRs replace thermal power plants, existing transmission infrastructure can be reused without extra investment. (Decrease potential costs)

R&D and Licensing

- As SMR **technologies are less mature** than Large-scale NPP, **significant R&D and licensing costs are required,** especially for Gen. IV, but also for Gen. III/III+. (Decrease potential costs)
- The greater the number of units produced, the more these costs can be spread out.

Manufacturing

- **Dedicated factories will have to be built** to manufacture these parts, which will also entail construction costs. (Decrease potential costs)
- Thanks to the above-mentioned levers, a **greater proportion of SMR components can be manufactured in factories** and will therefore require less time to produce.

Financing

- Initial projects will be pioneering, **involving substantial risk** and subsequently facing **higher debt and equity financing costs.** (Decrease potential costs)
- Once a **sufficient number of SMRs** will have been developed, they will be **less risky** and will be able to **benefit from advantageous financing** (debt and equity).

Operations

- SMRs are expected to have **higher operating costs** than large reactors, as a significant portion of the staffing costs is fixed, irrespective of the power output. Operations will be more **dispersed across the country**, requiring **greater coordination.** (Increase potential costs)
- **Number of FTEs** required to operate SMRs **varies widely** and depends on project specifications, ranging from 200 FTEs/SMR on-site for some Gen. III to 0 on-site for some Gen. IV projects. (Unknown)

Fuel

- **Reuse of spent fuel allowed by Gen. IV reactors** may impact fuel cost. To date, this impact is **unknown** as plutonium market does not exist. Increased toxicity and radioactivity of plutonium compared to uranium may drive cost up whereas pricing the waste processing service offered by such reactors may drive (net) cost down. (Unknown)

Decrease potential costs | Unknown | Increase potential costs

3

A major deployment is expected from the 2030s if certain conditions are met

Small modular reactors worldwide market

As energy transition gains momentum, **the share of nuclear energy is expected to double in the energy mix by 2050,** if the IEA scenarios materialize.

EY-Parthenon anticipates the first demonstrators being commissioned around 2030, with a **real acceleration in deployment from the 2040s** with the emergence of Gen. IV, which can respond to wider applications. Under realistic and accelerated scenarios, EY-Parthenon predicts 400-700 SMRs to be deployed by 2050 (c.60-100 GWe).

c.40% of SMRs capacity will be deployed for energy supply to the grid, followed by hydrogen (17%), steel and aluminium (14%), and district heating (11%). **Until 2040, lower-temperature heat applications** such as district heating, desalination, pulp and paper industries **will be preferred.** However, with the emergence of Gen. IV, new uses will emerge, particularly in cement, glass and ceramics.

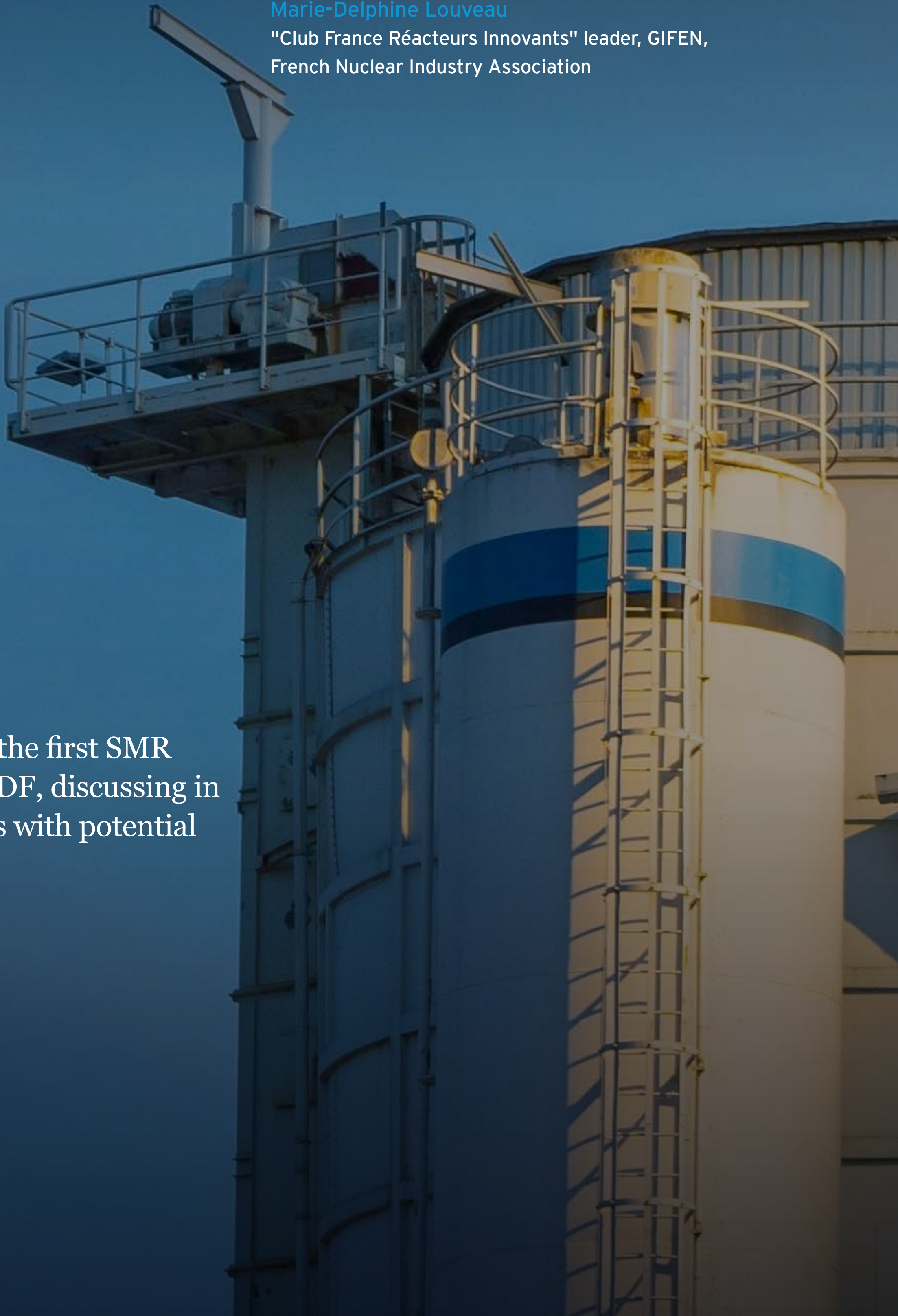
Key regions for SMRs would be Asia-Pacific (c.50%) driven by China, followed by Europe (17%) and North America (16%) respectively.

The overnight capital cost of a 150MWe SMR is expected to decline from c.US$1.7b in 2030 to c.US$0.75b in 2050 without inflation.

However, **successful deployment of SMRs relies on several enabling factors,** including regulatory mandates and capacity, industry participation, and government orchestration. The governments will play a key role not only in establishing regulations and roadmaps to augment nuclear adoption but also providing funding for initial projects that have high costs and complexity. The industry needs to move from a siloed structure to a more collaborative approach to ensure adequate manufacturing capacity and fuel supply. Implementing robust safety mechanisms, community engagement, skilled labor, and effective waste disposal is also needed.

Few countries have implemented solutions to ensure the deployment of SMRs, such as covering a percentage of construction costs at and above the projected costs. Governments can provide subsidy amounts per kW that can ramp down on each successive deployment similarly to recent supporting policies to renewables.
To provide price stability, the government can sign an offtake contract for some or all of the generation from an order book.

Other enabling factors could be standardizing the reactor design, obtaining ESG approvals at the beginning of projects, and streamlining the licensing regulatory process to ensure the SMRs development timeline stays on track.



> SMRs, real game changers, are of worldwide interest, as their characteristics meet needs other than those of high-power reactors.
> Their versatility will enable the industry to position itself for export in a wide range of markets.

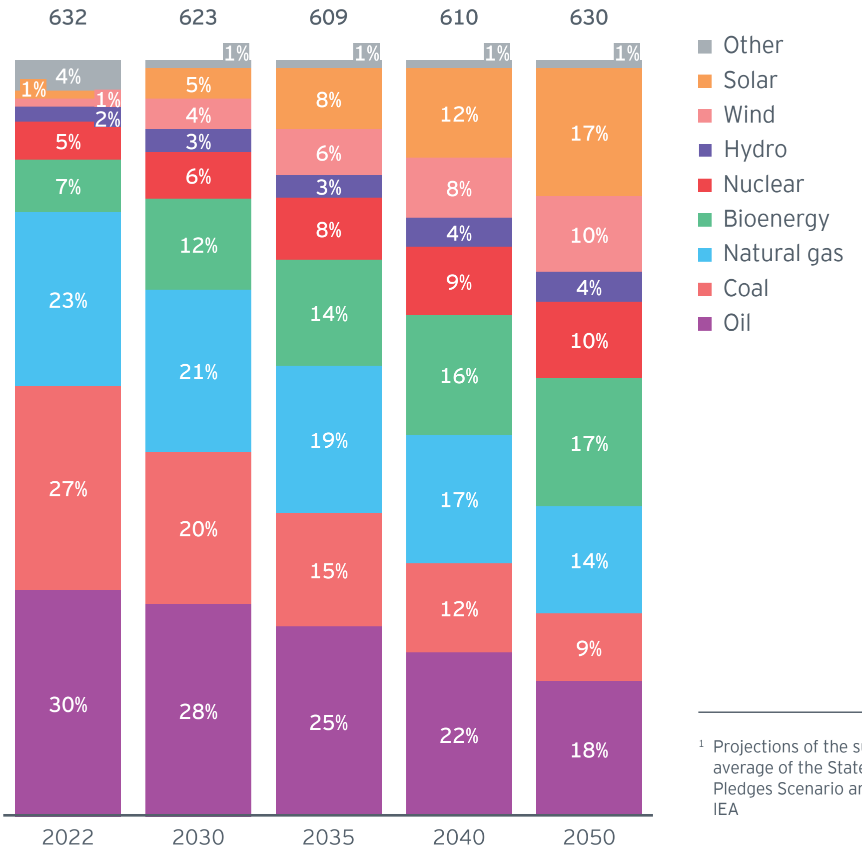
Marie-Delphine Louveau
"Club France Réacteurs Innovants" leader, GIFEN, French Nuclear Industry Association

> Nuward is developing the first SMR plant in France with EDF, discussing in parallel export projects with potential customers.

Renaud Crassous
Executive President, NUWARD

A promising market potential if IEA scenarios materialize

Global energy supply and mix, 2022-50
in EJ (exajoule)[1]

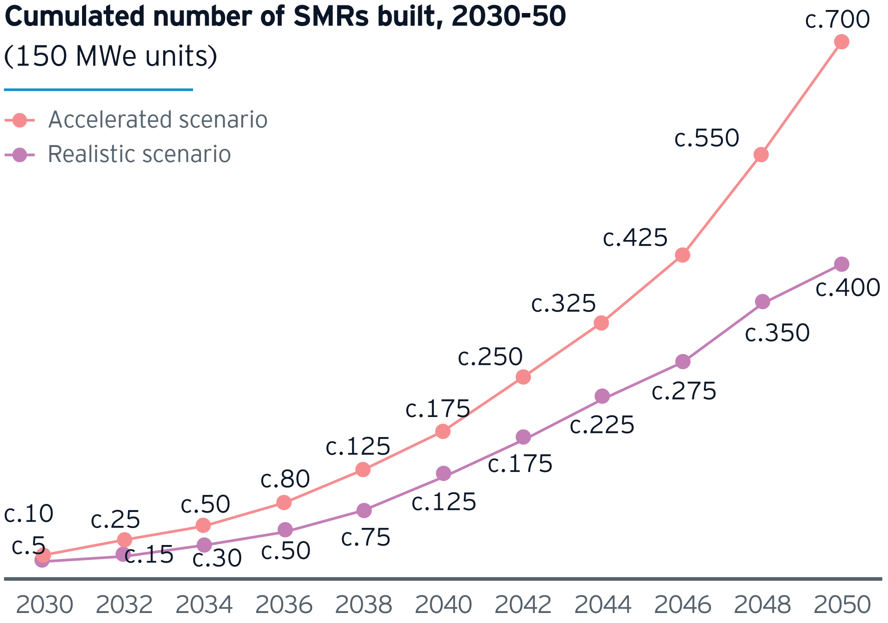


[1] Projections of the supply and energy mix refer to an average of the Stated Policies Scenario, Announced Pledges Scenario and Net Zero Emissions from the IEA

- IEA predicts a significant energy mix **shift from fossil fuels** (oil, coal, gas) **to low-carbon sources** (renewables and nuclear) in only 25 years.
- All scenarios are expected nuclear to play a key role in the energy transition with a planned **doubling in the energy mix between today and 2050** (5% to 10% of global energy supply). A tripling scenario from 5% to 14% is even planned in the Net Zero Emissions scenario.
- **In this context, what share of new nuclear construction could SMRs potentially capture?**
- In the next pages, EY-Parthenon presents its market size estimation until 2050. It is based on research, IEA scenarios and expert feedbacks. EY-Parthenon has determined SMRs penetration rate on new nuclear construction until 2050 and allocated it by application and geography.

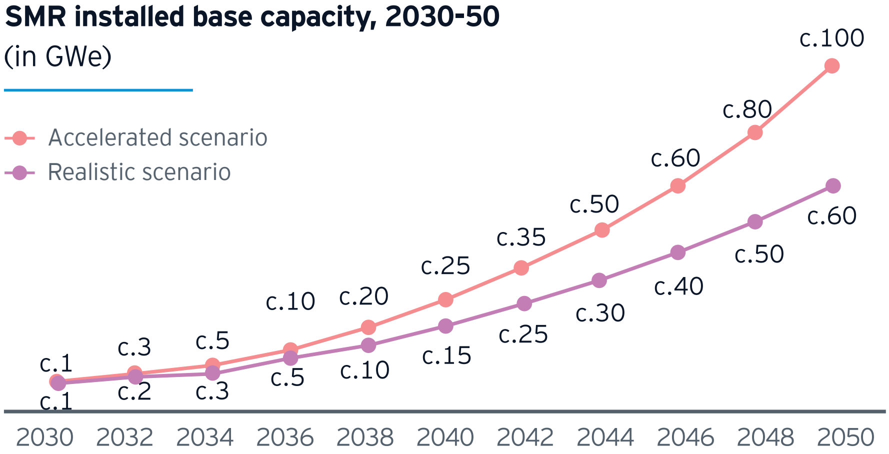
Estimated market size in number of SMRs (150MWe unit) and in capacity (GWe)

Cumulated number of SMRs built, 2030-50
(150 MWe units)



- EY-Parthenon anticipates the first demonstrators being commissioned around 2030, with a real acceleration in deployment from the 2040s onwards with the emergence of Gen. IV, which can respond to wider applications;
- EY-Parthenon forecasts a cumulated base of c.**125-175 SMRs in 2040** and **c.400-700 in 2050;**
- The SMR installed base would represent **c.1 GWe in 2030, c.15-25 GWe in 2040** and **c.60-100 GWe in 2050.**

SMR installed base capacity, 2030-50
(in GWe)



- **This estimation comes with caveats.** The outlook for nuclear is uncertain and subject to unpredictable political decisions.
- For instance, the support of governments on the projects and the capacity to industrialize the production will impact the SMR market significantly.
- EY-Parthenon has worked on **two complementary scenarios: an accelerated scenario and a more realistic scenario** based on different penetration rates. These two scenarios are, however, **based on the condition that the challenges to deployment have been overcome** (financing, industrialization, etc.).

> The most mature demand for SMRs comes from energy companies for electricity production, especially from existing nuclear operators.

Renaud Crassous
Executive President, NUWARD

SMRs will be a key part of tomorrow's energy landscape, meeting electricity and heating needs

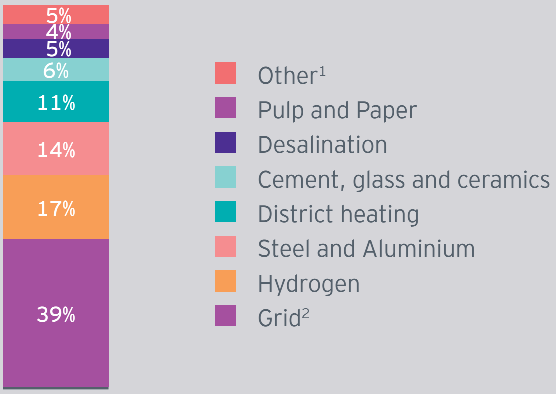
EY-Parthenon estimates that **50% of SMRs will be dedicated to the grid and district heating and 50% for the industry in 2050**:

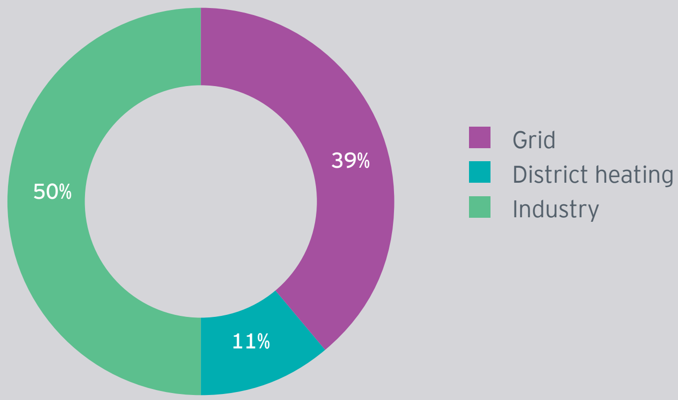
- The energy supply to the grid segment is the most important and will represent around 40% of SMRs capacity installed worldwide in 2050.
- In the industry, **the most promising segments are hydrogen** (massive electricity needs with the growing use of hydrogen in industry in particular) and **steel and aluminum** (mainly addressed for its electricity needs in arc furnaces and in the aluminum electrolysis process)

The promise of SMRs to provide low-carbon heat is confronted with the electrification of industry (e.g., desalination, steel). At least 75% of the energy produced by SMRs is expected to be electricity.

Until 2040, lower-temperature heat applications will be preferred for district heating, desalination (by distillation) **and the pulp and paper segment.** With the emergence of Gen. IV, which will be able to reach higher temperatures (>300°C), new uses will emerge, particularly in cement, glass and ceramics.

Number of SMRs built allocated by application in 2050





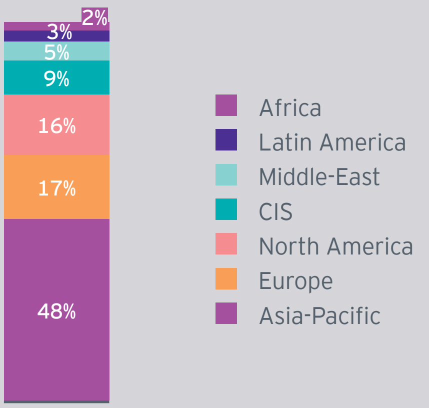
[1] Other includes **other applications** like food, textile, data center segments and other industrial usages.

[2] Grid includes **all grid application excluding the other segments** (Hydrogen, Steel and Aluminum, Cement, glass and ceramics, Pulp and Paper, Desalination, Other).

In 2050, **c.50% of built SMRs are expected to be located in Asia-Pacific** compared to 17% for Europe and 16% for North America;

- Rest of the world (CIS, Latin America, Middle-East and Africa) will account for c.20%;
- **Asia-Pacific will be driven by China** as the country stands at the forefront of nuclear energy with some already operational SMRs. China faces a strong challenge to decarbonize its industry and has identified SMRs as one of the solutions;
- In North America, the USA and Canada are investing heavily in SMRs and significantly increasing the number of projects;
- In Europe, France and the UK have solid SMRs projects, while Eastern Europe is very interested in purchasing this technology.

Number of SMRs built allocated by geography in 2050



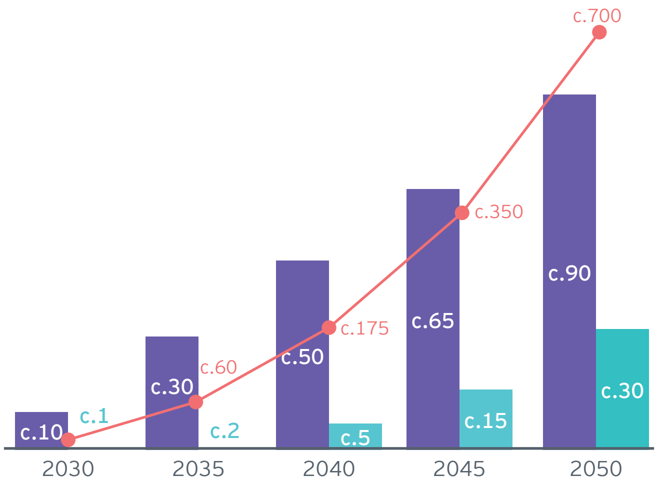
> Large heavy industry players want to buy **energy, not reactors.**
>
> Paul Gauthé
> CTO and cofounder, HEXANA

> Jimmy's business model is to **offer its customers a turnkey heat supply contract,** from financing to generator dismantling, with a competitive supply of carbon-free heat at an unchanged price for 20 years.
>
> Antoine Guyot
> CEO, Jimmy

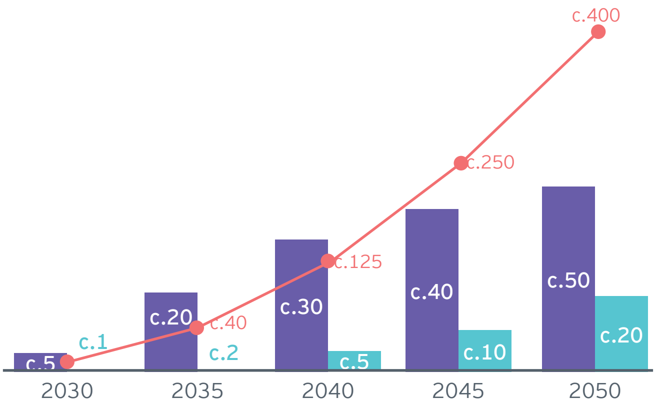
SMR market is estimated at c.US$50-90b per year in 2050 for capital expenditure in new build and c.US$20-30b for services including O&M and Fuel

Annual SMRs market value 2030-50
(US$b - inc.inflation at 2%)

Accelerated scenario



Realistic scenario



- SMR power plant and equipment market - Build
- SMR services market (O&M and Fuel) - Run
- Number or SMRs (150MWe unit)

Assumptions:

- An average **SMR size of 150MWe** is assumed;
- **Overnight capital costs of a 150 MWe SMR** are expected to be c.**US$1.7b in 2030** (c.US$12k /kWe) and **c.US$0.75b in 2050** (c.US$5k /kWe) without inflation;
- Assuming 2% inflation, this leads to **c.US$2.0b in 2030** (c.US$13k /kWe) and **US$1.3b in 2050** (c.US$9k /kWe);
- **Services costs** are assumed to be close to current large NPP projects at **c.US$180/kWe per year,** only following 2% inflation. This gives **US$30m/year** per 150MWe SMR in 2030 and **US$45m/year** per 150MWe SMR in 2050.

> Like all SMR developers, success in the UK will depend on government sponsorship and support, and the prioritizing and enabling of nuclear development, through a “whole of government” approach.

Stefano Buono
CEO, *newcleo*

> In terms of both financing and harmonized licensing, there is a political challenge at European level to facilitate the emergence of SMRs.

Sophie Rouzaud
Head of Financial and Strategic Analysis, Nuclear Valley

To deploy from FOAK to NOAK, SMRs have challenges to overcome

2023 Nuscale setback in Utah highlights that even if SMR can **lower construction cost and risk**, it remains nuclear technology, with **long and uncertain development cycles**. It therefore requires **strong and stable commitment** from all the key stakeholders over the **long-term** to be successful and overcome its intrinsic challenges.

1 Government sponsorship

- **Government sponsorship must be broad, holistic and resourced/funded on a multi-year/programmatic basis** in order to plug resource gaps as needed, from FOAK to NOAK deployment with simultaneous support to Gen. III and Gen. IV.
- It is important this support/public mandate transcends electoral cycles in order to **allow the industry to mature independently of political interference.**
- Equally, **exceptionally robust governance/oversight by government is required** in deliver to assure value for money and public trust over the long term.

2 Regulatory capacity

- **National regulatory mandates and resources need to be expanded** with a bias to enabling new, non-LWR and non-mature designs and accelerate licensing/permitting to facilitate the supply chain.
- **Regulators need to be encouraged/incentivized to cooperate internationally,** for example through the establishment of international regulatory bodies that could support development of national standards, methodologies, etc.

3 Supply chain consolidation

- **Industrial participation must be demonstrated and encouraged** in order to raise confidence levels across technology design, manufacturing, constructability and operability.
- The labor gap across manufacturing, construction, and operations needs to be closed.
- Nuclear fuel cycle has to be secured.
- Compliance with regulation and safety standards throughout the supply chain has to be ensured.

4 Ecosystem coordination

- **Technology designers and their partners must build organizations capable of engaging in efficient regulatory and licensing activities,** and demonstrate capacity to sustain licensing programs over the long term. This includes running cross-country licensing programs, similarly to NUWARD's Joint Early Review in Europe.
- **Value proposition for the partners needs to be defined:** off-take guarantees, financing, governance and risk management.

> The industry, governments and regulators now need to coordinate their efforts to allow long-term partnerships, give visibility to the stakeholders and therefore enable them to commit on ambitious, yet realistic, targets.

Marie-Delphine Louveau
"Club France Réacteurs Innovants" leader, GIFEN, French Nuclear Industry Association

> newcleo aims to play a key role in all parts of the SMR value chain and we have adopted an M&A strategy to support our vertical integration and the creation of a robust and resilient supply chain for critical components and skills.

Stefano Buono
CEO, *newcleo*

> Commitment is key. We welcome the increasing ambition from governments and the increased interest from private sector but we need to work to turn that into formal commitments.
> Our supply chains need that to support the investment needed.

Sam Hounslow
Commercial Director, Rolls Royce SMR Ltd

> The best way to achieve technological maturity is to build up a strong industrial ecosystem of partners, experts and laboratories.

Jean-Luc Alexandre
CEO, NAAREA

Conclusion

SMRs stand as one of the foundational pillars for the development of nuclear energy at large scale and enablers of net zero and 2050 capacity targets. **Potential opportunities for stakeholders** (designers/engineers, states, the finance industry, etc.) **could be significant.** However, given the current state of development, many challenges must be overcome to enable a large-scale deployment.

The success of SMRs may be assured for a handful of first-movers in the early 2030s that will have levered government support more successfully than the rest of the field.
However, as an industry, and to make an impact on the Net Zero 2050 ambitions, including energy security and affordability concerns, SMRs and AMRs can only be considered successful if nuclear industry infrastructure is revamped.
The areas where changes are necessary range from regulatory support and licensing, standards and methodologies, industrial codes, human capacity/training, off-taker incentives to develop and invest in new designs, site availability, public education, legislation and international treaties on export/ transport of nuclear technology.
New financing models will need to be developed in line with the new nuclear ecosystem, in order to deliver the many billions or trillions of USD that are needed to assure global policy objectives.

Contributors

Thanks

SMR developers and stakeholders

- EDF NUWARD
- GE Hitachi Nuclear Energy
- GIFEN
- Hexana
- Jimmy Energy
- NAAREA
- *new*cleo
- Nuclear Valley
- Rolls-Royce SMR Ltd
- Steady Energy
- Thorizon

EY contributors

- **Antoine Chauvigné**, France
- **Anton Poryadin**, USA
- **Bhavya Agarwal**, India
- **Birute Bobrovaite-Jurkone**, UEA
- **Bruno Bousquié**, France
- **Christoffer Clarin**, Sweden
- **David Stearns**, France
- **Gauthier Sorg**, France
- **Jamie Andrews**, UK
- **Julien Saigault**, France
- **Megha Tomar**, India
- **Olivier Bertrand**, France
- **Simona Horelicanova**, UK
- **Takuya Okamoto**, Japan
- **Victor Hammar**, Sweden
- **Yuto Takahashi**, Japan

EY Nuclear Center of Excellence

- **Adrian Bocher**, France
- **Anton E Poryadin**, USA
- **Birute Bobrovaite-Jurkone**, UAE
- **Björn Alexander Krupa**, Germany
- **Bruno Bousquié**, France
- **Chris C Lewis**, UK
- **Christian Grauers**, Sweden
- **Christoffer Clarin**, Sweden
- **David Stearns**, France
- **David Roxby**, UK
- **Giacomo Chiavari**, Italy
- **Guillaume Bouvard**, France
- **Hugo Jennequin**, France
- **Issam Taleb**, France
- **Jamie Andrews**, UK
- **Jeremie Haddad**, France
- **Julien Drevon**, France
- **Julien Saigault**, France
- **Levente Kovacs**, Hungary
- **Makoto Kido**, Japan
- **Mile Milisavljevic**, USA
- **Naoto Utsumi**, Japan
- **Paul Rees Jones**, UK
- **Pierrick Vaudour**, France
- **Rajeev Singh**, UAE
- **Ralf Seidenspinner**, Germany
- **Tomas Skucek**, Czech Republic
- **Victor Hammar**, Sweden
- **Vincent Gautier**, France
- **Yunus Ozler**, UK
- **Takuya Okamoto**, Japan
- **Yuto Takahashi**, Japan

EY | Building a better working world

EY exists to build a better working world, helping to create long-term value for clients, people and society and build trust in the capital markets.

Enabled by data and technology, diverse EY teams in over 150 markets provide trust through assurance and help clients grow, transform and operate.

Working across assurance, consulting, law, strategy, tax and transactions, EY teams ask better questions to find new answers for the complex issues facing our world today.

Contacts

Issam Taleb
EY Advisory France
issam.taleb@parthenon.ey.com

Jeremie Haddad
EY Advisory France
jeremie.haddad@fr.ey.com

Mile Milisavljevic
Ernst & Young U.S. LLP
mile.milisavljevic@parthenon.ey.com

About EY-Parthenon
EY-Parthenon teams work with clients to navigate complexity by helping them to reimagine their eco-systems, reshape their portfolios and reinvent themselves for a better future. With global connectivity and scale, EY-Parthenon teams focus on Strategy Realized – helping CEOs design and deliver strategies to better manage challenges while maximizing opportunities as they look to transform their businesses. From idea to implementation, EY-Parthenon teams help organizations to build a better working world by fostering long-term value. EY-Parthenon is a brand under which a number of EY member firms across the globe provide strategy consulting services. For more information, please visit ey.com/parthenon.

Studio BMC France – 2401BMC013.
SCORE N°: EYG no. 002003-24Gbl.
ED None.

In line with EY's commitment to minimize its impact on the environment, this document has been printed on paper with a high recycled content.

ey.com