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Energy Transition

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SMRs: missing link for a successful energy transition?

In addressing the challenges set by the decarbonisation of the global economy, **small modular reactors** (SMRs) **offer a potential solution for deploying dispatchable, low-carbon electricity generation** to complement large, conventional nuclear reactors (CNRs) and renewable energies.

SMRs are not, however, so much a technology as a type of reactor, different in size, design and modularity from those generally exceeding 500MW in operation or under construction in the world. Some 83 SMR concepts are currently under development. They offer a very wide variety of technological options, from adapting currently predominant concepts (3rd generation reactors) to exploring emerging nuclear concepts (4th generation reactors). The paradox is that the solutions with the highest degree of technological maturity today will not necessarily be the most competitive tomorrow.

SMRs also stand out for having a **wide variety of use cases**, ranging from inclusion in systemic frameworks for grid balancing or the generation of heat supplied to district heating systems to closed circuits for supplying electricity and/or heat to industrial sites requiring capacities of 1MW to 200MW.

SMR design and modularity point to **potential cost savings compared with CNRs**. However, the promise of reactors that would be cheaper than CNRs will only come about if the production of components becomes sufficiently industrialised to generate significant economies of scale within the industry.

Two conditions do appear essential if this sector is to continue its structuring and press ahead with its development: on the one hand, a continuous process of **selecting the technologies** that best meet the most relevant use cases, and, on the other, the **adoption of international safety standards and civil liability regimes**, as well as the adoption of legal and regulatory frameworks (carbon markets) propitious for the development of SMR projects.

In this context, **the financial sector will be called upon to play a key role in two ways:** firstly, **by encouraging the emergence of the most relevant concepts**, via fund-raising by technology developers; and secondly, as and when the conditions are met, **by supporting projects through asset financing**, and in so doing, encourage the industrialisation of the sector, as we have seen with renewable energies over the last decade and a half.

Contents

Growing interest in SMRs as demand for low-carbon electricity increases

Low-carbon electricity, a pillar of the energy transition

Small modular reactors (SMRs) have elicited growing interest over the past decade as a means of producing low-carbon electricity and/or heat, this phenomenon being inextricably linked to the **fast-developing climate emergency**.

This is in the context of the commitments made by 196 parties[1] at the UN Climate Change Conference (COP21) in Paris on 12 December 2015 to work towards holding "the increase in the global average temperature to well below 2°C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5°C above pre-industrial levels."[2]

Key milestones defined by the scientific community in line with this objective include, **for the global economy, achieving net zero by 2050 and generating negative CO_2 emissions throughout the second half of the century**. In particular, the IPCC reports[3] contain very precise modelling of greenhouse gas (GHG)/CO_2 emission pathways compatible with a scenario of maximum mitigation of current climate trends. Achieving the most favourable scenario of limiting warming to +1.5°C by 2100 is based on emissions reductions of 99% for CO_2 and 84% for all GHGs by 2050[4] (see table below).

IPCC: reduction in CO_2 / GHG emissions compatible with climate change mitigation

Climate scenarios		Reduction from 2019 emission levels (%)			
		2030	2035	2040	2050
Limit warning to +1,5°C (>50%) with no or limited overshoot	GHG	43 [34-60]	60 [49-77]	69 [58-90]	84 [73-98]
	CO_2	48 [36-69]	65 [50-96]	80 [61-109]	99 [79-119]
Limit warning to +2,0°C (>67%)	GHG	21 [1-42]	35 [22-55]	46 [34-63]	64 [53-77]
	CO_2	22 [1-44]	37 [21-59]	51 [36-70]	73 [55-90]

Source: IPCC (2023)

This multilateral and scientific framework outlines the contours of the energy transition that has been underway for the last decade or so to varying degrees throughout the world. The technological and policy pillars have been analysed in detail by the IPCC[5] and IEA[6].

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[1] 195 countries plus the European Union.

[2] Cf. https://unfccc.int/process-and-meetings/the-paris-agreement

[3] The IPCC's Synthesis Report of its Sixth Assessment report published in March 2023 contains the assessment of observational evidence and assesses the current implementation of adaptation and mitigation response options. Cf. https://www.ipcc.ch/report/sixth-assessment-report-cycle/

[4] Attention of various stakeholders focused on CO_2 emissions, as they account for around two-thirds of total GHG emissions. By convention, in climate literature, total GHG emissions are expressed in CO_2 equivalent.

[5] Ibid.

[6] In particular the Net Zero by 2050 scenario published in May 2021 and updated in October 2023. Source: https://www.iea.org/reports/global-energy-and-climate-model/net-zero-emissions-by-2050-scenario-nze.

In terms of emissions caused by energy end uses (around two-thirds of CO_2 emissions), **this transition is based on an almost total phase-out of fossil fuels** (oil, natural gas and coal) by 2050. With fossil fuels continuing to meet around 80% of the world's energy needs, the different scenarios for achieving net zero rely on reducing this to 20% or less over the next three decades.

In its Net Zero by 2050 report, the IEA[7] sets out in detail **key decarbonisation pillars** leading to the phase out of fossil fuels identified to date:

- **Deployment of low-emission electricity sources** (renewable energies and nuclear reactors). This deployment would itself pursue two objectives: on the one hand, replace existing thermal generation assets (coal, lignite, gas) currently responsible for almost 40% of CO_2 emissions worldwide[8]; on the other hand, support the electrification of uses in processes/activities relying on fossil fuels. This is particularly the case in mobility (individual vehicles or even buses powered by electric batteries), buildings (heat pumps) and industry (electric heating, electric arc furnaces in steel production, etc.).

- **Development of low-carbon energy sources** (biomass), **low-carbon gases** (biogas, low-carbon hydrogen and its derivatives[9]) and **associated synthetic fuels**[10] when electrification comes up against technical constraints that are difficult to overcome (land, air and sea transportation[11], certain heavy industries currently relying on coal or natural gas as an input in the production process[12]);

- **Energy efficiency and behavioural changes** to minimise as much as possible the energy content in the global population and GDP growth expected over the next three decades;

- **Large-scale development of carbon capture, utilisation and storage** (CCUS) to mitigate the climate impact of fossil fuel use where this is unavoidable (lack of low-carbon substitutes and/or scale of sunk costs associated with fossil fuel exit, notably in respect of stranded assets with the longest residual lives);

- **Development of negative emissions technologies**, in particular bioenergies with carbon capture and storage (BECCS) to generate electricity from biomass, and direct air capture (DAC) to capture CO_2 emissions directly.

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[7] Ibid.

[8] 39.8% in 2022. Source IEA: https://www.iea.org/reports/co2-emissions-in-2022.

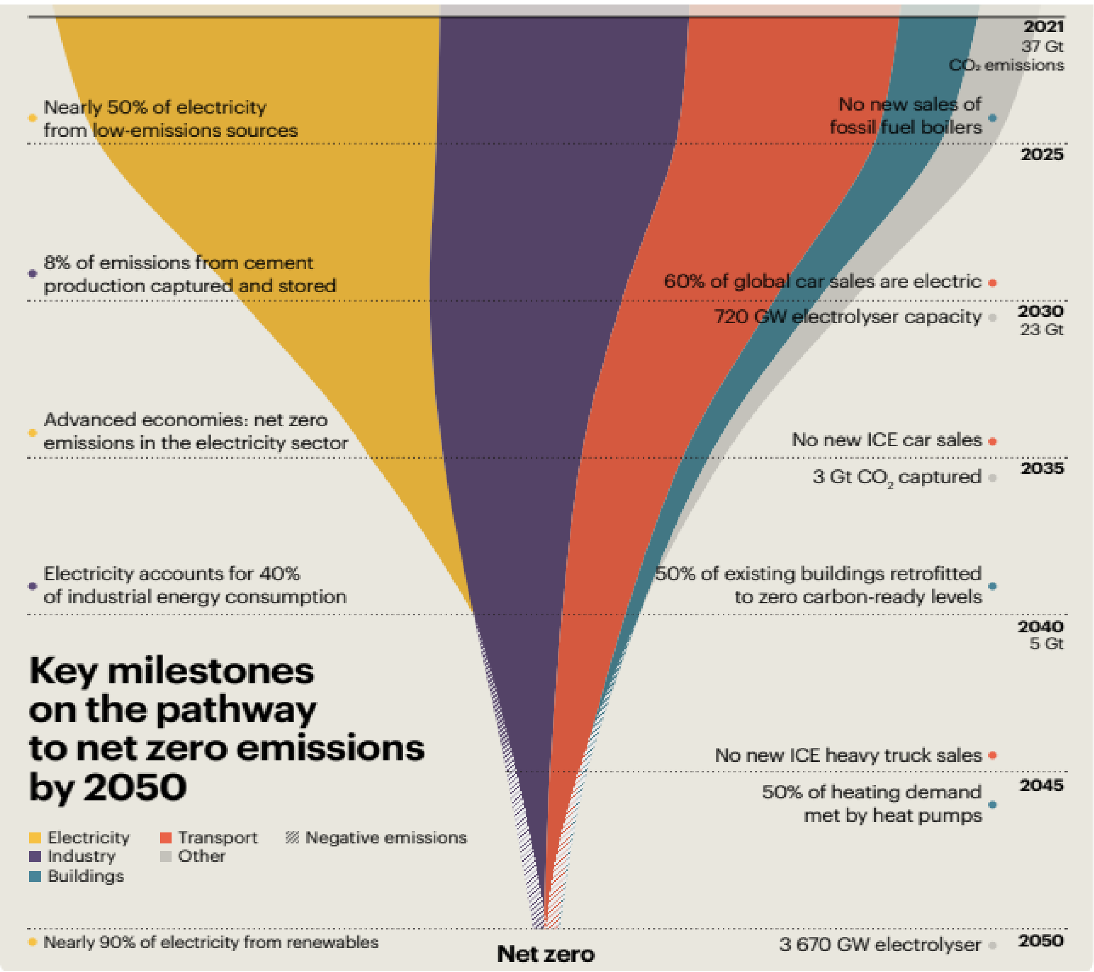
[9] Mainly ammonia.

[10] Mainly e-kerosene and e-methanol produced from the combination of low-carbon hydrogen and carbon dioxide extracted from stationary sources (thermal power plants, industrial sites).

[11] In transportation, the technical limitations of solutions based on electric batteries relate to their short driving range (which itself varies according to atmospheric conditions), charging time and the weight of the batteries relative to the means of conveyance.

[12] In the case of steel production, with the direct reduction of iron (DRI) process based on coal or natural gas. Also the case of hydrogen, which is now mainly produced using the methane reforming process, with natural gas as the main input.

IEA: Key milestones on the pathway to net zero emissions by 2050



Source: IEA (2023)

An analysis of the different pillars expected to underpin the energy transition shows not only the **scale of the electricity needs induced by this transition but also the centrality of low-carbon sources in the process of phasing out fossil fuels**. Low-carbon sources are essential for replacing fossil fuel-fired power plants and supplying electricity for new uses in the building, industry and transportation sectors. They are also essential for supporting the deployment of CO_2 capture solutions - CCUS and DAC being particularly energy-intensive processes - and for supporting the development of water electrolysis for hydrogen production. By way of illustration, the production of electrolytic hydrogen, which is currently anecdotal[13], would consume almost 20% of the world's electricity production by 2050.

In its Net Zero by 2050 scenario, the IEA estimates that **all these new uses imply that global electricity demand will increase over 2.5x by 2050**. In the next three decades, electricity demand can be expected to grow at a CAGR of 3.5%, which is considerably faster than the 2.5% CAGR from 2010 to 2020.

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[13] Renewable and low-carbon hydrogen accounted for less than 1% of global hydrogen production in 2022. Source: IEA 2023 – op. cit.

On the supply side, the replacement of existing thermal capacity and the satisfaction of new needs imply a **6.5x increase in electricity generation from low-carbon, renewable and nuclear sources between now and 2050** (see table below), representing an unprecedented acceleration in the rate at which associated capacity is commissioned.

IEA: key milestones in the annual development of low emission electricity generation by 2050

Key milestones	2022	2050
Electricity generated from low-carbon sources (TWh)	**11,281**	**76,603**
Wind and solar PV	3,416	54,679
Other renewable sources	5,183	13,752
Nuclear	**2,682**	**6,015**
Share of low-carbon sources in total electricity generated	**39%**	**100%**
Wind and solar PV	12%	71%
Other renewable sources	18%	18%
Nuclear	**9%**	**11%**
Additional annual low-carbon capacity (GW)	**344**	**1,268**
Wind	220	815
Solar PV	75	352
Nuclear	**8**	**21**
Other low-carbon sources	41	80

Source: IEA (2023)

SMRs emerging as a complement to CNRs in the development of nuclear energy worldwide

Faced with the expected increase in the need for low-carbon electricity, **the civil nuclear sector therefore has a key role to play alongside or in addition to the development of renewable energy sources**. The various energy transition scenarios (IEA, IPCC) emphasise the need, at global level, to develop existing nuclear capacity in proportions comparable to the expected growth in electricity demand, in parallel with accelerated development of wind and solar energies. The IEA estimates that, to achieve its Net Zero scenario, current nuclear capacity will have to increase by 2.2x (i.e. from 417GW in 2022 to 916GW in 2050[14]).

There is now a **broad consensus** on **the role of nuclear power in the energy transition and on the complementary role of civil nuclear power and renewable energy sources** in meeting electricity needs, mainly because:

- **Nuclear power provides constant and dispatchable energy**, as opposed to the fatal and intermittent nature of renewable energies. It should be noted in particular that **in France, the characteristics of the nuclear fleet enable a fine-tuned response to variations in electricity demand**. At the inter-seasonal level, unit shutdowns are planned in the summer, when demand is at its lowest. On a daily and intra-day basis, the design of the French nuclear fleet means that most reactors can modulate their output by up to 80% in less than thirty minutes. This

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[14] IEA (2023) op. cit.

flexibility helps to manage the intermittent nature of renewable energy generation and limits associated system costs[15].

- **Nuclear power is intrinsically less dependent on local natural conditions**, with the exception of water resources needed for the cooling circuit in the case of existing technologies[16/17]; and

- **Nuclear installations have a smaller physical footprint, which is of particular importance in densely populated countries**. By way of illustration, producing 1TWh per year requires around 60 square kilometres for onshore wind farms, 10 square kilometres for photovoltaic solar panels, but less than 0.6 square kilometre for nuclear installations[18].

This **complementary relationship** between civil nuclear power and renewable energy sources in the generation of low-carbon electricity is at play **within electricity systems, particularly in those of developed countries in the midst of decarbonisation, but also between electricity systems**. At global level, the development of nuclear power is helping to meet the challenge of land scarcity facing electricity generation in developed, highly urbanised countries/regions, while the development of renewable energies is seeking to take advantage of the abundance of these energy sources in other areas.

Given the challenges of developing and financing conventional nuclear reactors…

To meet these various challenges, **the traditional nuclear industry, based around so-called conventional nuclear reactors** (i.e. over 500MW[19]), **has elicited renewed interest** from major energy players and government authorities in recent years.

This renewed interest is illustrated in particular by the **inclusion of nuclear power in the Inflation Reduction Act (IRA)**[20]**, a major plan to support energy transition in the United States**, and, **in the case of the European Union, by its inclusion in the taxonomy** of activities making a substantial contribution to climate change adaptation[21].

As for governments, **the interest in renewing or developing ex nihilo nuclear capacity of individually significant size stems from their approach to energy planning**. In this context, by defining programmes for the deployment of conventional nuclear reactors, governments are primarily seeking to resolve a supply-demand equation that is doubly constrained in the electricity sector by the climate change issue and the operational difficulties raised by the accelerated development of renewable energy sources (see above). The development of a new fleet of large

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[15] Cf. https://www.sfen.org/rgn/france-flexibilite-nucleaire-favorise-developpement-renouvelables/#:~:text=Au%20niveau%20journalier%20et%20infra,syst%C3%A8me%20qui%20leur%20sont%20associ%C3%A9s.

[16] Regarding this point, please consult the series of studies by Natixis CIB Research on nuclear technologies, in particular 3rd generation reactors (January 2023): The future is NUclear… The future is UNclear…, Part III Gen 3: Evolution, not Revolution

[17] The dependence on water resources concerns in practice nuclear reactors located on the banks of rivers (river, river). This question does not arise for reactors installed by the sea.

[18] Encyclopédie de l'énergie (2019), https://www.encyclopedie-energie.org/dans-un-monde-neutre-en-carbone-pourra-t-on-se-passer-du-nucleaire/#:~:text=En%20termes%20d'emprise%20au,km2%20par%20du%20nucl%C3%A9aire

[19] The capacities mentioned in this study are expressed in electric capacity.

[20] Introduction of a specific nuclear production tax credit ($30bn) and federal financing mechanisms for new nuclear installations ($6bn) and the development of new technologies via the DoE's Advanced Reactor Demonstration Projects (ARDP) ($3.2bn).

[21] Regarding specifically nuclear, research, development, demonstration and deployment of innovative technologies, the construction and safe operation of new installations, the modification of existing installations for the purposes of extension, and electricity generation are included in the Taxonomy as low-carbon activities. Do no significant harm (DNSH) criteria apply to potential risks associated with the management of radioactive wastes and the dismantling of reactors. The main concessions won by the anti-nuclear lobby were that for new nuclear installations, the construction permit must be issued by 2045 by the competent authorities to be eligible, while for any modification of existing nuclear installations for the purposes of extension, this must be authorised by the competent authorities by 2040.

reactors will therefore be primarily aimed at replacing electricity generation facilities that are overwhelmingly fuelled by fossil fuels (as is the case in Poland) and renewing existing facilities (as is the case in France and the UK), while at the same time keeping pace with rising electricity demand (see above).

European Union and United Kingdom: review of existing nuclear capacity and capacity under construction or planned by 2050

Country	Current installed capacity		Construction underway		Projected capacity by 2050	
	Nb reactors	MW	Nb reactors	MW	Nb reactors	MW
Bulgaria	2	2.006	0	0	2	2,300
Croatia	N/A but Croatia co-owns Krsko power plant in Slovenia		0	0	N/A but Croatia has expressed interest in Krsko power plant extension	
Czech Republic	6	4,212	0	0	3	3,600
Finland	5	4,394	0	0	0, after the termination of the Hanhikivi 1 project with the Russia's RAOS in May 2022	
France	56	61,370	1	1,630	6, possibly 14	23, 100 (1)
Hungary	4	1,916	0	0	2	2,400
Netherlands	1	482	0	0	2	3,300 (2)
Poland	0	0			Up to 6	Approx. 10,000
Romania	2	1,300	0	0	2	1,440
Slovakia	5	2,308	1	471	1	1,200
Slovenia	1	688	0	0	1	1,100
Sweden	6	6,882	0	0	2 * 1,250 MW by 2035 / 10 reactors including SMR by 2045	
UK	9	5,883	2	3,260	8 (3)	>10,000
Total	**112**	**91,441**	**4**	**5,361**	**35**	**57,640**

(1) Total capacity of 14 EPR 2 reactors based on a unit capacity of 1,650 MW / (2) Based on maximum capacity (1,650 MW) of the projected reactors / (3) Potential start of construction of 8 reactors by 2030

Sources: World Nuclear Association, sundry, Natixis

In practice, however, this approach comes up against **the technological and financial challenges raised by the revival of civil nuclear power**.

In a June 2020 publication[22], the OECD emphasised **a number of difficulties raised by the development of new 3rd generation-type reactors which have been specifically designed to take into account experience feedback from the Chernobyl (1986) and Fukushima (2011) accidents**. The publication, which provides a global overview of recent nuclear projects completed or underway (China, Korea, the United States, Europe and Russia), highlighted **the extent of the cost overruns and delays experienced by construction projects for conventional nuclear reactors**. In the best cases (Sanmen 1 and 2 units in China), unit cost overruns have been limited to 50% ($3,154/kW vs. $2,044/kW) and delays to four years (nine years vs. five years) compared with initial budgets.

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[22] Cf. https://www.oecd-nea.org/upload/docs/application/pdf/2020-07/7530-reducing-cost-nuclear-construction.pdf.

In Europe, the various construction projects in Finland, France, the United Kingdom and Slovakia **have been plagued by particularly significant cost overruns and delays**, these projects getting underway after a total lull in new builds having lasted several years[23]. At the start of 2024, **further cost overruns** (between £5bn and £9bn in 2015 prices) **and delays** (four years) were announced for the project to build two EPRs at **Hinkley Point in the United Kingdom**[24].

Recent nuclear projects in Europe: delays and associated cost overruns

Reactor	Country	Capacity (MW)	Delay (years) (1)	Initial budget (€bn)	Final budget (€bn)	Cost overrun (€bn)
Olkiluoto 3	Finland	1,630	13	3.0 (3)	11.0	8.0
Flamanville 3	France	1,630	12	3.3 (4)	13.2	9.9
Mochovce 3	Slovakia	440	6	2.8 (5)	6.2	3.4
Mochovce 4		471	6			
Hinkley Point C (2)	UK	3,260	>6	18.0 (6)	31-34 (6)	13-16

(1) Estimated delay except for Oikiluoto 3 and Mochovce 3 / (2) Amounts in GBP / (3) Budget in euro 2005 / (4) Budget in euro 2007 / (5) Budget in euro 2009 / (6) Budget in GBP 2015

Sources: World Nuclear Association, sundry

Experience feedback from recent construction projects highlights **the difficulty, when developing conventional nuclear reactors, of achieving an adequate level of profitability**, the financial equation for new builds struggling to come to terms with two structuring parameters in the sector: the scale of the costs of the nuclear power plants and the sensitivity of total fixed costs to construction time.

Unit costs for 1,600MW EPRs that have been completed or are under construction in Europe are well over €10bn for what can still be considered as firsts-of-a-kind. At the same time, the latest update communicated by EDF in March 2024 for the six reactors planned in France between now and 2050[25] puts costs at €67.4bn. Unit costs per reactor are therefore still expected to exceed €10bn, despite probably factoring in the economies of scale and learning curve effects expected from the implementation of a nationwide construction programme. This cost update may be interpreted as evidence of the French nuclear industry's persistent difficulties in setting in motion the virtuous circle of the 1970s, 1980s and 1990s, which enabled unit construction costs to fall by 30% in constant currency values between 1975 and 2000.

Moreover, **nuclear project economics is extremely sensitive to the construction time of the reactors, through the play of interest during construction (IDCs)**, that is to say the debt charge mobilized to support the construction costs without cash-flows associated.

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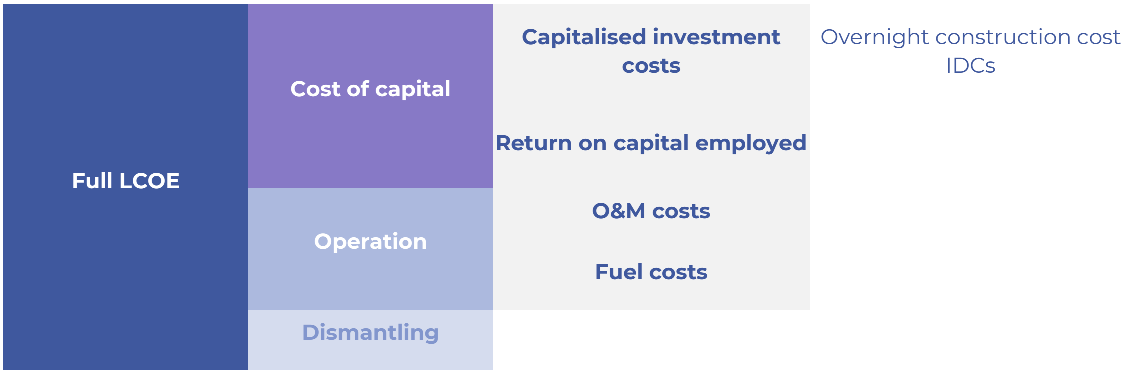
[23] France is a case in point, eight years having elapsed between the completion of Civaux 2 in 1999 and the start of work on Flamanville 3 in 2007.
[24] CF. https://www.edf.fr/sites/groupe/files/epresspack/7023/Hinkley-Point-C-PR-23012024.pdf
[25] Cf. https://www.lesechos.fr/industrie-services/energie-environnement/exclusif-nucleaire-la-facture-previsionnelle-des-futurs-epr-grimpe-de-30-2080380#:~:text=EDF%20%C3%A9value%20d%C3%A9sormais%20%C3%A0%2067,%2C7%20milliards%20d'euros.

A detailed analysis of the levelised cost of electricity (LCOE)[26] for nuclear power, i.e. expressing in €/MWh the full cost per unit of production, highlights **the importance of the cost of capital and construction time in the investment costs for nuclear construction projects** (see diagram below), in particular because of the impact of these two parameters on the amount of interim interest paid during constructions

Given the preponderantly fixed costs characterising the nuclear industry, **interest during construction alone constitutes a significant component of the total project cost**. Any delay in completing construction automatically leads to an increase in interest expenses, with a snowball effect. According to the OECD[27], **interest during construction generally represents ≥20% of total investment costs for nuclear construction projects**. The proportion does vary considerably from one region to the next, being dependent on the cost of financial resources and actual delays experienced.

Levelised cost of electricity (LCOE) for nuclear power



Source: OECD (2020)[28]

The sheer magnitude of the construction costs and the potential impact of various contingencies during the construction phase, mainly in driving up interest during construction, highlight the extreme complexity of large-scale nuclear projects. To attract private investors in sufficient numbers, these factors **imply a very specific economic and financial structuring of projects, so as to**:

- **Provide a high level of visibility on cash flows** from the electricity produced by the nuclear power plant once commissioned through mechanisms limiting price and/or volume risks[29] for production, but also
- **Limit the impact on the return on capital invested of contingencies** during the asset's lifetime (construction, operation, and decommissioning phases) that are by definition difficult to parameterise.

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[26] LCOE is the ratio of lifetime costs to lifetime electricity generation, both of which are discounted to their present value applying a discount rate that corresponds to the cost of the capital having financed the nuclear power plant. Costs include investment and operation costs over the assumed life of the nuclear power plant.

[27] Op. cit.

[28] Op. cit.

[29] See part III of this study for an analysis of these mechanisms when applied to the structuring of an SMR project.

A review of development projects for large conventional nuclear reactors shows that these issues remain, particularly in Europe, on account of the cost overruns and delays experienced by recent and current new builds (see above). Changes by the British government to the mechanics of its support for new nuclear projects provide a good illustration of the scale of these issues. Instead of the contract for difference (CfD) model chosen for Hinkley Point C, the government switched to a regulated asset base (RAB) model for the planned Sizewell C project in order to attract private investors. Under this new model, the UK government intends to remunerate the project developer/operator from the start of the construction phase, effectively eliminating the construction risk since all actual asset development costs are ultimately covered. With this model, the risk of capital expenditure overruns due to interest during construction is extinguished, insofar as the assets under construction are remunerated directly, and the construction risk is transferred to UK consumers/taxpayers. Despite these changes, there has still been no final investment decision, as both the developer/operator of the two reactors, namely EDF, and the UK government wish to limit their total share in the project special purpose vehicle to 20% each[30]. The search therefore goes on for other equity investors. In light of these factors, **the main challenge in attracting private capital seems to stem from the sheer size of the project to be financed and the scale of the investment for the players involved**. Assuming that the project will be financed 60% by debt and 40% by equity[31] and that the total construction cost will be in the middle of the currently estimated £25bn-£35bn[32] range, i.e. £30bn, to dilute the British government and EDF to 20% each would require raising £7.2bn of equity capital, so one would be looking at a particularly large round of financing and individually significant ticket sizes.

… SMRs offer key advantages compared with CNRs

Against the backdrop of rapidly growing needs for low-carbon electricity along with the multiple difficulties reviving the construction of conventional nuclear reactors (CNRs), particularly in Europe, **interest is currently emerging in another class of nuclear reactor of different size and design, small nuclear reactors (SMRs)**.

Being extremely diverse in capacity and design[33], **SMRs stand out from CNRs on three counts**:

- They are **far smaller**, with capacities typically ranging from 5MW (or less) to 500MW. Note, however, that as SMR concepts have been developed to take advantage of the modular nature of the equipment, it is possible to have installed capacities that near 1GW[34];

- **They are modular**. In broad terms, their manufacture is based on a large-scale application of the value chains found in aircraft and ship building, enabling the manufacture, in specialised plants, of 60 to 80% of a reactor's components, which will then be transported by road, rail or sea to the site of the nuclear power plant. This modularity means that economies of scale can be expected when component manufacturing processes become more industrialised, driving down the cost of these components. The modular nature of SMRs also offers the possibility of increasing their power in successive "layers" to keep up with final demand;

- **They are based on a generally simpler design from a civil engineering perspective**. For some reactor lines, the design is in fact derived from marine propulsion, particularly military (submarines), applying an integral approach that incorporate all the elements of the primary and secondary circuits in a single piece

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[30] Cf. https://www.neimagazine.com/features/featurewhen-does-new-nuclear-become-investable-10490681/
[31] Typically, the leverage ratio for electricity transmission system operators (REE, RTE, Snam, Terna).
[32] Cf. https://utilityweek.co.uk/edf-says-hinkley-point-c-could-cost-up-to-35bn/
[33] See part II of this study for a detailed presentation of the different concepts and characteristics for the SMRs under development.
[34] A case in point is the NuScale VOYGR-12 with a generating capacity of 924MW, which is powered by 12 modules of 77MW each - see below.

of equipment[35], unlike power reactors generally designed around a complex set of pipes, heat exchangers, pressurisers and pumping equipment, etc.

Because of these three ground-breaking features, **SMRs offer key advantages over conventional nuclear reactors** in operation or under construction around the world. At this stage in the development of SMRs, however, **these advantages remain largely theoretical**. The fact is that only three SMRs are in operation worldwide. Two are connected to an electricity grid in Russia and the third, a 4th generation reactor, was started up in 2021 in China[36] (see below).

Broadly speaking, the advantages of SMRs can be divided into two distinct categories: **technical and financial** advantages, on the one hand, and those linked to the **multiplicity of potential use cases**, on the other.

Technical and financial advantages: small is (almost) beautiful!

Compared with conventional nuclear reactors, SMRs present a series of key technical and financial advantages, namely:

- **More affordable… in absolute terms**. With a (much) smaller capacity than conventional nuclear reactors, in particular EPRs (1,600MW), construction costs for SMRs are inherently lower. At the same time, however, SMR concepts being at the prototype phase, this means that the cost estimates released by industry players are subject to caution. Technology developers (including those, such as NuScale, that are most advanced in the transition to commercial deployment of their concepts) have had to revise their construction cost estimates substantially upwards in recent months. These cost revisions reflect both the recent inflation in raw materials and components in a global inflationary environment, as well as changes in the design of equipment as it moves from concept to 'real life'[37]. In a report published in May 2023[38], based on disclosed estimates from developers, World Nuclear News and integrated resource plan estimates, Wood-Mackenzie concluded that first-of-a-kind SMR costs could reach between $6,000/kW and $8,000/kW, on which basis **construction costs could reach in the order of $2.4bn to $3.2bn for bigger SMRs (i.e. with a capacity of 400MW)**.

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[35] See Part II.

[36] Cf. https://www.academie-sciences.fr/pdf/rapport/221020_SMR.pdf

[37] See detailed analysis of the factors having led to the termination of the NuScale SMR project in Utah, cf. https://www.utilitydive.com/news/nuscale-uamps-project-small-modular-reactor-ramanasmr-/705717/#:~:text=The%20estimated%20costs%20of%20the,for%20UAMPS%20members%20to%20bear.

[38] Cf. https://www.woodmac.com/horizons/making-new-nuclear-power-viable-in-the-energy-transition/

These cost estimates mean that **SMRs are more affordable in absolute terms than conventional nuclear reactors, but not necessarily more competitive** in terms of unit production costs[39]. This is all the more true when estimated construction costs for SMRs are compared with construction costs for wind and solar PV. According to the latest IRENA study in August 2023[40], average construction costs were $876/kW for solar photovoltaic, $1,274/kW for onshore wind and $5,461/kW for offshore wind in 2022. Cost comparisons obviously need to be put into perspective: in the case of SMRs, it is likely construction costs will land somewhat lower (nth-of-a-kind effects and economies of scale manufacturing the components - see above); in the case of renewables, there are the challenges of integrating capacities that are intermittent by nature into the electricity systems (see above). However, these comparisons do also underline **the need for specific policy and regulatory frameworks to promote the global deployment of SMRs**. These issues are analysed in detail in part III of this study;

Comparison of construction costs for nuclear and renewable energies ($/kW)

.Capacity type	Unit cost ($/kW)
Nuclear : SMR prototypes	6,000 – 8,000
Nuclear: conventional reactors	3,200 – 10,000+
Onshore wind (1)	1.274
Offshore wind (1)	5.461
Solar PV ('utility scale') (1)	876

'(1) Weighted average of construction costs for capacities commissioned in 2022 globally

Sources: IRENA, OECD, Wood-Mackenzie

- **Reduced construction lead times and risks.** The three main characteristics of SMRs (small size, modularity and simplicity of design from a civil engineering perspective) are key levers for reducing asset development risk. For one thing, the construction phase is inherently shorter (four to six years vs. nine years in the best cases recently identified - see above) and less complex than for conventional nuclear reactors. These factors have a number of implications for the SMR business model and the industry financing schemes. In particular, they point to the development of financing methods based on assets rather than on the creditworthiness of developers/operators, as is typically the case for conventional nuclear reactors. Potential ways of financing the sector are analysed in detail in Part III;

- **Generation capacity can be sited nearer consumption centres**. With lesser core inventories and improved passive safety systems (see below), SMRs offer the prospect of a potential reduction in the emergency planning zones (EPZ) surrounding nuclear facilities, intended to allow evacuation and emergency response in the event of an accident[41]. Although it is the safety authorities that will have the final say and it would have to be socially acceptable, a reduction in the size of these zones would open up new prospects for the development of nuclear capacities. It would bring nuclear capacity closer to towns and industrial sites, offering direct outlets for the production of heat and/or electricity, and thus the prospect of decarbonising various infrastructures that are currently powered by fossil fuels. SMRs could supply heating networks (replacing coal that is still

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[39] This study does not include a comparison of SMRs, CNRs and renewable energy capacities in terms of LCOE, focusing instead on a comparison of construction costs. By construct, the determination of LCOE includes an assumption about the cost of capital, and therefore the assets' level of risk (see above). At this stage, assessing the risk of SMRs remains purely theoretical, as just three units are in service worldwide (Russia and China).

[40] Cf. https://www.irena.org/Publications/2023/Aug/Renewable-Power-Generation-Costs-in-2022

[41] EPZs for conventional nuclear reactors typically have a 15-kilometre radius, but developer NuScale estimates that its SMRs would only require a buffer zone of 40 acres (16 hectares).

predominant in northern and eastern Europe) as well as industrial sites that require heat and/or electricity (chemicals/petrochemicals, cement, steel, etc.). At the same time, **the development of SMRs in place of conventional nuclear reactors deployed to a more "systemic" end** (see above) **would require less network development** to connect the production of electricity and heat to end consumers;

- **Greater social acceptance.** In addition to their intrinsic level of safety (see below), SMRs present, due to their small size, more limited risks in the event of an accident, the environmental impact then being limited to the immediate environment[42]. They also require a smaller physical footprint than conventional nuclear reactors, particularly in terms of emergency planning zones (EPZ).

A wider range of use cases

With the ability to supply electricity and/or heat[43], their greater scalability, and the lesser challenges and constraints associated with their development (construction costs and risks, physical footprint, need for associated network infrastructure, etc.), **SMRs offer a very wide range of potential use cases**.

Broadly speaking, these can be grouped into **three main categories**:

- **"System" uses for reactors with a capacity of 200MW or over**. This may include supplying district heating networks, with SMRs replacing coal-based capacity. This use of SMRs is explicitly envisaged for district heating networks in Finland as part of a planned phase-out of coal by 2029[44]. For electricity supply, the deployment of SMRs can be envisaged to serve relatively isolated areas in lower middle-income countries[45]. SMRs are thus emerging as a solution for getting around the obstacles associated with developing networks on a national scale, as well as the economic barrier represented by the cost of conventional nuclear reactors. SMRs can also be used as substitutes for gas-fired capacity to balance the grid, accompanying the build-up in renewables in developed countries that are in the process of decarbonising their electricity supply;

- **"Decentralised" uses in a closed-circuit logic**. For these uses, SMR applications will vary according to the underlying installed capacity. Capacities in excess of 100MW will be suitable for electricity and/or heat supply to data centers, heavy industry sites (steelworks, cement works, chemical and petrochemical plants, electrolytic capacities, seawater desalination plants, etc.). Smaller capacities or even micro reactors (1MW) could meet more limited needs for electricity and/or heat, for example supplying heat to a network of units producing synthetic kerosene from biomass using the Fischer-Tropsch process, supplying electricity for CO_2 direct air capture[46], etc. In these cases, SMRs may, for already established uses, replace fossil thermal capacities;

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[42] Académie des sciences, op. cit.

[43] Co-generation system in the context of combined power and heat production by the same nuclear reactor.

[44] CF. https://world-nuclear.org/information-library/country-profiles/countries-a-f/finland.aspx

[45] Per the World Bank classification, cf. https://www.worldbank.org/en/country/mic/overview

[46] GE Vernova announced in August 2023 that it had won a tender from the US Department of Energy (DoE) to test the use of SMR to power a network of DAC units in Texas.
Cf. https://www.ge.com/news/press-releases/ge-vernova-selected-by-the-us-department-of-energy-to-lead-pre-feasibility

- **Transition from carbon intensive generation assets.** The deployment of SMRs with significant capacity (>200MW) is also being considered to replace coal-fired power plants that have already been shut down or are nearing the end of their life as part of policies to modernise and decarbonise electricity systems. The benefits of this approach are numerous: use of existing infrastructure and resources (land, access to water for cooling circuits, electrical equipment[47], steam circuit components, etc.), preservation of local workforce, insofar as the skills to operate a coal-fired power plant are, for the most part, transferable to an SMR, etc. All these factors point to savings of 15% to 35% on the cost of construction of new capacity[48], as well as shorter completion times. **Many countries around the world are thinking along these lines**, including Bulgaria, France, India, Poland, Romania, the United Kingdom and the United States. Romania is planning to develop its first SMR on the site of the Doicesti coal-fired power station. It has already signed a front-end engineering and design (FEED) contract with NuScale[49,50].

> All in all, SMRs present numerous advantages over conventional nuclear reactors, even if some, such as construction costs, need nuancing. These advantages should be analysed less in terms of potential competition between two types of capacity than in terms of emerging complementarity for the generation of electricity from nuclear energy to meet the needs arising from the worldwide phase-out of fossil fuels. **SMRs thus offer an opportunity to develop civil nuclear power as close as possible to the end uses, particularly in lower middle-income countries.**

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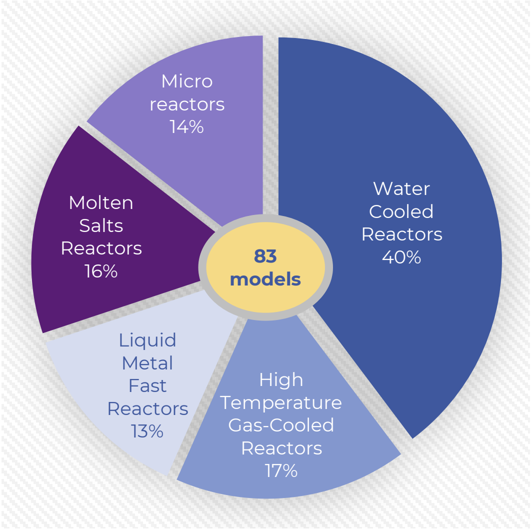
[47] Mainly substations and power lines.
[48] Cf. U.S. DOE, Investigating Benefits and Challenges of Converting Retiring Coal Plants into Nuclear Plants, 2022 H.R.5376 -117th Congress
[49] Cf. https://www.iaea.org/newscenter/news/repurposing-fossil-fuel-power-plant-sites-with-smrs-to-ease-clean-energy-transition
[50] Cf. https://www.energy.gov/ne/articles/8-things-know-about-converting-coal-plants-nuclear-power#:~:text=The%20Majority%20of%20U.S.%20Coal,host%20advanced%20nuclear%20power%20plants.

Technological overview: 83 concepts at various stages of development

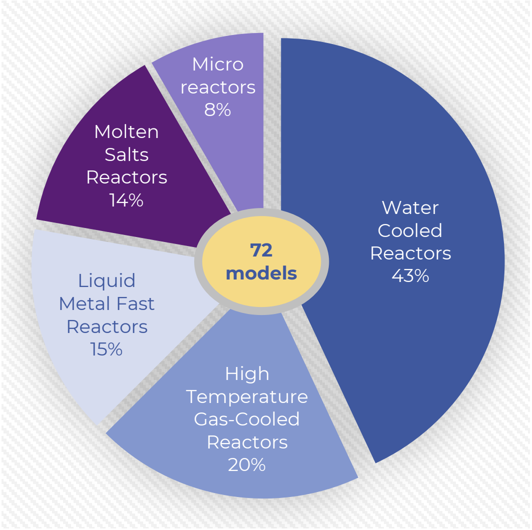
While a consensus is rapidly emerging on the usefulness of SMRs as part of the energy transition, there is still considerable technological diversity in the concepts under development. The IAEA, for example, reports the existence of 83 projects in 18 countries[51], all at different stages of maturity. This represents a 15% increase on 2020, suggesting that the time for standardisation is not yet ripe.

Technological diversity of proposed SMR designs (2022)



Sources: IAEA, Natixis

Technological diversity of proposed SMR designs (2020)



Sources: IAEA, Natixis

Detailed understanding of the various technological elements at play is a necessary preamble to any discussion on the economic viability - and therefore the financing - of the assets under consideration. Among the criteria most likely to influence future value and associated cash flows, one shall pay particular attention to:

- **The complexity of the system's architecture**. How expensive is it to test, build, operate and maintain? Does the reactor exhibit strong operational stability? Will it last for 60 years?
- **Fuel type and cycle**. What is the contemplated fuel technology? What is the required level of enrichment? Is fuel supply abundant? How often is the reactor taken offline and refilled?
- **Nominal capacity and overall efficiency**. How much energy can be produced per unit of fuel? Is the conversion from thermal to electrical energy satisfactory?
- **Potential co-generation revenues**. Can the reactor produce enough heat to support high-value industrial applications?
- **Waste management streams**. What are the expected volumes? How will the different kinds of radioactive byproducts be reprocessed or disposed of?

This section aims at to providing the reader with a preliminary basis for reflection[52].

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[51] Advances in Small Modular Reactor Technology Developments, IAEA, 2022 Edition
[52] For a deeper dive into nuclear technology topics, we refer the reader to our recent work: The Future is NUclear, the future is UNclear – Part II to V, E.Benoist, Natixis, January-February 2023.

Water-cooled SMRs: high technological readiness does not equate economic viability

According to the IAEA, 40% of the SMR designs currently under review belong to the water-cooled category. Of these, over **80% are based on conventional pressurised water reactor frameworks** (PWR), drawing on more than 5 decades of operational and regulatory experience and offering the highest degree of technological readiness.

As a reminder, the physics and mechanics underlying this type of infrastructure work as follows:

- In the reactor's core, a large fissile nucleus such as Uranium 235 absorbs a neutron and splits into lighter elements, releasing kinetic energy, gamma rays and more neutrons in the process. The latter are absorbed by other fissile atoms and trigger new fission events, eventually leading to a **chain reaction**;
- Water is used as a **moderator** (to slow down neutrons and increase the probability of fission), and a **coolant** (to carry heat away from the reactor);
- To that end, it is pumped around the core under **very high pressure** (155 bars). This keeps it liquid despite temperatures of around 300°C;
- Heat is then transferred to a lower pressure water circuit where **steam** is generated;
- Steam is used to activate a **turbine / alternator system** and generate electricity;
- A **condenser** returns water to the steam generators whilst residual heat is lost to the environment (in the form of clean vapour or warm water, depending on plant location and architecture).

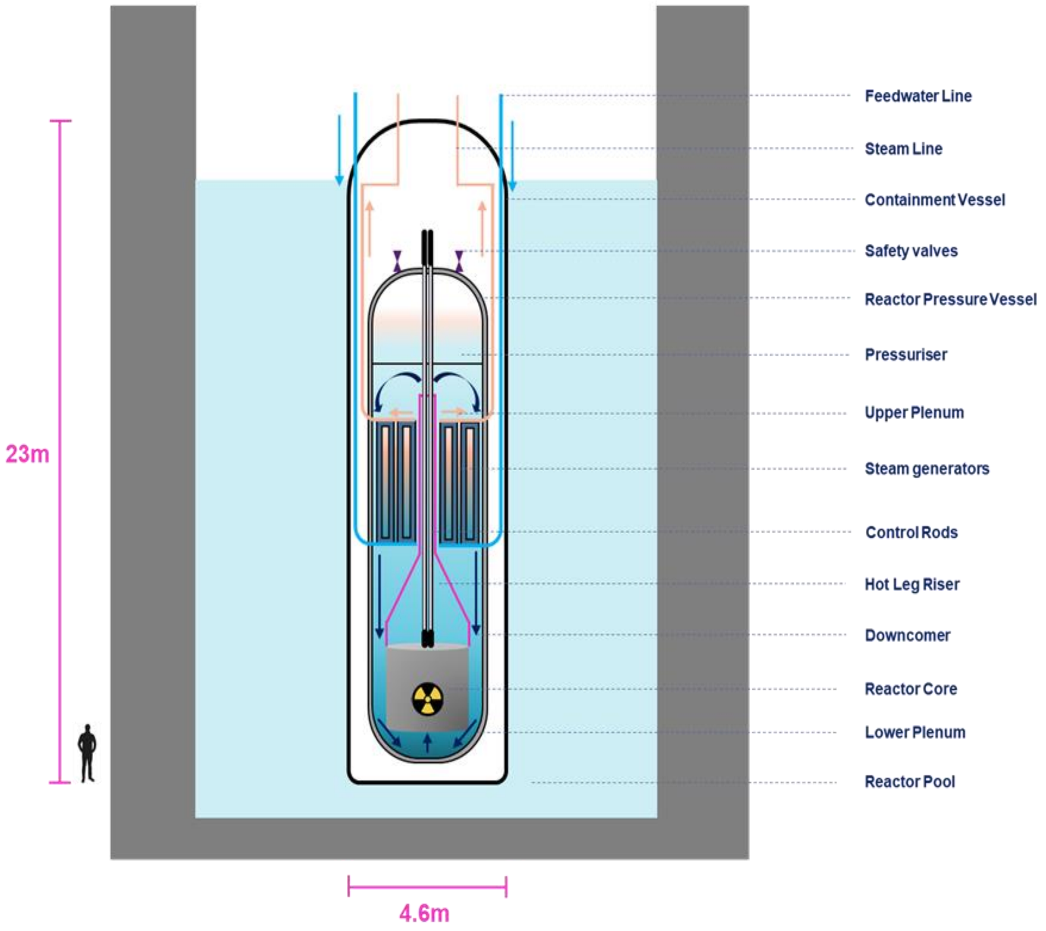
PWR technology is well understood and considered safe. It benefits from strong operational stability thanks to simple active and passive reactivity control mechanisms:

- **Active**: a higher concentration of boric acid in the water moderator leads to greater neutron absorption and fewer fission events. The insertion of control rods filled with silver, indium and cadmium can also moderate or shut down the reaction if necessary;
- **Passive**: a large negative void coefficient allows for self-regulation of the power output. If temperature rises unexpectedly in the core and water starts boiling in the primary loop, the lower density of the coolant results in a diminished ability to thermalise neutrons and therefore a decrease in the produced energy levels.

Still, **switching to SMR scale is no trivial exercise**:

- **PWR-based nuclear plants involve a complex tangle** of piping, pumps, valves and heat exchangers spread over separate cooling loops. Bringing all these elements together in a small and compact architecture requires great ingenuity;
- **Many SMR manufacturers have chosen to borrow from marine propulsion technology** (military submarine mostly) and follow an "integral" approach, incorporating most of the machinery into a single vessel;
- **The Voygr prototype developed by NuScale is an interesting example**: in this type of unit, core-heated water moves upwards through a central riser, using buoyancy and convection forces. It passes through the steam generators where it transfers its thermal energy to the feedwater line, turning it into superheated steam. As it reaches the top of the riser in a colder and therefore higher-density state, it is pulled back by gravity to the bottom of the reactor and the cycle starts again. This natural circulation phenomenon removes the need for active pumping while the smaller number of vessel penetrations reduces possible leakage points and offers enhanced resistance to loss of coolant accidents.

Simplified representation of a NuScale Integral Light Water MRS:



Source: Natixis, adapted from NuScale's documentation

- However, such configuration creates **many engineering challenges**. For instance, there are obvious risks in over-simplifying cooling systems to make them more compact and streamlined. Integral architectures incorporating a steam generator inside the main pressure vessel may also call for alternative tube geometries, such as helical coils, which exhibit different behaviours under extreme conditions of pressure, temperature and radioactivity. The list of potential issues is long: even with extensive component modelling and testing, the lack of operating experience is a concern.

The construction of nuclear reactors close to urban or industrial areas requires novel safety systems to secure regulatory approval for the reduction of emergency planning zones. To reassure authorities, many SMRs allow for extended coping times[53]. The Nuward reactor, for example, provides for the passive management of all design basis conditions scenarios without the need for any operator action, any external ultimate heat sink, any boron injection or any external electrical power supply for more than 3 days. NuScale, for its part, claims that it can provide unlimited coping time in emergency situations. Although desirable, these features can entail significant modifications to the conventional layouts, such as new safety valve arrangements or larger coolant inventories to generate greater inertia against power transients.

SMRs are expected to enable better load following to adapt to grid demand in real time and compensate for the intermittence of increasingly widespread renewable energy sources. As such, they must be capable of handling frequent power modulation between 100% and 25% of nominal capacity and rapid returns to base load whenever necessary. Sadly, nuclear reactors are complex systems that generally thrive on stable operations. For example, their minimum stable output varies during the fuel irradiation cycle and power modulations cannot exceed certain speed thresholds without stressing parts or equipment. Considerable work is needed to develop components and systems that can withstand such demanding modus operandi.

Multi-module SMRs are often designed to manage a large number of production units from a single remote-control room. This represents a significant departure from the generally accepted practice of 2 units per room. The robustness and constant availability of the software must therefore be demonstrated and protected by state-of-the-art cyber defences.

It is clear, therefore, that **building a smaller version of a traditional pressurised water reactor does not necessarily mean obtaining an operating license more quickly**. In January 2023, NuScale became the first SMR company to obtain NRC certification for one of its PWR designs. The process took six years and involved multiple technical revisions to address the regulator's safety concerns. When the company announced its intention to increase power from 50 to 77 MWe, new approvals were required, further delaying the commercial launch. In November 2023, after numerous budget overruns, the manufacturer’s flagship project in Idaho was cancelled because too few customers signed up to receive its power amid rising costs. The company's setbacks suggest that building an economically viable FOAK[54] remains a challenge, even on a smaller scale and within the confines of a proven technology. But there are also more structural physical limitations that can weaken the long-term prospects of a water-cooled SMR infrastructure project beyond the construction of the first few units.

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[53] Coping time: the period of time between the onset of an accident and the moment when human intervention is required to avoid serious repercussions…

[54] FOAK: first of a kind reactor.

Only a small portion of the thermal energy produced is converted to electricity (typically between 29% and 34% depending on models). Taking a closer look, the thermal efficiency of the turbine block is proportional to the ratio of output vs. input heat in the system. Carnot's theorem allows us to calculate its theoretical upper limit:

$$n = 1 - \frac{T_{output\ (cold)}}{T_{input\ (hot)}}$$

Where:

n = *thermal efficiency of the turbine*
Toutput = *Temperature at the condenser level (in Kelvins)*
Tinput = *Temperature at the steam generator level (in Kelvins)*

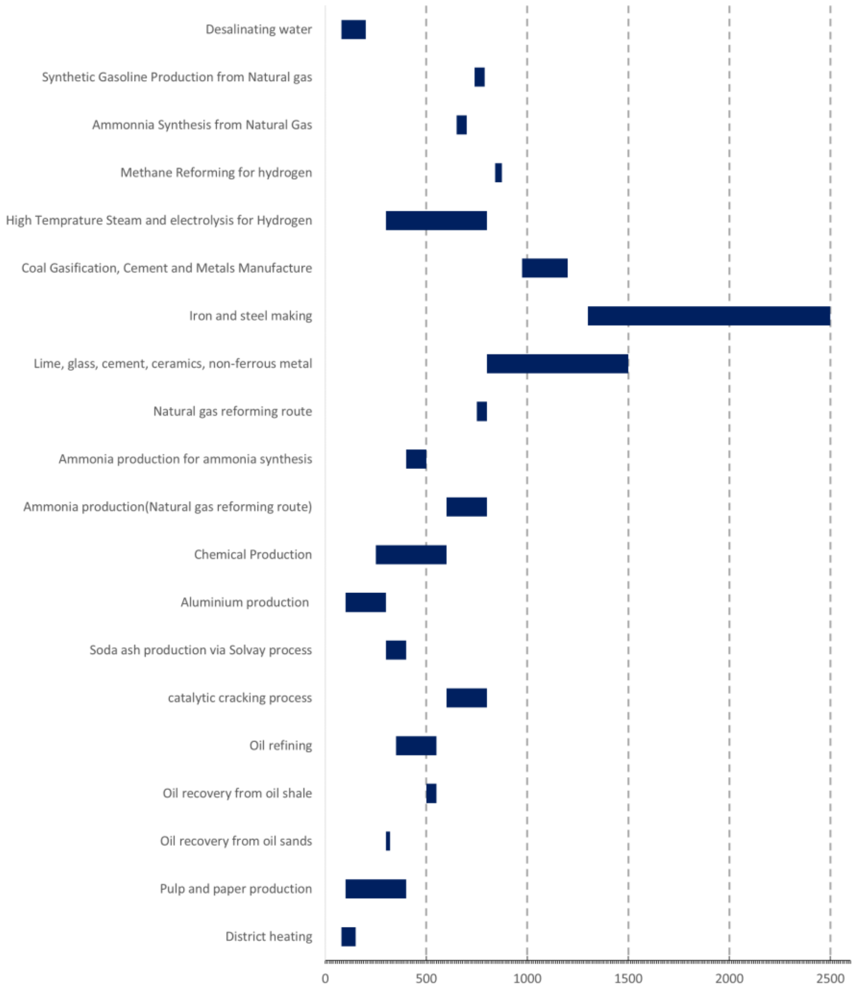
To increase efficiency, **condenser temperature must decrease, or steam generator temperature must rise**. Unfortunately:

- **Condenser temperature is constrained** by the natural temperature of the cooling fluid employed (water from a reservoir or ambient air in the case of dry cooling) and does not offer much room for maneuver…
- **Steam generator temperature is constrained** by the physical limitations of the reactor itself and by the need to protect fuel integrity.

All things considered, beyond the optimisation currently underway, **the thermal efficiency of water-cooled SMRs is likely to remain underwhelming,** which will affect their long-term competitiveness.

To some extent, thermal efficiency problems could be offset by the extraction of more systematic co-generation profits (heat + electricity). However, **the relatively low output temperature of PWR structures (300°C) prevents them from fully supporting high value heat-intensive industrial applications** beyond district heating and desalination projects.

Temperature required for different industrial processes.



Sources: various, Natixis

Finally, it is **hard to ignore the question of waste management** when considering new nuclear power facilities. Most conventional PWRs run on low-enriched-uranium (less than 5% enrichment) and generate an average burn-up discharge[55] of 50 to 65 GWd/tU. Their SMR equivalents tend to exhibit lower efficiency (on average, between 30 and 45 GWd/tU), largely due to weaker neutronics and greater neutron leakage as a result of smaller core dimensions. This has **three direct consequences**:

- **A low burn-up is normally associated with a shorter fuel cycle.** In other words, the reactor must be taken off-line every 18 to 24 months for a partial refill, which can last several weeks and lowers the availability of the equipment over its useful life span;

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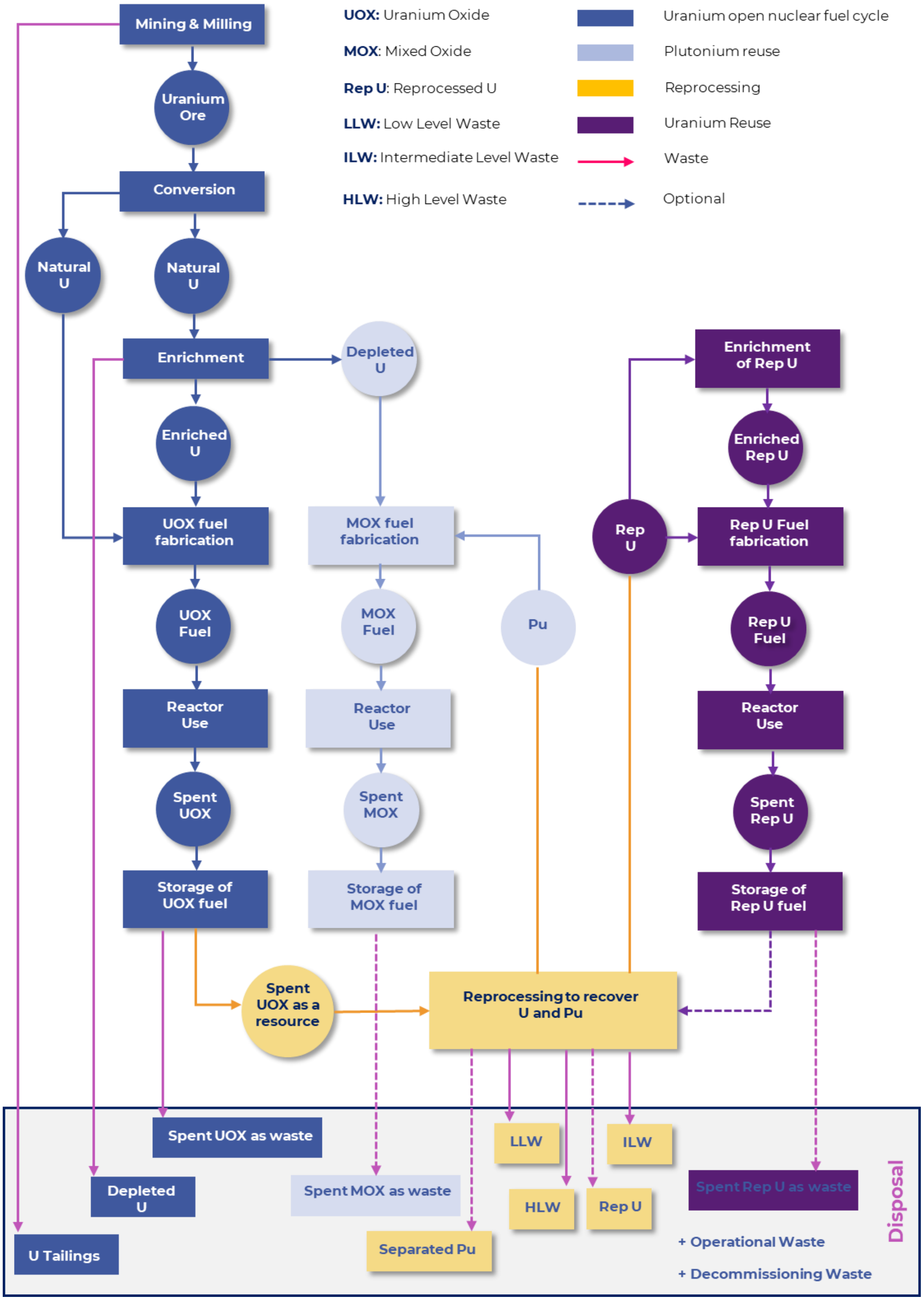
[55] Burn-up refers to the quantity of energy that can be extracted from a specific amount of fuel. For nuclear reactors, it is measured in GWd/tU (Gigawatt-days per metric ton of uranium).

- **SMRs of the PWR type will generate a significant amount of plutonium**, unburnt fissile materials, and radioactive waste. By way of illustration, on average, for conventional reactors, 95% of spent fuel is uranium that can be re-enriched and reused. 1% is plutonium that can be incorporated into MOX. 4% is non-recoverable waste (mostly fission products and minor actinides) and requires vitrification, conditioning in stainless steel containers and storage;

Schematics of wastes and materials likely to be generated at different stages of the nuclear fuel cycle in a pressurized water reactor



Source : AIEA[56]

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[56] Cf. https://www.iaea.org/publications/14739/status-and-trends-in-spent-fuel-and-radioactive-waste-management

- **The earlier-mentioned neutron leakage issue** – although not specific to light water technologies – **may also cause greater activation of the materials around the core**. Stanford academics[57] estimated in 2022 that SMRs would produce at least 9 times more neutron-activated steel than their conventional peers. Significant additional costs may therefore be incurred for the adequate management of all associated waste streams and decommissioning.

Unsurprisingly, the physical limitations described above have led many industry players to turn to more innovative fourth-generation technologies, which offer compelling solutions to the problems raised, both from a technical and cost-efficiency angle, albeit with a lower level of technological readiness.

4th generation SMRs: revolutionary, but far from mature...

Unsurprisingly, the physical limitations described above have led many industry players to turn to **more innovative 4th generation technologies**, which offer convincing solutions to the issues raised, both technically and economically, but with a lower level of technological maturity.

High Temperature Gas Cooled Reactors

Among 4th generation models, **High Temperature Gas-cooled Reactors** (HTGRs) **are often considered the most mature**. For instance, China started commercial operation of its first HTR-PM power plant unit in December 2021, while other companies such as Jimmy (France), X Energy (USA) or General Atomics (USA) are making rapid progress on their respective roadmaps.

HTGRs are graphite-moderated, helium-cooled reactors designed to tolerate outlet temperatures of between 750°C and 1,000°C, for improved thermal efficiency in the range of 35% to 53% and greater compatibility with high-temperature process heat applications.

They differ from second generation gas-cooled reactors in their fuel technology (TRISO) and the configuration of their core compartment. TRISO stands for TRi-structural ISOtropic particle fuel. Each particle is made of a kernel containing Uranium Oxide (UO2) or Uranium Oxycarbides (UCO) surrounded by four layers of carbon and ceramic materials preventing the release of radioactive fission products. TRISO particles have been engineered to withstand temperatures of 1600°C without cracking or melting. They are also more resistant to neutron irradiation, corrosion, and oxidation. Finally, they provide greater safety and protection against illicit diversions for weapons purposes. They can be encapsulated in compact cylinders, themselves inserted in the channels of graphite prismatic blocks inside the core…or embedded inside graphite spheres the size of a tennis ball called “pebbles” and piled inside the reactor vessel as part of a continuous refueling process.

HTGRs’ main challenges are still largely related to the manufacture of high quality TRISO particles. The number of suppliers is limited, and the multi-stage manufacturing process requires a high degree of precision to deliver particles to the correct specifications. This has sometimes prompted reactor manufacturers to set up their own TRISO production lines in order to better control the supply chain (X Energy, Kairos…). While this solution offers a degree of security, the development costs are high.

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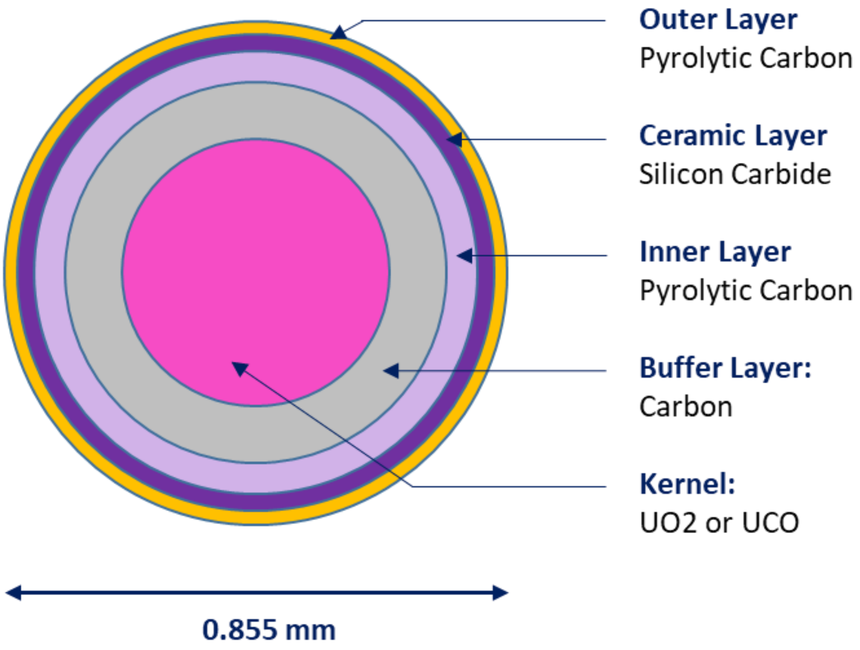
[57] Nuclear waste from small modular reactors, Krall et al, May 2022.

HTGRs also run on HALEU fuel, which is currently not commercially available anywhere…except in Russia. As a result, the Americans are racing to develop their own production capabilities, with Centrus Energy now operating a pilot scheme and looking to secure funding for a capacity of 6,000 kilograms per year by 2027. Fabrication costs will be higher than for conventional LEU, and with an estimated demand of 40,000 kilograms by the end of this decade for the US only, prices are likely to be well supported.

Internal structure of a TRISO fuel particle



Source: Natixis

Finally, **the disposal of TRISO pebbles adds a layer of complexity** as spent fuels need to be extracted from their graphite containers before being chemically dissolved. The volumes of radioactive waste may be large and demand sizeable reprocessing facilities.

Liquid Metal-cooled Fast Neutron Reactors

Arguably, **Fast Neutron Reactors** (FNRs) **come next on the scale of technological readiness although** past experience in the conventional domain has not always been conclusive: the Superphénix program in France is understood to have cost around $10bn before being shut down in 1997, while the Monju plant in Japan incurred similar levels of expenditure before meeting the same fate. The BN-600 (600 MWe) and BN-800 (880 MWe) in Russia are the only large demonstrators in operation today. In the SMR category, Russia is also building a 300 MWe prototype (the BREST-OD-300) while other manufacturers such as Newcleo (Italy) or Westinghouse (USA) are in the early design phase.

FNRs – sometimes called fast-spectrum reactor – are nuclear reactors in which **the fission chain reaction is sustained by fast (high energy) neutrons** as opposed to slow (thermalised) neutrons.

FNRs do not require a moderator (water, heavy water, graphite, etc.) to produce fission energy. To some extent, this simplifies their architecture, as systems related to moderator management are removed and the size of the core can be reduced.

One of the main differences with earlier generation reactors lies in the **type of coolant used**: usually liquid metals. Sodium and Lead are the most common materials employed: they are weak neutron absorbers and have excellent thermodynamic characteristics allowing them to perform at very high temperatures without the need for pressurisation. This is both a source of safety vs. standard PWR models and an enhancing factor of thermal efficiency (range of 36 to 47%). It also widens the scope of potential process heat applications.

Beyond these considerations, it is actually the **ability to entertain a closed fuel cycle and limit the complexity of high-level waste management that is truly revolutionary**. Indeed, fast neutron physics exhibits unique properties:

- **More neutrons are emitted after fission**, which serves to maintain the chain reaction while allowing more fissile material to be produced than is consumed through the conversion of fertile material placed in and around the core in a "blanket" - a technique known as 'breeding'.

  Fast breeders are therefore capable of producing their own fuel: fertile uranium-238 can be turned into fissile plutonium-239 and recycled into MOX for further usage in the reactor. Other cycles are possible too: for instance, fissile uranium-233 can be bred directly from fertile thorium-232 (limiting in this case the risks related to the proliferation of weapon-usable plutonium).

  The conversion ratio[58] of a conventional light water reactor is 60%. In contrast, fast neutron reactors can be engineered to have conversion ratios well above the 100% mark (for example, the Phénix sodium-cooled prototype operated in France between 1973 and 2009 achieved 116%...);

- In an increasingly environmentally conscious world, however, **fast-spectrum reactors can play another fundamental role**. While the probability of capture of a fast neutron is considerably lower than that of a thermal neutron, **the probability of fission after capture is much higher** for the full range of actinides produced in the reactor (as shown in the table below).

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[58] The conversion ratio is the ratio of new fissile atoms produced to fissile atoms consumed.

Probability of fission after capture by range of actinides from the reactor

Isotope	Fission Probability (Thermal Neutrons)	Fission Probability (Fast Neutrons)
Thorium-232	Not Fissile	Not Fissile
Uranium-232	59%	95%
Uranium-233	89%	93%
Uranium-235	81%	80%
Uranium-238	Not Fissile	11%
Neptunium-237	Not Fissile	27%
Plutonium-238	7%	70%
Plutonium-239	63%	85%
Plutonium-240	Not Fissile	55%
Plutonium-241	75%	87%
Plutonium-242	Not Fissile	53%
Americium-241	Not Fissile	21%
Americium-242m	75%	94%
Americium-243	Not Fissile	23%
Curium-242	Not Fissile	10%
Curium-243	78%	94%
Curium-244	Not Fissile	33%

Source: Wikipedia

This suggests that after prolonged exposure to a high-energy neutron flux, the most radioactive elements in the core are “burnt” and split into more manageable and less radiotoxic fission products with a much shorter half-life.

Instead of being used to breed more fissile content, FNRs can be converted into high-performance burners. Stockpiles of high-level waste are thus minimised, relieving pressure on future deep-underground repositories and reducing the operational costs usually associated with waste management streams.

Despite decades of R&D, **FNRs are still faced with a long list of technological hurdles**:

- Like HTGRs, **they require fuels with a high fissile content**, such as 20% enriched uranium or MOX to compensate for the lower probability of interaction with high energy neutrons in the core. The **supply chain issues** raised earlier therefore also apply to this category of reactors.

- Sodium reacts vigorously with water to produce sodium hydroxide and hydrogen which can burn and cause potential explosions, creating **major safety concerns**. In fact, many occurrences of sodium fire have been reported at past or existing FNR facilities.

- Meanwhile, lead has a melting point of 327°C, which requires pre-heating of the primary circuit before start-up and constant temperature monitoring during operation to avoid coolant solidification. The **material is opaque and does not facilitate inspection**. It is very dense and increases the weight of the equipment and its seismic vulnerability. It is also known to cause serious corrosion at higher temperature.

Molten Salt Reactors

Last but not least, **molten-salt reactors** (MSRs) have the **lowest level of technological readiness** but **promise unrivalled design flexibility and cost effectiveness**.

Although only two such reactors were ever built (at the Oak Ridge National Laboratory in Tennessee) and abandoned in the late 1960s due to technical difficulties deemed insurmountable by the political elite of the time, **a growing number of privately funded startup companies seem intent on revisiting the concept** and have already launched preliminary discussions with their regulator. These include Terrestrial Energy (Canada), Moltex (Canada), Thorizon (Netherlands), Kairos Power (USA) and Seaborg Technologies (Denmark).

Moving away from solid fuel technologies, they are **based on a framework where fissile material is dissolved in a liquid hot salt solution that can be used simultaneously as a fuel** (to generate heat) **and as a coolant** (to transfer heat away from the reactor). They can operate in thermal or fast spectrum, burner or breeder mode and use a wide range of fuels, including plutonium-239, uranium-235, or uranium-233 derived from fertile thorium-232.

We list some of their **most attractive characteristics** below:

- Molten salts have v**ery good thermal conductivity and volumetric heat capacity**, two essential properties of high-quality coolants. They are chemically stable at high temperature (no problematic interaction with air or water) and remain liquid over a wide temperature spectrum. This results in high thermal efficiencies in the region of 40% to 45%. Moreover, these high temperatures are achieved without pressurisation, which improves safety conditions and removes the need for large containment structures;

- Even at high temperature, molten salts produce **very low vapour pressure**, which allows for smaller (and cheaper) pipe sizes, tanks and associated equipment in the primary and secondary loops;

- Molten salts enjoy **low viscosity** and therefore have a high capacity to flow around internal circuits even with smaller pumping or heat exchanger equipment;

- The density of fluoride salt is roughly twice that of water and decreases linearly with temperature. This allows for **smaller core sizes and provides a passive safety advantage** as fuel materials expand when temperature rises, and fewer fission reactions subsequently occur in the core;

- Some neutron-absorbing fission products such as Xenon or Krypton are poorly soluble in fluoride salts. They are easily separated from the fuel and removed from the stream. This ensures **optimal fuel burnup conditions and reduces decay heat after shutdown**;

- In some cases, spent salts can be reprocessed on site to separate more fission products from actinides and return fissile materials to the core until they are burnt. This **continuous refuelling process minimises waste, yields higher fuel efficiency and lengthens fuel life** to between 4 and 7 years, increasing reactor availability;

- Incidentally, molten salts can also be **used to temporarily store heat** from a reactor, providing added capacity at peak time and enhanced grid flexibility.

However, scientists and engineers still need to find ways around **major difficulties** before these designs can realistically enter a commercial phase:

- Some of the chemical compounds used in the salt mixtures are highly toxic. For instance, exposure to 4mg/m^3 of Beryllium is immediately dangerous to life and health. **Additional safety measures may be necessary** when handling the material;

- The circulation of fuel in the primary circuit poses a **problem of contamination of equipment** such as pumps or heat exchangers and greatly complicates maintenance, which must be envisaged in remote mode only, using robotic tools;

- At high temperature, under intense irradiation, **molten salts cause acute corrosion problems and extremely resistant materials must be developed** to avoid repeat system failure. To date, the Hastelloy N alloy[59] developed by the Oak Ridge National Laboratory is a good candidate but is not robust enough to withstand many years of operation. Until more satisfactory solutions are found, MSRs are unlikely to operate very reliably over long periods of time;

- Finally, **we still do not know how the spent liquid fuel will ultimately be disposed** of once it can no longer be reprocessed. During the life of a MSR, fuel salts may have to be discarded several times due to changes in their physical properties (neutron efficiency, fissile solubility, viscosity, excessive melting point rise, etc.). There is no consensus yet as to when and how this type of liquid waste will be discarded and stored. Building specialised equipment and facilities will likely prove costly.

> Perhaps somewhat counter-intuitively, from a purely technological point of view, **the most mature 3rd generation SMRs are not the ones that will provide the cheapest electricity in the long term**. It is therefore not surprising to see the emergence of a dynamic ecosystem of privately funded innovators seeking to accelerate the development of 4th generation prototypes, with the aim of resolving once and for all the nagging issues of low efficiency and radiotoxic waste production. In most cases, however, **large scale commercial deployment of these revolutionary solutions will not come for another decade, and access to stable funding will continue to decide who lives to fight another day**.

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[59] Hastelloy N is composed of: nickel: 71 wt%, molybdenum: 16 wt%, chromium: 7 wt%, iron: 5 wt%

Main SMR families – summary of the main technico-economic parameters

SMR	PWR	HTGR	LMFR	MSR
System Complexity	Complex tangle of pipes, valves, boron injectors, heat exchangers and high pressure equipment.	Unconventional configuration of core compartment	No moderator. No pressurisers.	No pressuriser. No large containment structure. Smaller pumping, pipes, tanks and equipment.
Operational Stability	High (5 decades of operational experience)	High (despite some challenges linked to the flammability of the graphite moderator, and no negative void coefficient)	Low (particularly in the case of liquid sodium coolants)	Very Low (acute corrosion problems, equipment contamination risks)
Fuel	LEU 14-30 month refueling cycle	HALEU / TRISO Online (pebbles) or up to 360 month refueling cycle	HALEU / MOX 4-20 years refuelling cycle	Flexible / LIQUID SALT MIXTURE Continuous, online, up to 20 years refuelling cycle
Thermal efficiency	29-35%	35-53%	36-47%	40-45%
Process Heat Compatibility	Low	Very High	High	High, with added possibility of storage
Waste generation	High volumes. Conventional reprocessing and disposal.	High volumes. Additional complexity due to TRISO particles.	Ability to burn problematic actinides in the core	Online batch processing is possible, but lots of questions regarding the disposal of spent liquid salts.
Technological Readiness	++	+	-	- -
Long Term Economic Potential	-	+	++	++

Sources: AIEA, various, Natixis

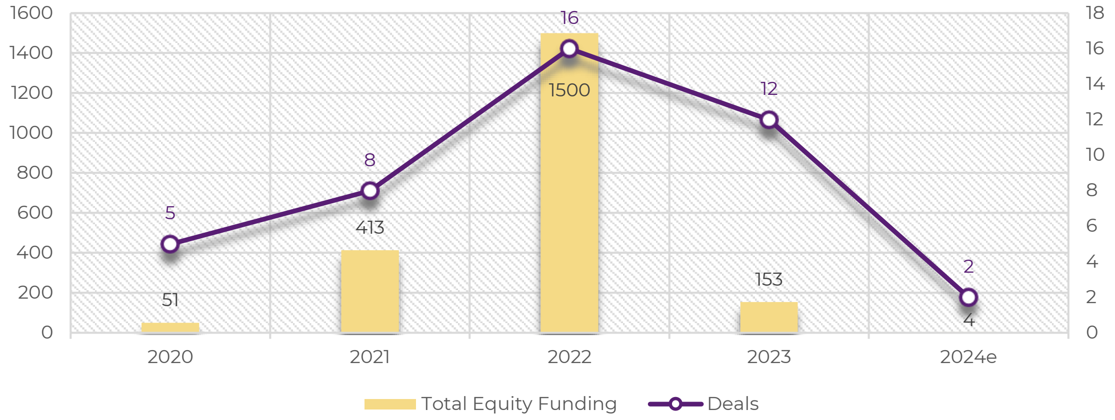
Financing the SMR sector: from pure equity play today to asset-based financing tomorrow?

For the main stakeholders in the sector (technology developers, governments, potential users), the challenges in terms of financing are twofold: on the one hand, over the next five to ten years, resources are needed to bring the various concepts to maturity until their commercial rollout; on the other hand, in parallel with financing the technologies, the introduction of asset-based financing needs to be encouraged to replicate as far as possible the conditions that helped drive down costs over the last 15 years for renewable energy (i.e. wind and solar photovoltaics).

Technology developers are still largely reliant on private equity funding and government support policies

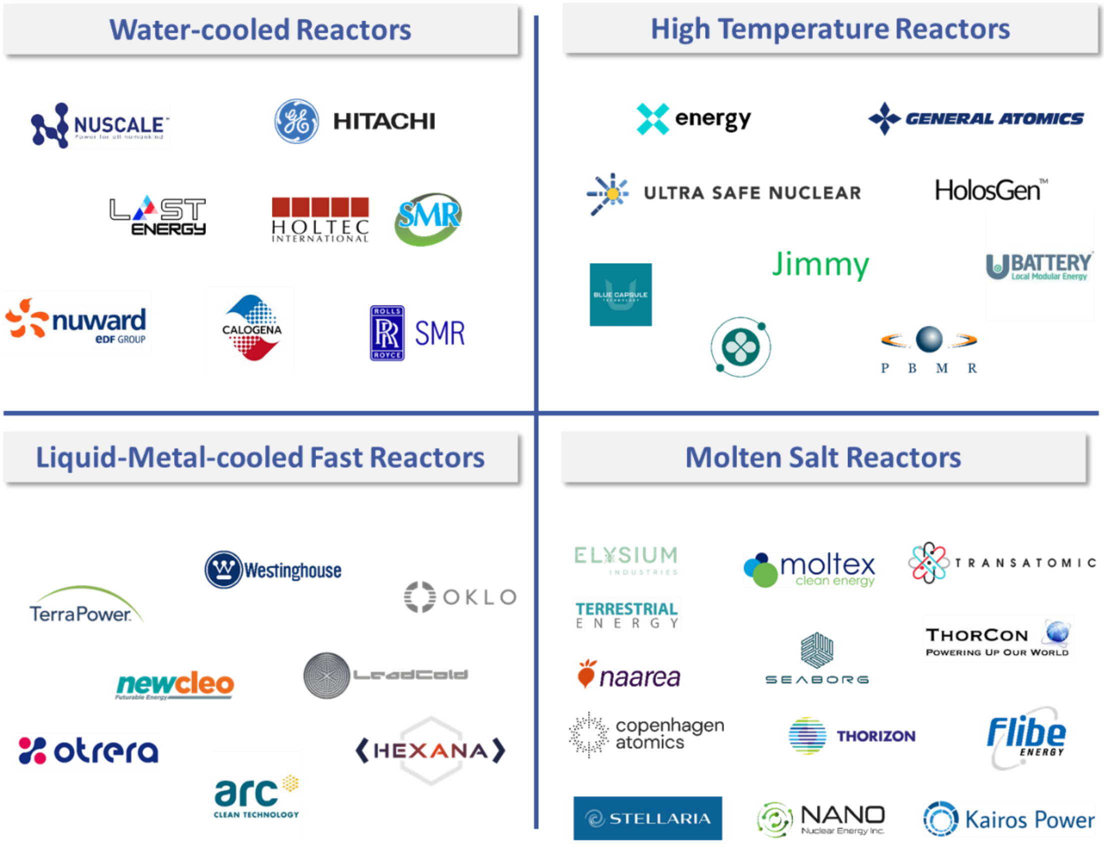
While large conventional nuclear facilities generally remain the preserve of the state, SMRs are able to attract a broader range of technology developers, from multinational conglomerates to VC-funded startups. Since 2020, more than $2.1 billion of private equity capital has been invested worldwide in the SMR startup ecosystem (ex-nuclear fusion). These young, innovative companies are not afraid to take risks, and often choose to focus on the challenges of the 4th generation in order to bring clean, abundant and inexpensive energy to market.

SMR (excluding nuclear fusion): total equity financing activities since 2020 ($m)



Sources: CB Insights, Natixis

Mapping of major SMR manufacturers by type of technology – ex nuclear fusion



Sources: companies, Natixis

To date, **TerraPower**, which was founded by Bill Gates in 2008 and is developing a sodium-cooled fast-spectrum reactor with an integrated molten-salt energy storage system **has topped the fund-raising league tables with more than $930m secured over 7 rounds**. It is planning to start building its first Natrium power plant at a site in Wyoming in June 2024, with a view to bring it online by 2030. The facility will be taking over part of the infrastructure of a retiring coal-fired plant to simplify construction.

In Europe, **Newcleo**, which was founded in 2021, managed to raise a total of $434m over two rounds from the Agnelli family and other Italian investors. It is now planning to deliver a series of lead-cooled fast neutron reactors in France (2030, 30 MWe) and the UK (2032, 200 MWe) and to open a MOX production line to close its fuel cycle completely.

Elsewhere, companies like **Nuscale**, or **X-Energy** experimented with SPACs[60] early on:

- In May 2022, the former began trading on the New York Stock Exchange, having merged with Spring Valley Acquisition Corp for a combined valuation of $1.9bn. It raised $380m in the process, which it then used to accelerate the development of its pressurised water SMR technology (with mixed success, as noted in the previous section);

- The latter announced its own SPAC merger with Ares Acquisition Corp in December 2022 with a pre-money valuation of $2bn and a potential $1bn windfall for the combined entity. 9 months later, valuation fell to $1.05bn and in October 2023, the deal was abandoned due to “persistently volatile market conditions”. Instead, in December 2023, the manufacturer of high-temperature pebble bed reactors opted to finalise its Series C with a more frugal $80m from Ares;

- These setbacks did not discourage Oklo, which in July 2023 joined forces with Sam Altman's SPAC AltC Acquisition Corp, for a pre-money valuation of $850m and up to $500mn of fresh capital. The transaction is still scheduled to take place in 2024 and the company’s first liquid metal-cooled microreactors are expected to go online by 2027.

It would take a very long time to go through the details of all the recent financing rounds in the sector. Suffice it to say that, despite the wide variety of underlying systems and power generation approaches proposed, most deals have in common the fact that investors, public and private, are essentially buying a long-term equity story.

Unfortunately, equity stories are subject to capricious market conditions, evolving macro-economic contexts and risk-averse phases of dwindling liquidity. As the graph on page 33 shows, **2023 proved to be much more challenging from a fundraising perspective than 2022 and 2021**. For listed companies, short selling pressure and continuous analyst scrutiny can also create difficult situations: between August 2022 and February 2024, the Nuscale share lost nearly 90% of its value, making it much more complicated to raise additional capital without severely diluting existing shareholders…

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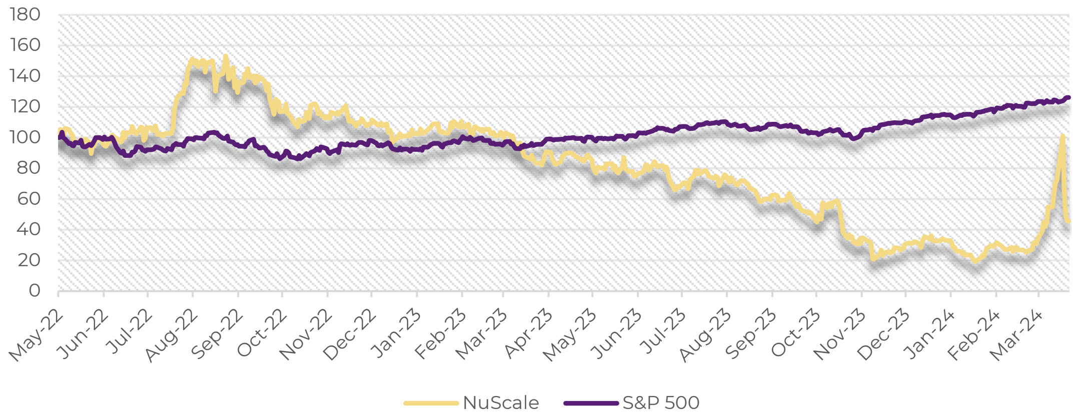
[60] Special purpose acquisition company: a shell company without an underlying operating business at the time of its initial public offering, whose shares are issued on a stock market with a view to making an acquisition or completing an initial business combination in a specific sector of the economy before a predetermined date.

NuScale: stock performance since deSPAC vs. S&P 500



Sources: Bloomberg, Natixis. March 22, 2024. Past performance does not prejudge future performance

Meanwhile, cash reserves tend to shrink rapidly, and public partnerships are often necessary to stabilise business prospects and reassure stakeholders.

Given the strategic nature of the underlying assets, **policy makers are generally supportive of the ecosystem**:

In the US, the **2021 Infrastructure Investment and Jobs Act and 2022 Inflation Reduction Act have provided the funding for several important DoE initiatives** through the Office of Nuclear Energy:

- **The Advanced Reactor Development Program**, for instance, supports 10 US companies in the development of clean nuclear energy. Most notably, it is allocating $2.5bn to two demonstrator projects (TerraPower's Natrium and X-Energy's Xe-100) with a goal to bring them online within 5 to 7 years;

- **The HALEU availability program** has received $700mn to secure a domestic supply of high-assay low-enriched uranium and reduce dependence on Russia for 4th generation reactor designs;

- **Tax credits** of up to 30% of the initial capital cost (Investment Tax Credit) or up to $25 per MWh produced (Production Tax Credit) will be granted to eligible companies working on clean electricity technologies;

- **The DoE's Loan Programs Office** has also been expanded and now has $400bn of low-cost debt capital to allocate to large scale energy infrastructure projects that retool, repower, repurpose or replace existing or legacy infrastructure, or enable operating energy infrastructure to avoid, reduce, utilise or sequester air pollutants or greenhouse gas emissions. Furthermore, it can provide guarantees to lower the cost of commercial bank loans.

In Europe, political division currently prevents the implementation of an EU-wide advanced nuclear program. Indeed, a group of 13 pro-nuclear countries led by France opposes a group of 13 pro-renewable countries led by Germany and Austria, creating tensions and disagreements over funding priorities. That said, in February 2024, the European Commission launched an **Industry Alliance for Small Modular Reactors**, targeting a wide range of SMR stakeholders including vendors, utilities, specialised nuclear companies, financial institutions, research organisations, training centres and civil society organisations to reinforce the nuclear supply chain in Europe and strengthen EU cooperation. It remains to be seen whether this initiative can quickly lead to concrete measures to support the nuclear revival effort in the region. In the meantime, member states are likely to pursue their own independent strategies. As the European Commission's financial arm, the European Investment Bank (EIB) has sent out conflicting signals on SMRs of late, although its new President, Nadia Calviño, recently declared that she had "no objection in principle to stepping up the financing of nuclear activities"[61]. Pending clarification of an EU framework that would be favourable to nuclear new builds in general and SMRs in particular, Member States will probably pursue their own strategies.

France, for example, **intends to devote €1bn to the development of its own SMR champions**, as part of the France 2030 program, of which €500m for the EDF Nuward project. It has also selected 11 additional startups to lead the charge. These companies will receive financial support of €129.8m, coupled with additional technical support from the CEA (the French Alternative Energies and Atomic Energy Commissions).

France: details of the funds allocated to SMR technology developers under France 2030 (€m)

Company	France 2030 Funding (€m)	Technology
Jimmy	32.0	High temperature gas-cooled reactor
Newcleo	14.9	Fast neutron reactor with lead coolant
Otrera Energy	11.0	Sodium-cooled fast reactor
Naarea	10.0	Fast neutron reactor with molten salt coolant
Hexana	10.0	Sodium-cooled fast reactor
Renaissance Fusion	10.0	Stellarator nuclear fusion
Stellaria	10.0	Fast spectrum molten salt reactor (liquid fuel and cooling)
Thorizon	10.0	Fast spectrum molten salt reactor (liquid fuel and cooling)
Blue Capsule Technology	9.1	High temperature sodium cooled Reactor
GenF / Taranis	7.8	Nuclear fusion by inertial confinement
Calogena	5.2	Pressurised water reactor

Source: Sifted, Natixis.

Post-Brexit UK does not want to be left behind: in its 2020 10-Point Plan for a Green Industrial Revolution, it announces the creation of a £385mn Advanced Nuclear Fund, with up to £215m earmarked for SMRs. It also commits up to £170m for a R&D program on Advanced Modular Reactors. In January 2024, the government added a £300m investment in a proprietary HALEU fuel programme, the first of its kind in Europe. Finally, Great British Nuclear (the body responsible for implementing the government's long-term vision of generating up to 24 GW of nuclear power in the country by 2050) is currently running a beauty contest between six shortlisted companies (EDF, GE Hitachi, Holtec, NuScale, Rolls Royce and Westinghouse), to

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[61] Cf. https://www.euractiv.fr/section/energie-climat/news/le-financement-de-grands-projets-nucleaires-par-la-bei-devra-encore-attendre/

establish which will best deliver operational SMRs by the mid-2030s. The winners are due to be announced in spring 2024, with official contracts awarded shortly thereafter.

In 2018, **Canada presented its SMR Roadmap** after a 10-month consultation with various stakeholders, including the Ministry of Energy and Natural Resources, the provinces and territories, industry, utilities and others. It was followed in 2020 by an official Action Plan for the development, demonstration and deployment of SMRs at home and abroad. In 2021, the province of Ontario announced a partnership with GE-Hitachi to build an initial 300 MW SMR in Darlington (the BWRX-300, a pressurised water design), which was subsequently expanded to 4 reactors for a total capacity of 1.2 GW. In 2022, the state-owned Canada Infrastructure Bank committed $970m to the project's preparation phase. In 2023, the government launched the Enabling SMR Program with $29.6m over 4 years to help develop supply chains for SMR manufacturing, strengthen fuel supply security and fund research on safe SMR waste management solutions in the country. The first Canadian SMRs are expected to go online by 2029 with several provinces outside of Ontario now showing interest to build their own SMR capabilities.

> Altogether**, the major OECD nuclear powers are determined to provide, to varying degrees of financial participation, the necessary support for the SMR** industry to accomplish its mission in a more stable environment. However, the inertia and administrative burden attached to public funding processes can also prove detrimental and call **for alternative funding approaches to be explored.**

Characteristics of SMRs point to the emergence of asset-based financing arrangements

Among the factors that could potentially determine the success of the various SMR concepts are the actual conditions under which they will be deployed, first and foremost **funding**.

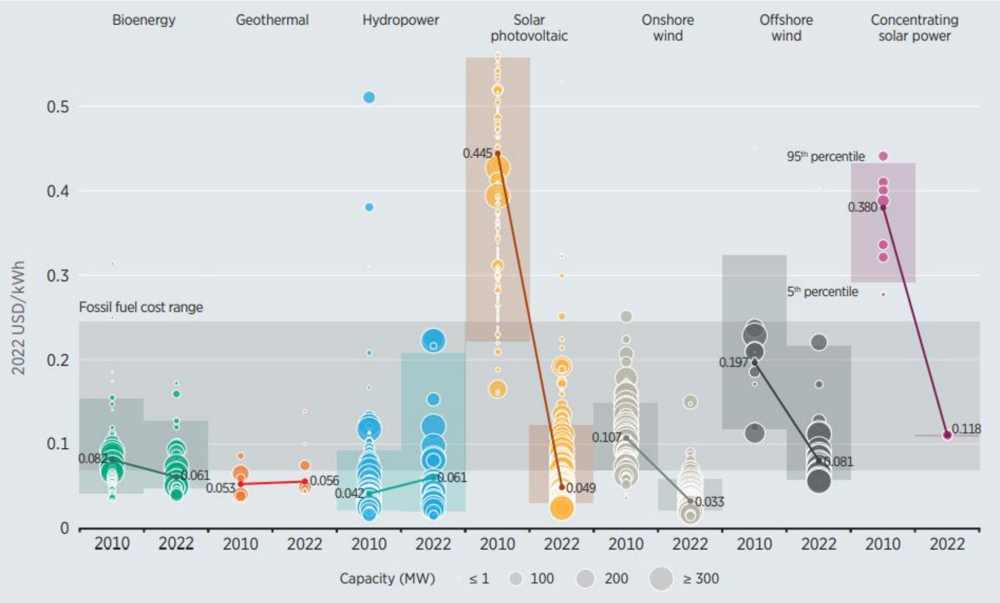
Marking a paradigm shift from conventional nuclear reactors in terms of the size, manufacture and design of nuclear generation equipment, **the emergence of SMRs could be accompanied by a paradigm shift in their financing, with potential recourse to asset-based solutions** (non-recourse debt, leasing) by opposition to the balance sheet of the developers/operators.

From an industrial standpoint, this is of crucial importance. **The possible deployment of asset-based financing could play a key role in bringing about a maturing of the industry**, particularly the industrialisation of component manufacturing through a proliferation of investments and increased competition between equipment suppliers, but also between project developers, and even between potential providers of capital[62].

Role of asset-based financing in the development of renewable energies

In this respect, the recent development of renewable energies around the world highlights **the substantial role played by the availability of asset-based financing in bringing about a massive fall in LCOE** (see above) **for all renewable technologies**. The case of solar PV is particularly emblematic, with an 89% fall in LCOE (2022 $/kWh) over the period 2010 to 2022[63].

Renewable energies: change in LCOE for utility-scale renewable power technologies, 2010-2022 ($/MWh)



Source: IRENA

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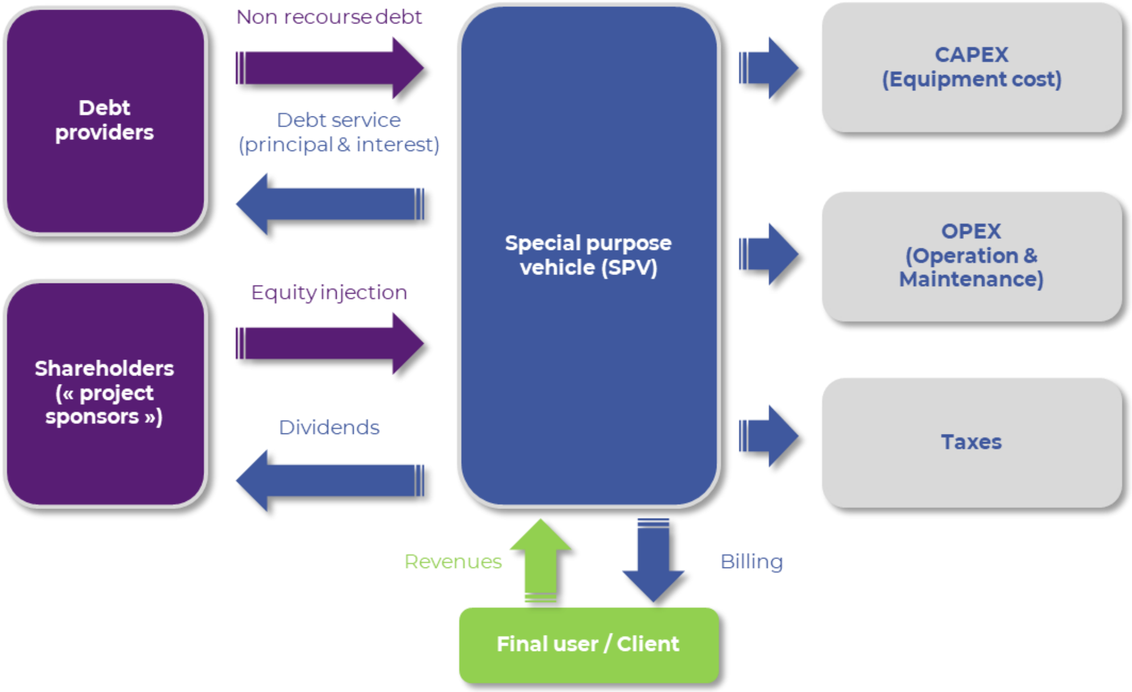
[62] This study does not address the other types of financing that should gradually emerge to support the development of the sector: fuel financing, financing of the industrial tool underlying the manufacture of SMR components, etc.

[63] IRENA, op. cit.

The **systematic recourse**, in the early 2000s, **to support mechanisms to encourage electricity generation from renewable energy sources** (in the form of price guarantees[64] and/or volume guarantees[65]) **led to the development and then widespread adoption of asset-based financing**. Broadly speaking, this type of project financing involves ad hoc legal structures bearing the risk associated with the development and operation of the assets, rather than the balance sheet of the private companies acting as project sponsors. For creditors, these schemes offer little or no recourse against the sponsors[66], unlike corporate financing, in which creditors can potentially pursue their claim against the other assets on the borrower's balance sheet in the event of default. In the case of project financing, the risk associated with the asset is therefore both ring-fenced and limited (compared with the risk to which the borrower is exposed in the case of general purpose corporate debt).

Renewable energies: non-recourse asset-based financing



Source: Natixis

In parallel, with the maturing of onshore wind and solar photovoltaic technologies, **commercial banks have been able to offer leasing finance solutions to project developers**, enabling them to avoid large upfront cash-outs to acquire the equipment. In the case of lease financing, commercial banks purchase the equipment directly from the manufacturers and lease it back to the project developers under leasing agreements, generally for periods of three to seven years. At the end of the

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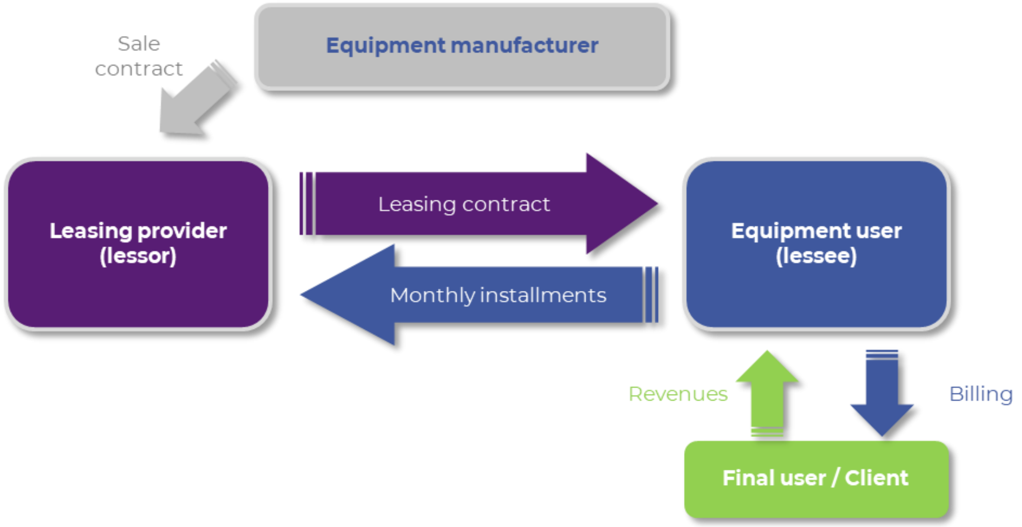
[64] **Price guarantee mechanisms can be feed-in tariffs (FiT)** agreed to by the public authorities over the entire lifetime of the asset, or **feed-in premiums (FiP)** ensuring a minimum price for renewable electricity supplied to the grid, whatever the wholesale price. In the second case, the FiP accompanies the ramp-up in the supply of electricity from renewable energy sources as it applies to direct sales of renewable electricity on the wholesale market. **A variant of the FiP is the contract for difference (CfD)** in which, once again, the operator sells its production directly on the wholesale market and is offered a guaranteed price (strike price). If the strike price is lower than the wholesale price, the operator must repay the difference. Otherwise, the operator receives the difference.

[65] There are generally two types of volume guarantee mechanisms: one is systematic, in the form of priority injection into the grid, thereby addressing the physical constraint linked to the intermittent nature of renewable sources; the other, used in the United States and the United Kingdom in the early 2000s, is in the form of green certificates, obliging electricity suppliers to secure part of their electricity from renewable producers.

[66] The potentially most favourable recourse available to creditors in the one afforded by step-in rights, which are analysed below.

lease term, the equipment is returned to the lessor, unless the lessee exercises the purchase option[67].

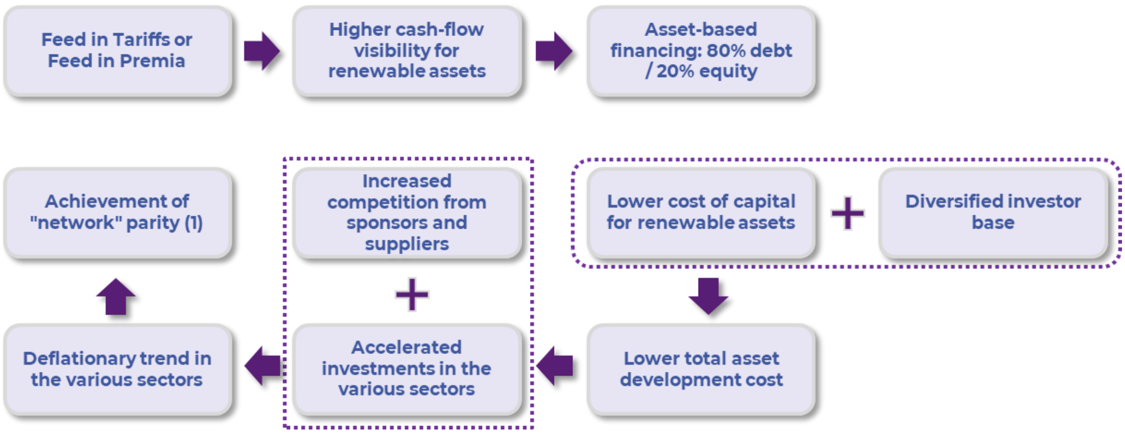
Renewable energies: asset lease financing



Source: Natixis

For the main renewable technologies, **these different financing solutions have become widespread** with, for project-type financing, up to 90% of assets being financed in this way. Widespread recourse to project financing has meant that, **for developers, the size of their balance sheet no longer constrains the potential volume of assets to be deployed**, this being dependent rather on operating conditions[68] and the guarantees offered by the public authorities. Combined with historically favourable financing conditions over the period 2009 to 2022, this decoupling has encouraged a **profusion of projects to an extent such as to fuel a deflationary movement** for the different renewable technologies.

Renewables: key factors driving price competitiveness for wind and solar technologies



(1) in certain cases

Source: Natixis

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[67] For additional insight, see BPCE Lease, Industrial equipment assets: leasing contracts at the core of the economic recovery

[68] Generation capacity of the assets.

Given their characteristics, SMRs would lend themselves to asset-based financing

One of the advantages offered by SMRs is precisely that it would be conceivable to develop **financing solutions** for this sector of the nuclear power industry **based on the cash flows generated by the assets**, solutions which until now have been **virtually non-existent for conventional nuclear reactors**[69].

From the capital providers' standpoint, **arranging project financing in the form of asset-based lending has traditionally come up against hurdles of five types**[70]:

- **Size of nuclear power plants and associated construction costs** (see above). The scale of budgeted construction costs and the length of time reactors will be in operation (40 or even 50 or 60 years) moreover require extensive coverage of risks that could affect cash flows, in the form of price and/or volume guarantee mechanisms (see above);
- **Lengthy construction times**. There results from this that a fair amount of time elapses between raising the capital required, on the one hand, and the actual commissioning of the installation, when the first financial flows are generated to repay creditors (debt servicing) and remunerate shareholders (dividends), on the other. In this respect, the scale of the construction projects means that capital providers have to project themselves far ahead in time compared with other electricity generation technologies. By way of comparison, while it takes nine years in a best-case scenario to build a conventional nuclear reactor today (see above), it only takes two to three years to build a combined cycle gas turbine. For conventional nuclear reactors, as indicated above, the already lengthy construction time is coupled with a risk of cost overruns and delays, the effect of which is to inflate the level of capitalised fixed costs to an extent that potentially invalidates initial assumptions about the return on capital invested (see above);
- **Significant political and regulatory risks** (change in the role of nuclear power in the energy policy of the country concerned[71], changes in the organisation of the market and/or in the pricing of electricity produced from nuclear energy) **arising from the life of the assets**;
- **Practical difficulties in implementing effective risk sharing**, particularly of risks associated with the reactors' operation. In the case of equipment suppliers, the magnitude of the potential liabilities associated with this type of risk has led to a limitation of the guarantees, whose durations generally do not cover the life of the assets (see above);;
- **Difficulties arranging step-in rights**, when these are generally incorporated into project-type financing and enable creditors, in the event of difficulties in the construction or operation of the asset, to take effective control of the special purpose vehicle. Difficulties are of a legal and/or practical nature: the obligation to hold a licence to operate a nuclear power plant, specific expertise associated with

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[69] The only example to date of non-recourse financing for a nuclear power plant is the Barakah project (cumulative capacity of 4,200MW) in the United Arab Emirates. However, the non-recourse debt raised on this occasion covered a very limited proportion of the total cost of the project: $250m provided by National Bank of Abu Dhabi, First Gulf Bank, HSBC and Standard Chartered, out of a total of $24.4bn in capital raised. Source: https://www.enec.gov.ae/about-us/overview/barakah-one-company/

[70] Cf. https://www.thebanker.com/Removing-the-nuclear-power-project-financing-hurdles-1504252839

[71] A case in point is Germany. Following the accident at the Fukushima-Daiichi nuclear power plant in March 2011, the federal government unilaterally called into question the agreement signed a few months earlier, in September 2010, with the country's nuclear power plant operators. This agreement provided for the extension of the lifespan of reactors commissioned after 1980. The accident in Japan led the federal government to immediately shut down the reactors commissioned before 1980 and to cancel the decision to extend the lifespan of those commissioned after that date.

the ownership and operation of nuclear reactors, exposure to potentially significant liabilities in the event of an accident (see below), etc.;

- **Significant decommissioning costs, including for the long-term management of nuclear waste**, which requires setting up balance sheet provisions and diverting cash flows to fund these liabilities[72] that could otherwise have been applied to remunerate capital employed.

It is the combination of these issues that explains why **the corporate model has emerged as the default financing solution** in the civil nuclear industry. In contrast to project financing, this model relies on the developer/operator's ability to raise equity and, above all, debt based on its creditworthiness to develop its asset base. By way of illustration, in Western Europe, at the height of the development of major civil nuclear programmes (i.e. in the 1970s and 1980s), **their financing was based on**:

- **The credit quality of electricity utilities,** itself supported by a highly regulated sector organisation (existence of vertically integrated monopolies) and reinforced by an implicit sovereign guarantee, the main electricity companies being majority-owned by their reference government[73];

- **Guarantee mechanisms/financing solutions** provided by export credit agencies (ECAs) for the reactors; or even

- In some instances, **guarantee mechanisms** for the debt of a utility provided by its reference State so as to encourage the raising of quasi-sovereign debt[74].

In contrast, because of their characteristics, **SMRs** would lend themselves more readily to the development of asset-based financing:

- **Lower costs and shorter construction times**;

- A civil engineering design that **intrinsically reduces the risk of cost overruns and delays** during construction phase;

- **Their size limits the scale of potential risks** (accident, radioactive leak) that lending banks will not want to take on as part of non-recourse financing.

  All in all, the combination of these factors **means that the economics of SMR projects are less sensitive to financing conditions** (cost of capital) **and construction conditions** (construction time) affecting interest during construction (see above). Ultimately, this **helps to reduce the financial risk associated with this type of asset** and to improve the financing terms compared with those that could be obtained for conventional nuclear reactors.

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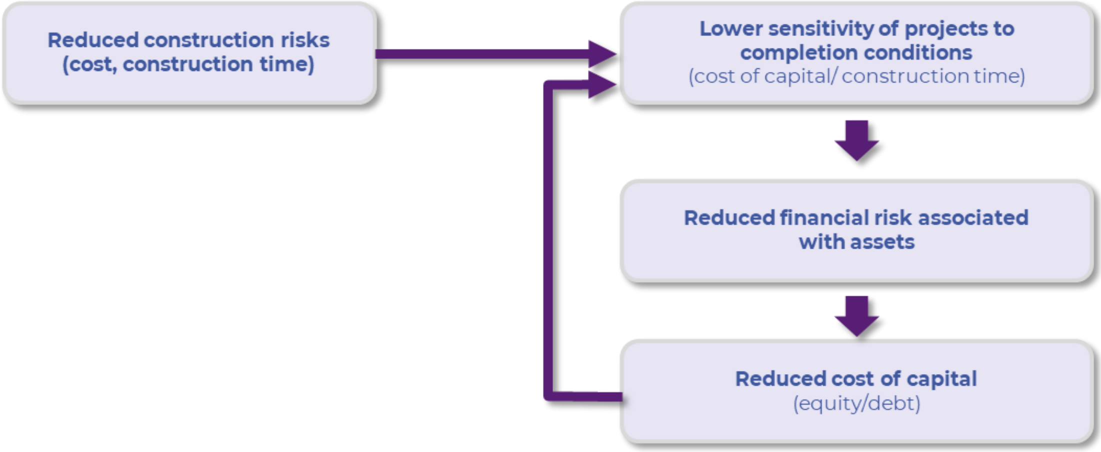
[72] Top-up of dedicated asset funds to generate cash flow to cover reactor decommissioning and long-term waste management costs as they arise.

[73] The case for all electricity utilities in Western Europe, with the exception of those in Germany and Belgium where a model involving the federal states or local authorities became the norm.

[74] The Banker, op. cit.

SMR vs. CNR construction risks: economic and financial implications



Source: Natixis

Use cases that favour project financing

In addition, the wide range of use cases for SMRs within specific operational frameworks (see above) opens up the **possibility of supplying electricity and/or heat production under long-term contracts to private or public entities**. Insofar as they offer price and/or volume guarantees for this production, long-term supply agreements can be a key element in encouraging asset-based financing of SMR projects. This financing would then take the form of project financing similar to that used in renewable energies, probably tweaked to take account of risk factors specific to SMRs (see below).

As commercial banks will not normally consider arranging non-recourse debt below certain minima (typically €100m)[75], **asset-based financing could be envisaged for a single SMR or groups of SMRs with a total capacity of at least 15MW**.

Long-term contracts for the supply of electricity and/or heat would be conceivable in the case of:

- **"System" uses**, via regulated tariffs or CfDs (see above) concluded with the public authorities to supply a given area. Prices for the electricity and/or heat would then be set in such a way as to enable the SMR operator to recover investment, operation and dismantling costs, within a mutualised framework, i.e. borne as a "system cost" by all the electricity consumers in the area concerned;

- **"Decentralised" uses**, which could be for a private customer (industrial) or public customer (as in the case of the potential deployment of SMRs to supply DAC units at the behest of government - see above). These uses would be governed by private law contracts as applicable to power purchase agreements (PPA) at price levels that would, once again, cover all project lifetime costs. Unlike the system uses described above, these decentralised uses are intended to develop as a closed circuit, raising specific financial issues, which are analysed below.

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[75] Threshold generally applied by commercial banks (corporate and investment banks - CIBs) in order to generate a sufficient margin on project financing, taking into account (i) the cost of access to financial resources (borrowed on the interbank market) and (ii) overhead costs. It should be noted, however, that local banks have much lower intervention thresholds than CIBs for setting up non-recourse financing. Depending on their appetite for "nuclear" risk, they would therefore be able to provide this type of financing for individually small SMRs (< 15 MW).

Series of milestones will have to be passed to favour adoption of asset-based financing

However, for the various SMR concepts under development, **recourse to asset-based financing promises to be a long and winding road**. Attracting private capital secured on project assets requires two main sets of conditions to be met: political and regulatory, on the one hand, and technological and financial, on the other.

At government level: a general framework favourable to the sector

The development of SMRs and, even more so, the development of asset-based financing cannot be achieved without a **sector-friendly public framework**, which would:

- **Mitigate the general legal and political risk**. The risk of asset stranding associated with any change in the political or regulatory framework modifying the conditions for developing and/or operating SMRs must be explicitly covered. This can be achieved by including change of law clauses in contracts binding the SMR project developer and a public entity[76] (see above).

  Along these lines, it is **conceivable that public guarantees could also be given to cover the implications of a change in the law** during the performance of contracts with private entities[77].

  The **other key element to be considered** by governments to reduce the risk associated with the operation of future SMRs **is the appropriate calibration of nuclear civil liability** (NCL) covering possible accidents (radioactive contamination) and compensation for the resulting victims. When it comes to insurance, governments have it in their power to reduce the risk borne by reactor operators, since it is governments who lay down, in certain cases in line with the provisions of the applicable international treaties, the conditions for the application of NCL in the event of an accident: (i) establishing the exclusive liability of the operator of a nuclear installation; (ii) determining any reduced-risk installations, (iii) limitation of liability in amount, i.e. per nuclear installation and per accident, (iv) limitation of liability in time and of the categories of nuclear damage opening entitlement to compensation, etc.[78] Since NCL must be insured, governments can intervene to limit both the extent of the theoretical risk borne by the operator of the nuclear installation and the cost of the insurance taken out to cover this liability;
- **Recognise and quantify the specific climate benefits of SMRs through carbon pricing mechanisms**. In industry, SMRs are intended to replace carbon-intensive electricity and/or heat generation. However, at least initially, the deployment of SMRs will have to overcome cost-competitiveness issues (significant fixed costs, not fully developed technologies and low industrialisation of component manufacturing at this stage). In the absence of specific carbon mechanisms, these issues combine to make the electricity and/or heat generated by SMRs more expensive than that generated by fossil fuels[79]. Implementing mechanisms that set a price per tonne of CO_2 emitted or avoided offers a lever for reducing this additional cost and therefore improving the competitiveness of SMRs supplying electricity and/or heat to industrial users. One of these mechanisms is the development of a market in carbon emission allowances, such as the Emissions Trading Scheme (ETS) operated by the European Union since 2005. In practice, the

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[76] Case of a contract for the sale of electricity and/or heat under a systemic framework (CfD, regulated tariff). This type of guarantee was provided by the British government as part of the negotiations with EDF regarding the terms of the CfD for Hinkley Point C.

[77] For example in the case of a PPA with an industrial buyer.

[78] Cf. https://www.sfen.org/rgn/responsabilite-civile-nucleaire-entree-en-vigueur-des-conventions-de-paris-et-de-bruxelles-18-ans-apres-leur-adoption/

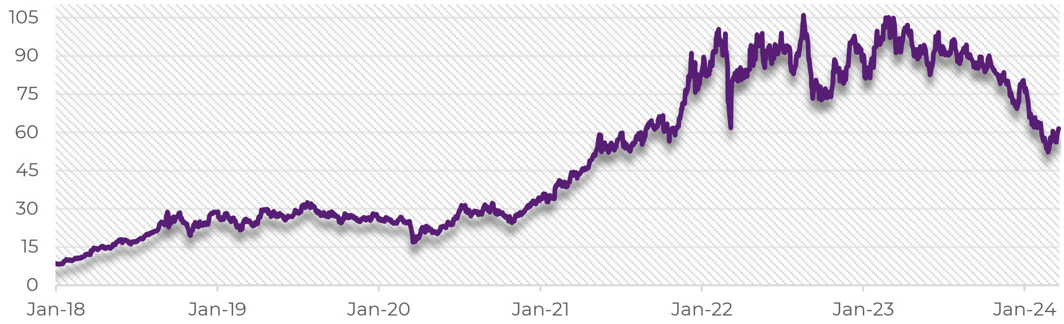
[79] No comparison provided between SMR and renewable technologies in an industrial setting as operations essentially require a supply of electricity and/or heat that is both constant (equivalent to base load consumption) and controllable.

EU ETS is a cap-and-trade system. The public authorities set a cap on emissions, revised each year to reflect specific climate objectives. They allocate emission allowances free of charge and/or auction off these allowances to the operators of the installations concerned, leaving the operators to trade these allowances on the market as they see fit. Operators unable to cover their actual emissions will buy emission allowances from operators with spare allowances.

The steady strengthening of the EU ETS over the past decade has resulted in the **gradual introduction of carbon regulations that favour the development of SMRs for the various case uses in industry**. In particular, changes made have included: (i) the systematic auctioning of emission allowances in the electricity sector since 2013, (ii) the scheduled phase out of free allowance allocations in the steel, aluminium, cement, chemicals, petrochemicals industries between 2026 and 2035, in parallel with (iii) the phased introduction of a **carbon border adjustment mechanism** (CBAM) for electricity and the aforementioned industries between 2026 and 2035, so as to put European and non-EU manufacturers on an equal footing in terms of carbon constraints.

It should be noted that, while only direct carbon emissions are concerned at this stage, the mechanism **could be revised to include indirect emissions**, i.e. take into account emissions from the generation of purchased electricity consumed by the industrial activities concerned. Such a development would strengthen the potential role of SMRs in the European market supplying electricity-intensive activities: steel, aluminium, chemicals, etc.[80]

Change in EU carbon allowance price since 2018 (2024 forward price, €/ton CO_2)



Source: Bloomberg

Mitigate main risk during construction and operation at project level

At project level, attracting capital providers will depend on satisfying a series of **key conditions for reducing the risk associated with conditions affecting the construction and operation of SMRs**:

- **Successful completion of the prototype phase**. Given the uncertainties associated with the actual construction costs of the first SMRs (see above), capital providers will probably wait for the successful development of the first-of-a-kind for the most advanced concepts (to have assurances that costs and deadlines will be met) before considering implicitly assuming a construction risk as part of project-type financing;

- **Ascertaining specific credit risk associated with a decentralised deployment of SMRs**. The conclusion of a bilateral PPA accompanying the development of SMRs

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[80] Source: https://www.europarl.europa.eu/news/fr/press-room/20221212IPR64509/climat-accord-sur-un-nouvel-instrument-de-lutte-contre-les-fuites-de-carbone

in a closed-circuit logic (production of electricity and/or heat for direct use by one or more buyers) introduces a specific credit risk. The fact that the reactor is not connected to the general electricity grid exposes the SMR cash flows to the risk of default by the buyer(s). While this risk is not, strictly speaking, specific to SMRs, since it is already encountered when party to "physical" green PPAs[81], its potential effects are multiplied by significant fixed costs characterising the nuclear power industry. In this respect, **it should be noted that, in France, BPI, a public sector entity, has recently made available an insurance-type guarantee covering the performance of industrial offtake agreements**[82]. Covering up to 80% of the contractual revenues lost in the event of default by the buyer, it is specifically designed to limit the financial risk exposure of renewable electricity producers arising from the cyclical nature of industrial activity. This solution could eventually be replicated for the generation of electricity and/or heat by SMRs to reduce the credit risk arising from closed-circuit projects.

On the other hand, **certain key conditions** for arranging non-recourse debt appear to be **more difficult or even problematic in the case of SMR-type assets**:

- **Aligning the term of electricity and/or heat purchase agreements with the expected life of the assets** (30 years 40 years), in order to secure cash flows over the longest possible period. This alignment is generally sought with the aim of obtaining debt maturities that reduce annual cash flows devoted to debt servicing (interest payments and gradual repayment of principal) and ultimately minimise the amount of equity in the total coverage of investments.

  While this alignment is conceivable in the context of "system" uses of SMRs involving a public sector buyer and a CfD/regulated tariff (see above), it seems **highly hypothetical in the context of PPAs with industrial buyers**, as corporate PPAs rarely exceed 12 to 15 years. These factors suggest that the **closest replication of the conditions under which renewable energies are financed** (so with debt accounting for a very large proportion of the capital raised - see above) **will be found in assets developed within the framework of "system" uses** with public sector buyers rather than within the framework of "decentralised" uses in a closed-circuit logic with private sector buyers in the industrial sector;

- **The integration of step-in rights for the benefit of creditors**, for the same legal and operational reasons as for power reactors (see above).

Lastly, **the introduction of lease-type financing** for SMRs with a capacity of less than 15MW **seems conceivable, but within a framework that is precisely mapped out for the commercial banks concerned**. In theory, this type of scheme offers the possibility of deploying asset-based financing for capacity that does not individually meet the threshold set by commercial banks for arranging project financing. However, implementation comes up against the very nature of the equipment in question and raises the same difficulties as the inclusion of step-in rights in the nuclear generation industry. The variety and scale of the liabilities and potential associated risks are all elements that commercial banks will not want to assume as owners of the equipment, except in a **framework that unambiguously separates ownership from operation**.

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[81] These contracts are concluded by renewable energy producers with buyers in the industrial sector as well as in the services sector (data centres, for example). In this context, the renewable capacities are directly connected to the buyers' installations. In contrast, "virtual" PPAs involve two other types of players (aggregators and suppliers) and are based on a system that guarantees buyers the renewable nature of the purchased electricity. This type of contract makes it possible to separate the contracting of electricity volumes with a developer from the physical flows associated with this production.

[82] Cf. https://www.bpifrance.fr/catalogue-offres/garantie-electricite-renouvelable-ger

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