Energy
Transitions
Commission

The role of nuclear in clean power systems

Expert Workshop

2nd October 2025

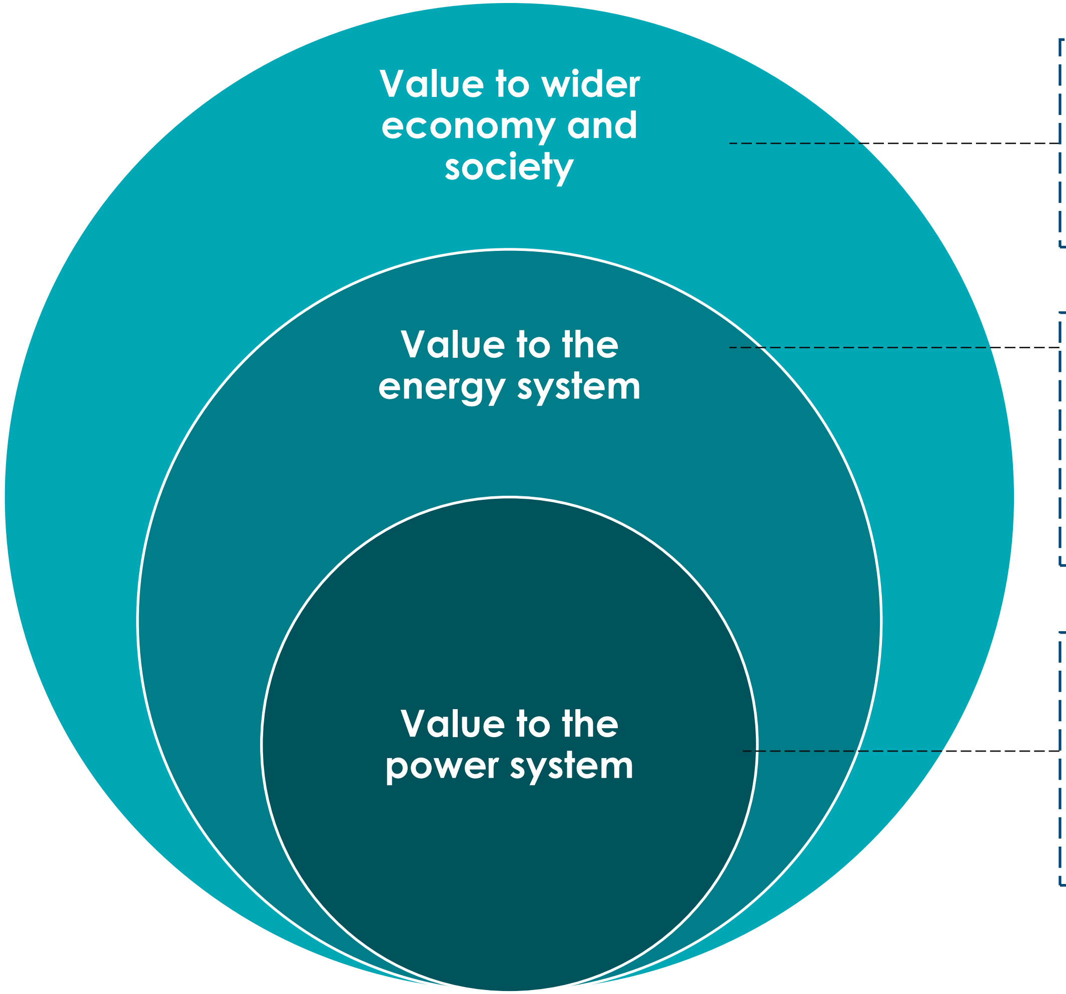
Introducing the ETC's Nuclear & Geothermal workstream

- **Context:** In many regions of the world, wind and solar will be the most cost-competitive and scalable new clean electricity generation sources. But in some places, fast growing demand, limited land availability, or the high cost of balancing the power grid could make other clean sources attractive.

- **This new workstream explores the key question:** What is the role of nuclear & geothermal electricity in future power systems, alongside wind and solar generation, in different regions of the world? Can they be delivered at low cost? Where needed, how can their deployment be scaled faster?

- Workshop schedule
  - **Workshop 1: The role of Nuclear** (Oct 2025)
  - **Workshop 2: The role of Geothermal**
  - **Workshop 3: Key enablers to scale Nuclear and Geothermal**

Value of nuclear power should be assessed holistically against alternatives



Value to wider economy and society

Value to the energy system

Value to the power system

★ *Considerations around: Economic value-add and jobs; Environmental risks; Energy security*

Hybrid applications (E.g. heat, hydrogen, desalination)

★ *Total system costs (e.g. LCOE, balancing, grid expansion & grid stability costs)*

Considerations on diversification and resilience

To understand how nuclear can complement a high renewable system

★ = in-depth focus in this workshop

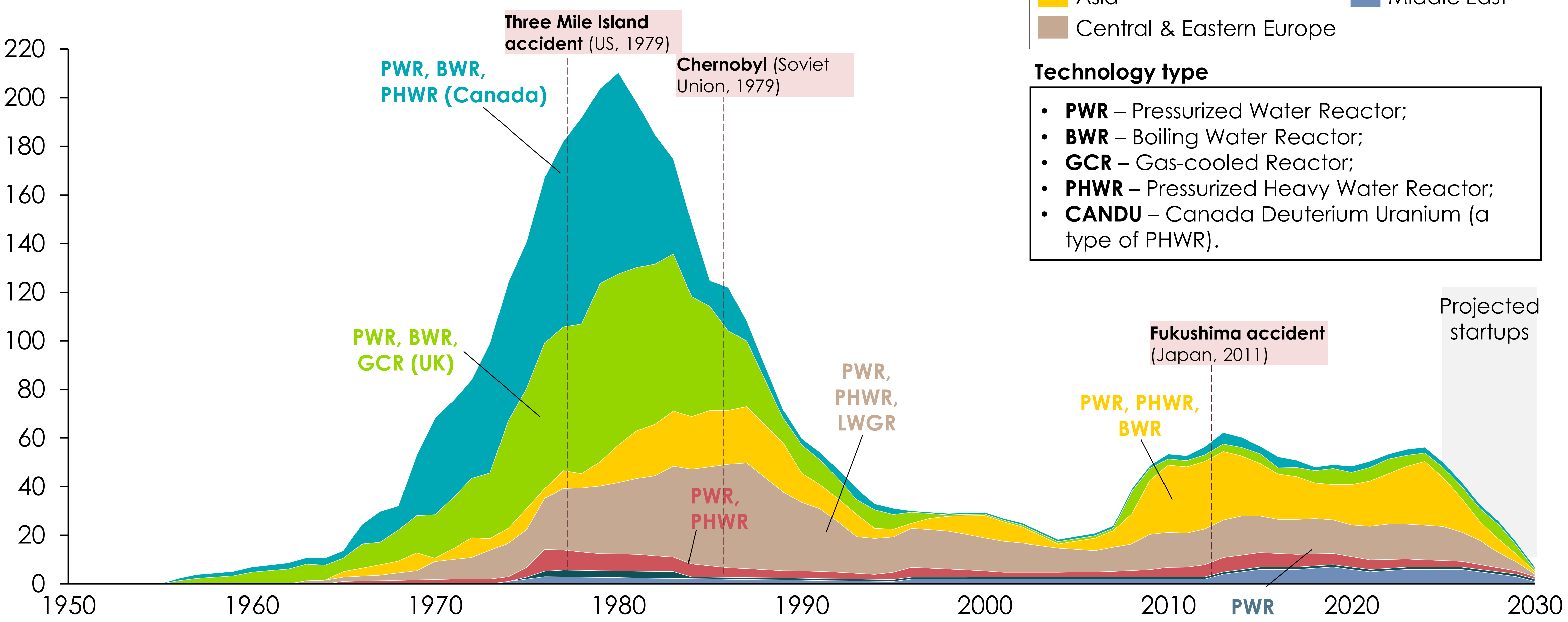
Agenda

- **Context: the state of play of nuclear**
- Techno-economics and understanding “system value”
- Wider risks and benefits
- Emerging conclusions

Nuclear power deployment peaked in the 1980s in the West, with a recent peak in Asia

Reactors under construction by year by region

GW (dominant reactor types annotated)



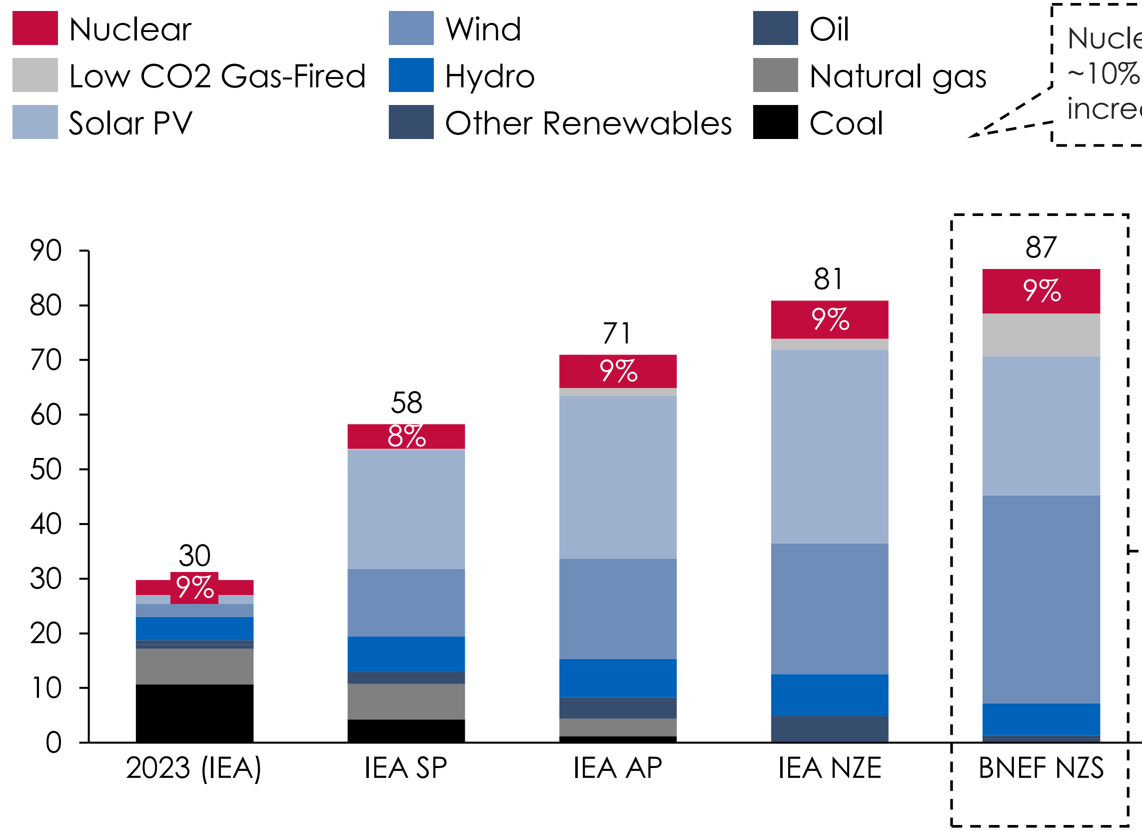
Technology type

- **PWR** – Pressurized Water Reactor;
- **BWR** – Boiling Water Reactor;
- **GCR** – Gas-cooled Reactor;
- **PHWR** – Pressurized Heavy Water Reactor;
- **CANDU** – Canada Deuterium Uranium (a type of PHWR).

Source: adapted from Mycle Schneider Consulting (2024), *The World Nuclear Industry Status Report 2024*; World Nuclear Association (2025), *Reactor Database*

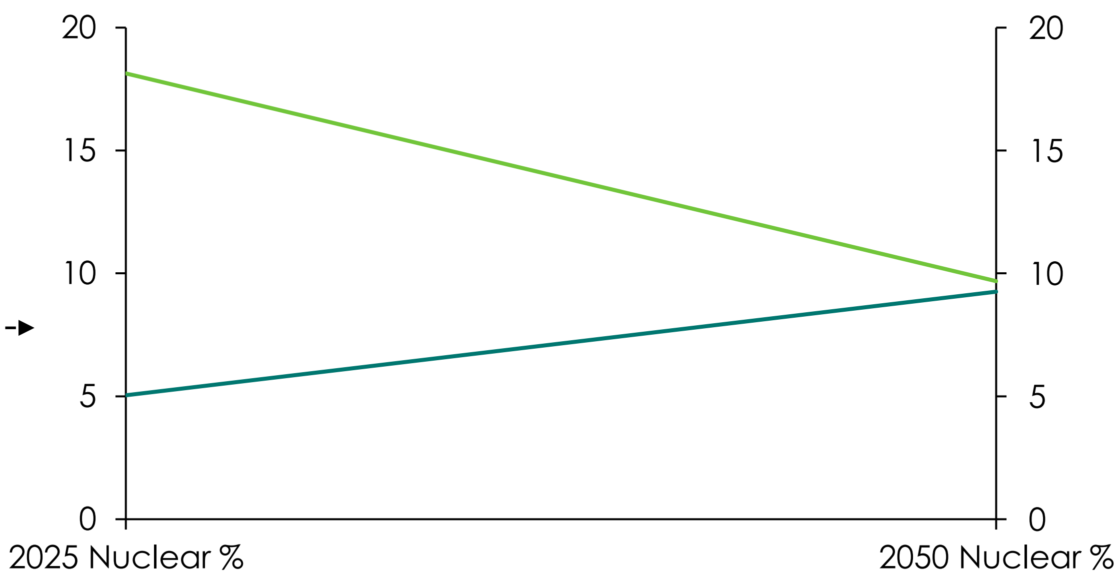
Future power system scenarios suggest nuclear meets ~10% of total generation, requiring a significant increase in generation compared to today

Global nuclear vs non-nuclear generation by scenario (2023 and 2050)
‘000 TWh



Nuclear share globally remains ~10% even as total generation increases by 2-3x by 2050.

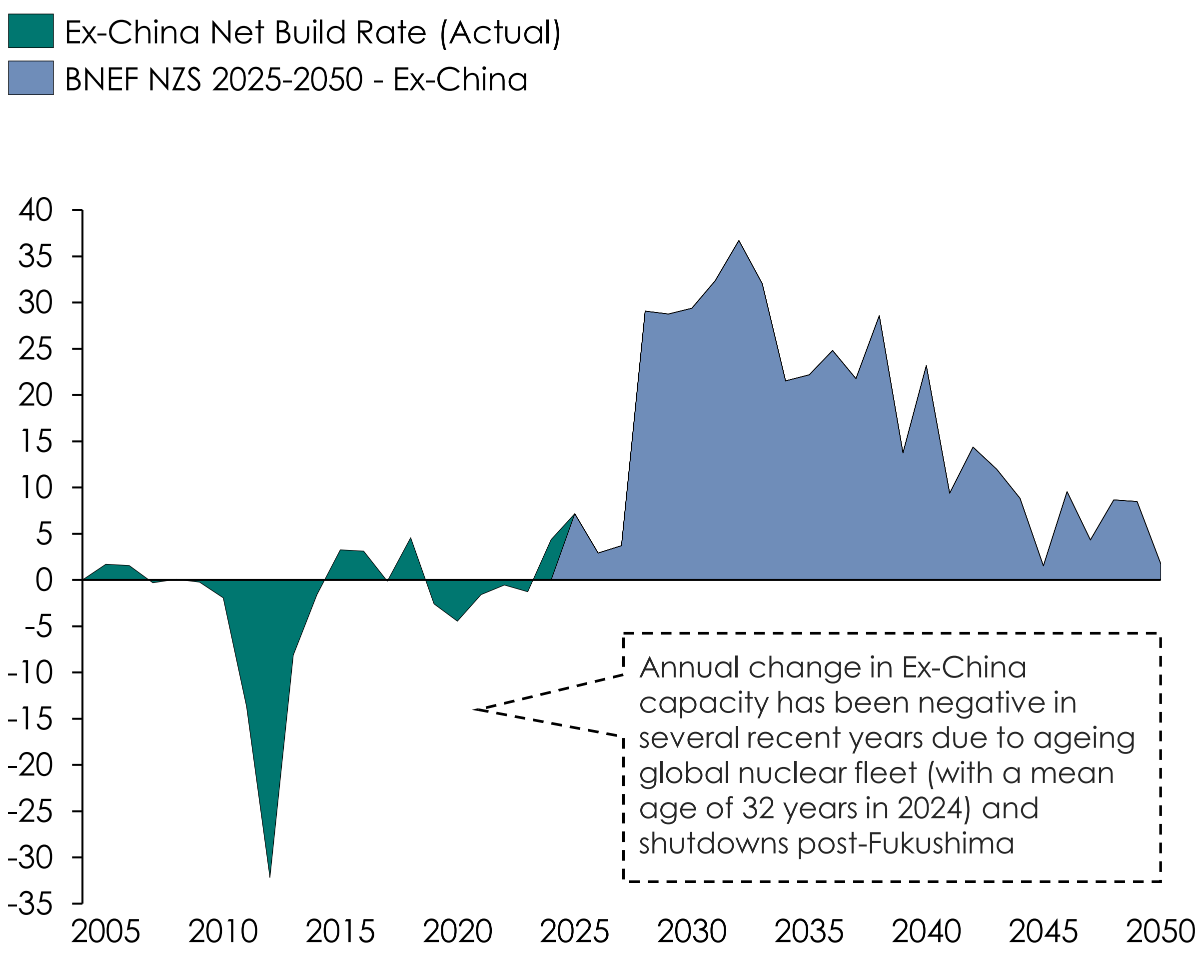
Average nuclear share of generation by region in BNEF NZS
% of Generation



In many cases, nuclear plant lifetimes can and should be extended safely. Nuclear plant lifetime extensions are frequent but do present some risks (e.g. structure/component ageing, technical limitations and physical ageing of system design).

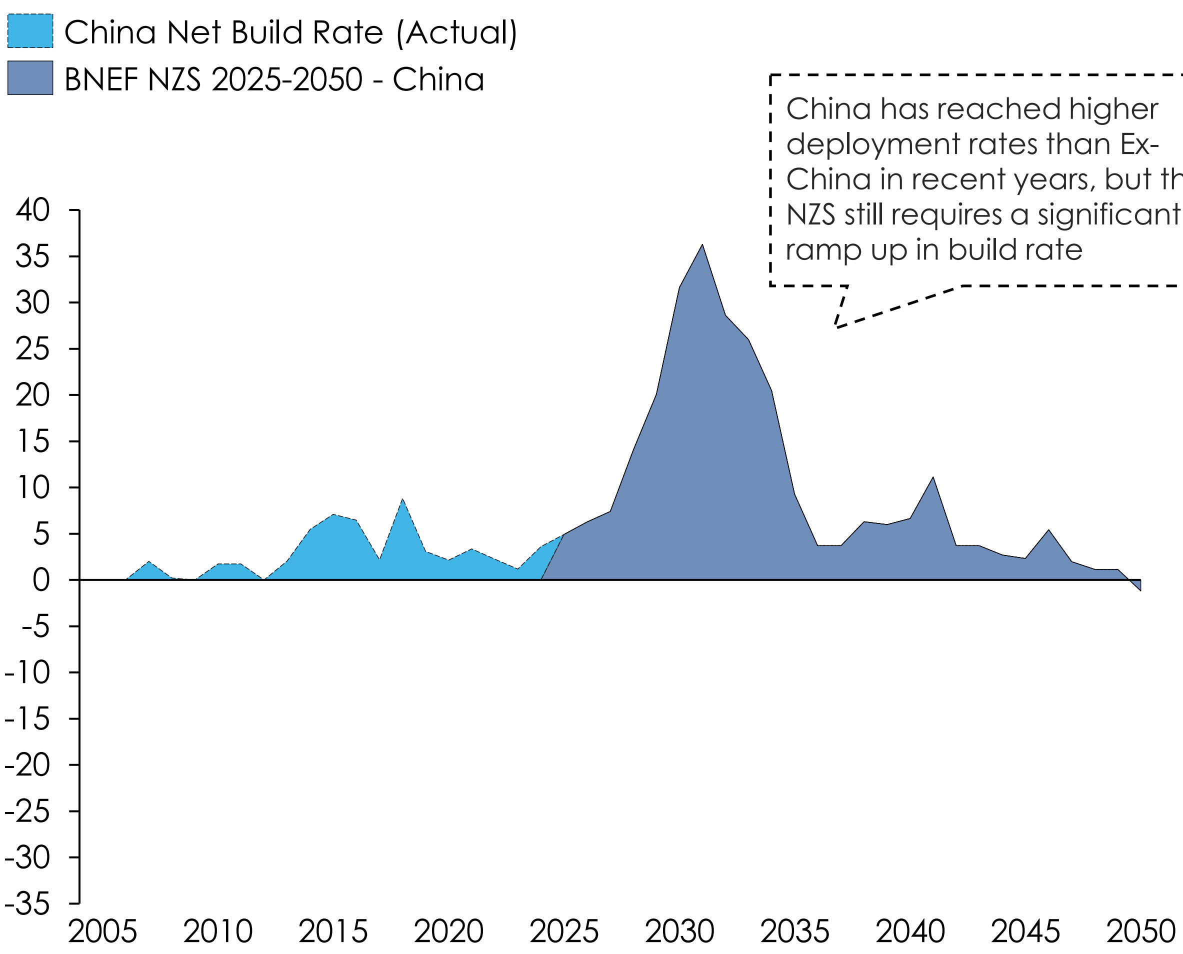
Notes: Nuclear generation includes conventional and SMR. SP = Stated Policies, AP = Announced Pledges, NZE = Net Zero Emissions, ETS = Economic Transition Scenario, NZS = Net Zero Scenario.
Sources: BNEF (2025), *New Energy Outlook 2025*, IEA (2024), *World Energy Outlook 2024*

Nuclear build rates lag far behind what is indicated in most Net Zero scenarios



Ex-China nuclear annual change in nuclear installed capacity, 2005 - 2050
GW/y

Annual change in Ex-China capacity has been negative in several recent years due to ageing global nuclear fleet (with a mean age of 32 years in 2024) and shutdowns post-Fukushima



China nuclear annual change in nuclear installed capacity, 2005 - 2050
GW/y

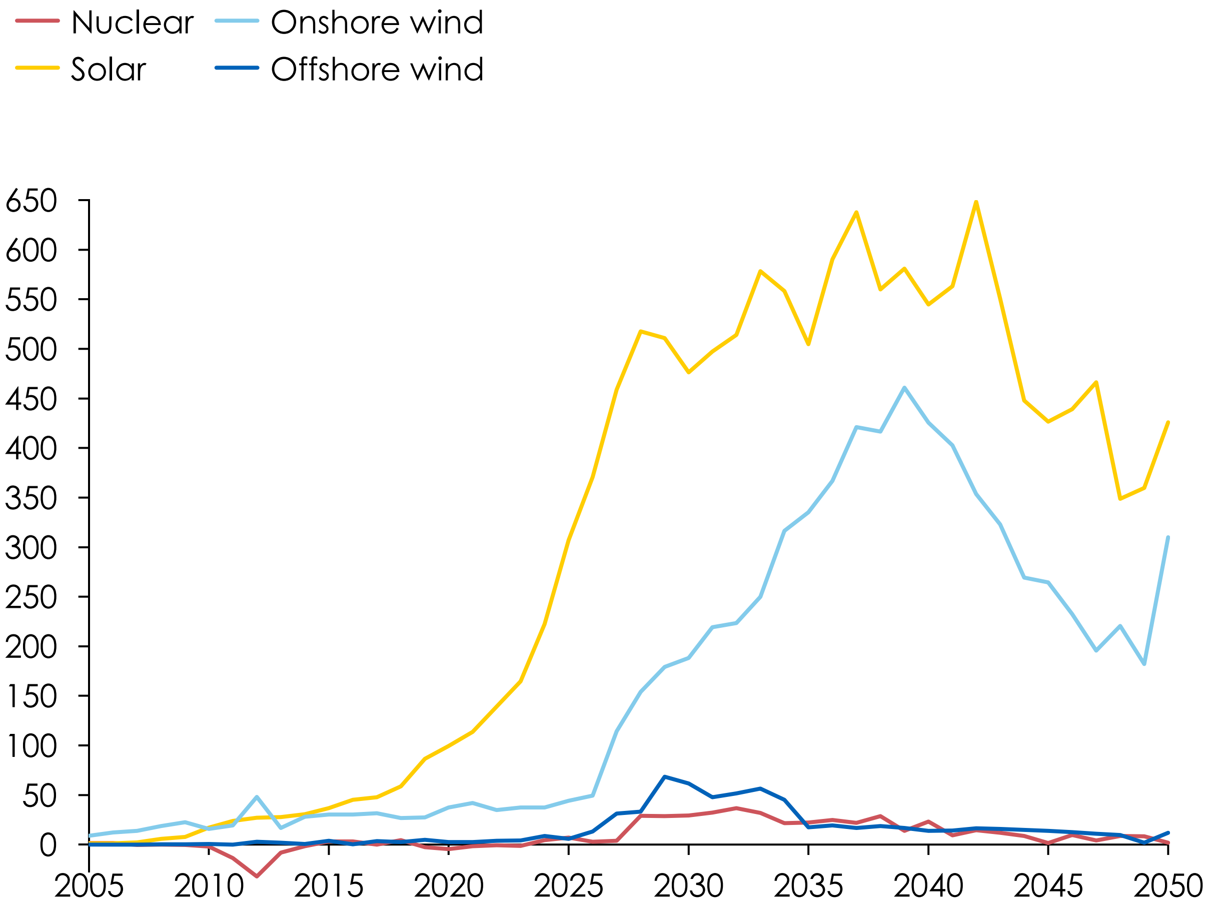
China has reached higher deployment rates than Ex-China in recent years, but the NZS still requires a significant ramp up in build rate

Source: BNEF (2025), *New Energy Outlook 2025*

Solar and onshore wind will dominate capacity additions; nuclear likely to be a small share

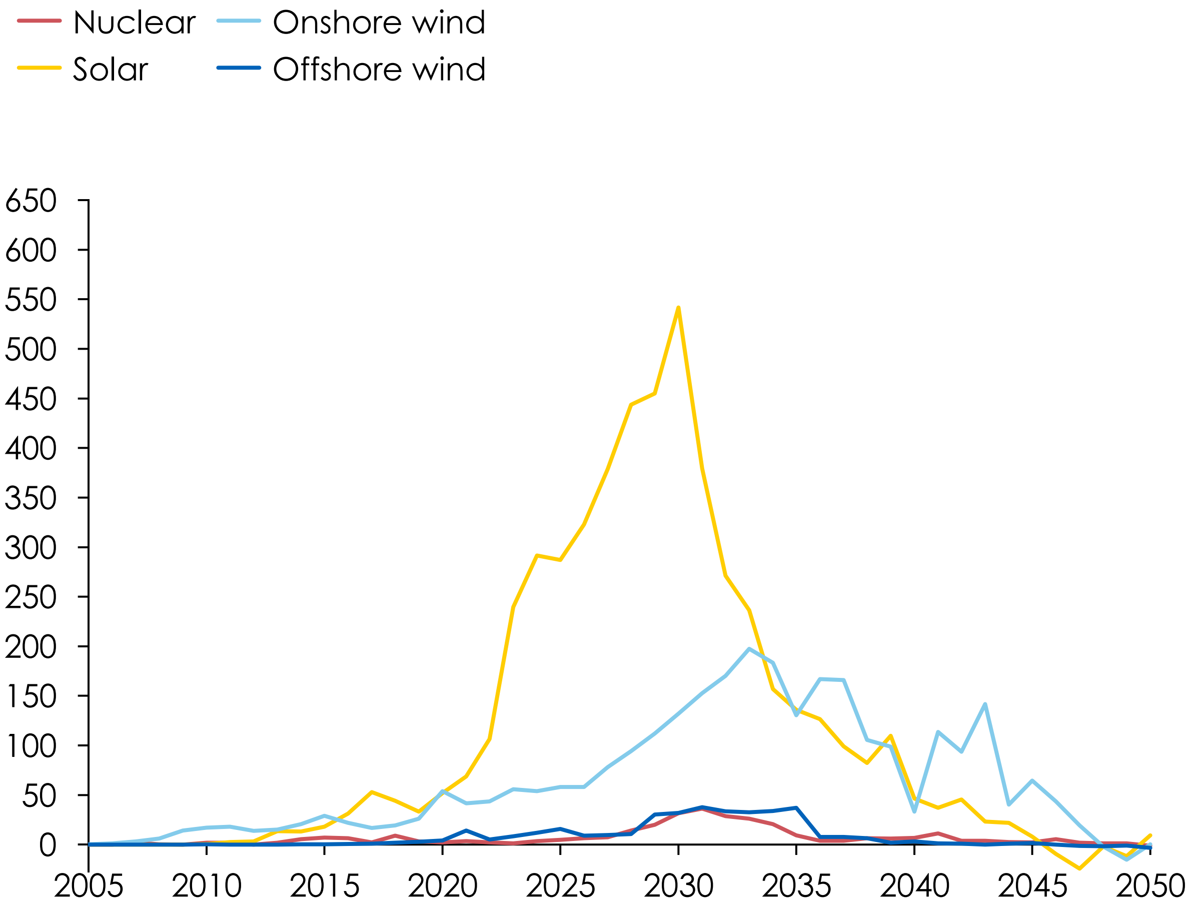
Ex-China annual change in clean power installed capacity

GW/y



China annual change in clean power installed capacity

GW/y

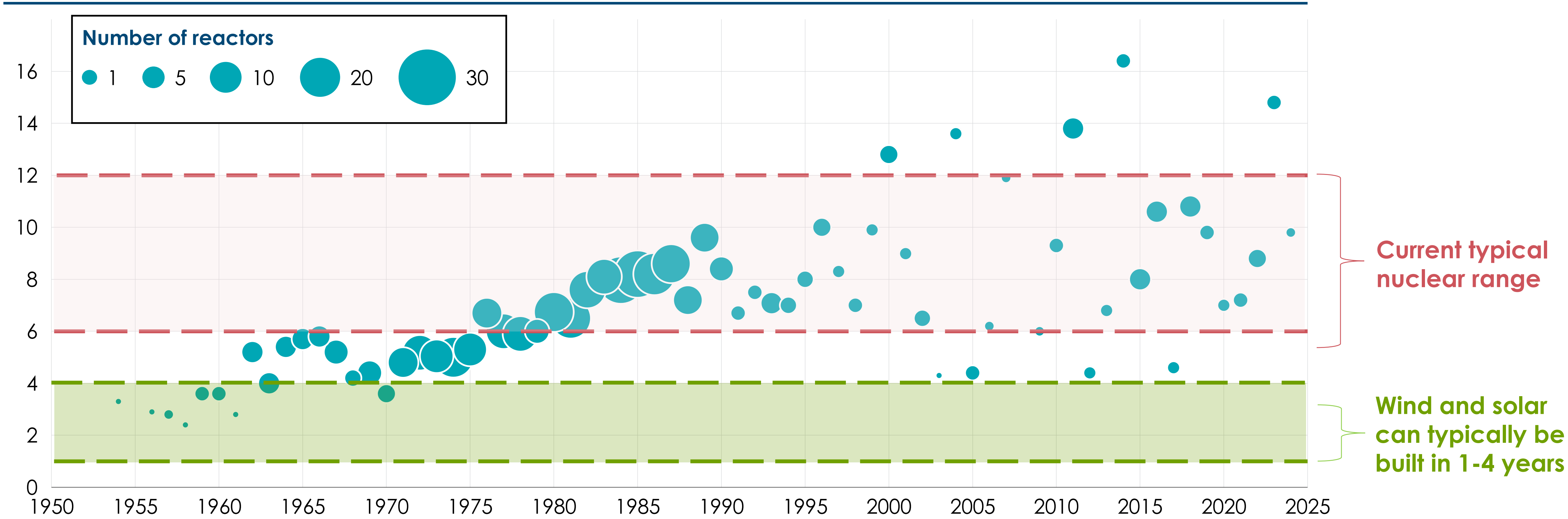


Source: BNEF (2025), *New Energy Outlook 2025*

Average nuclear construction times have trended upwards, in contrast to renewables that can be built in under three years

Average annual durations from final investment decision to commissioning over time

Years



Average construction times have increased significantly, particularly in the West

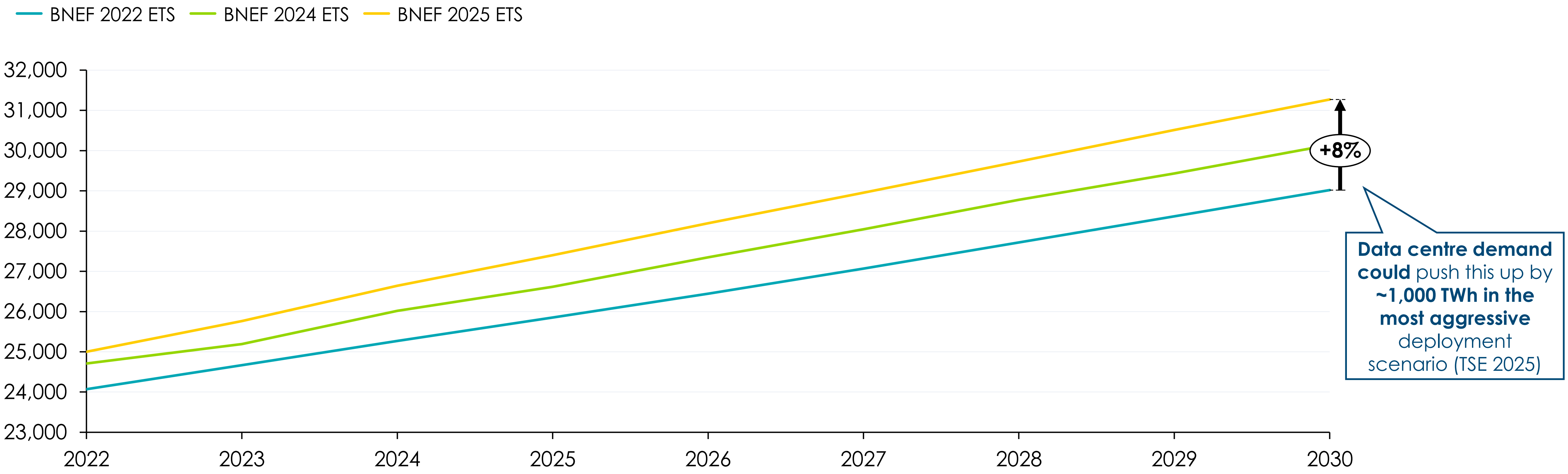
New nuclear will add 1,000 TWh in the next 10 years while solar will add 10,000 TWh

Sources: Adapted from Mycle Schneider Consulting (2024), *The World Nuclear Industry Status Report 2024*; Financial Times (2025), *Can the nuclear industry find a better way to build?*; A. Gumber (2024), *A global analysis of renewable energy project commissioning timelines*

Demand projections in BNEF's ETS scenarios have been revised up, amid fast growing power demand

BNEF's ETS 2022 – 2030 global electricity demand by publication year

TWh



Data centre demand could push this up by **~1,000 TWh in the most aggressive** deployment scenario (TSE 2025)

Continuously increasing demand projections could require increased ambition to meet growing demand and squeeze out fossil fuels from electricity production

Source: Systemiq analysis for the ETC; BNEF (2022/24/25) *New Energy Outlook*

Increasing interest from Big Tech, as well as country ambition

Big Tech announcements

- **Meta** signed a 20-year deal with Constellation Energy Corp. ro4 power from an Illinois reactor
- **Google** signed a deal with Kairos Power for a new fleet of SMRs sited near data centres by 2030-2035
- **Amazon** signed a deal with Talen Energy for ~1,900 MW from Susquahanna plant, through 2042
- **Microsoft** signed a 20-year deal to restart Unit 1 of Three Mile Island (“Crane Clean Energy Centre”), ~835MW, expected start 2027

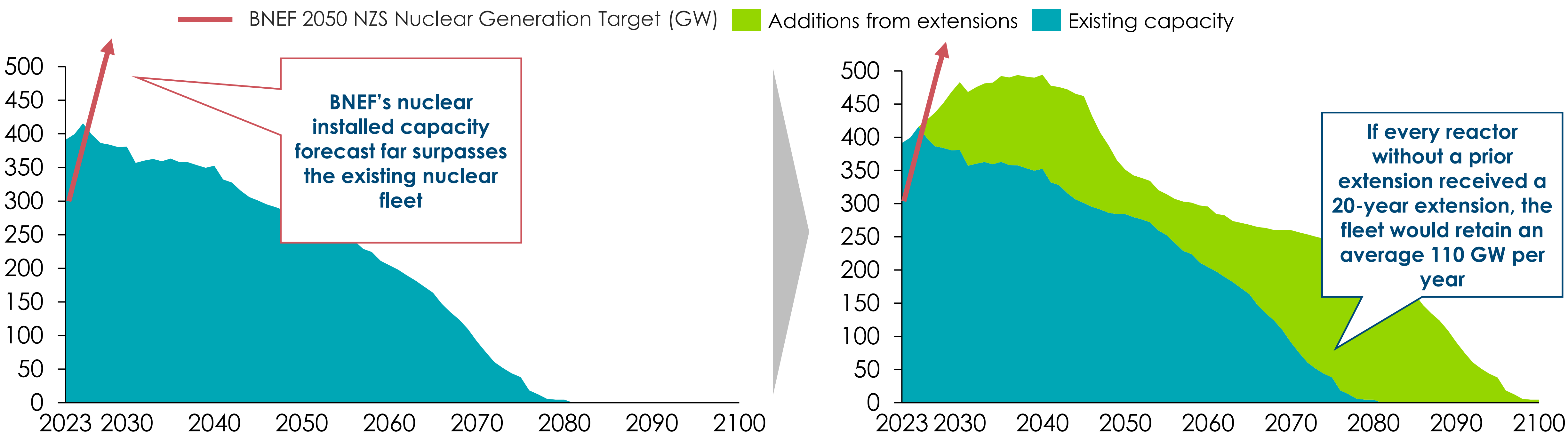
Country ambitions

- **At COP28 (UAE), over 20 countries signed a declaration to triple nuclear power capacity by 2050** (e.g. US, Canada, France, Korea, UAE, UK)
- **US** has set out a plan to deploy 200 GW by 2050, with a target of 35 GW by 2035 (vs 97 GW today)
- **China** has over 30 reactors under construction, target to reach to 200 GW by 2035 and 400 GW by 2050 (vs 57 GW today)
- **India** has set targets to reach 22 GW by 2032, and 100 GW by 2047 (vs 7.5 GW today)

Meta Google amazon Microsoft

COP28 UAE

While the focus of this work is on new nuclear capacity, ETC believes that extensions should be pursued where feasible and safe



Global nuclear fleet with existing capacity

GW

BNEF's nuclear installed capacity forecast far surpasses the existing nuclear fleet

Global nuclear fleet with lifetime extensions

GW

If every reactor without a prior extension received a 20-year extension, the fleet would retain an average 110 GW per year

Governments should keep plants operating as long as technically and safely possible

- According to the IEA, extensions are low-cost: typically USD 500–1,100/kW, yielding <$40/MWh LCOE
- Continued operation is technically feasible when safety and ageing-management requirements are met

Note: Assumptions include that lifetime extensions would be 20 years of added operation. While projects can receive repeated extension certificates, it has been assumed in this model that a project is only extended once. There is a high chance that projects will be extended multiple times, making the savings from extensions higher than shown in the graph on the right.

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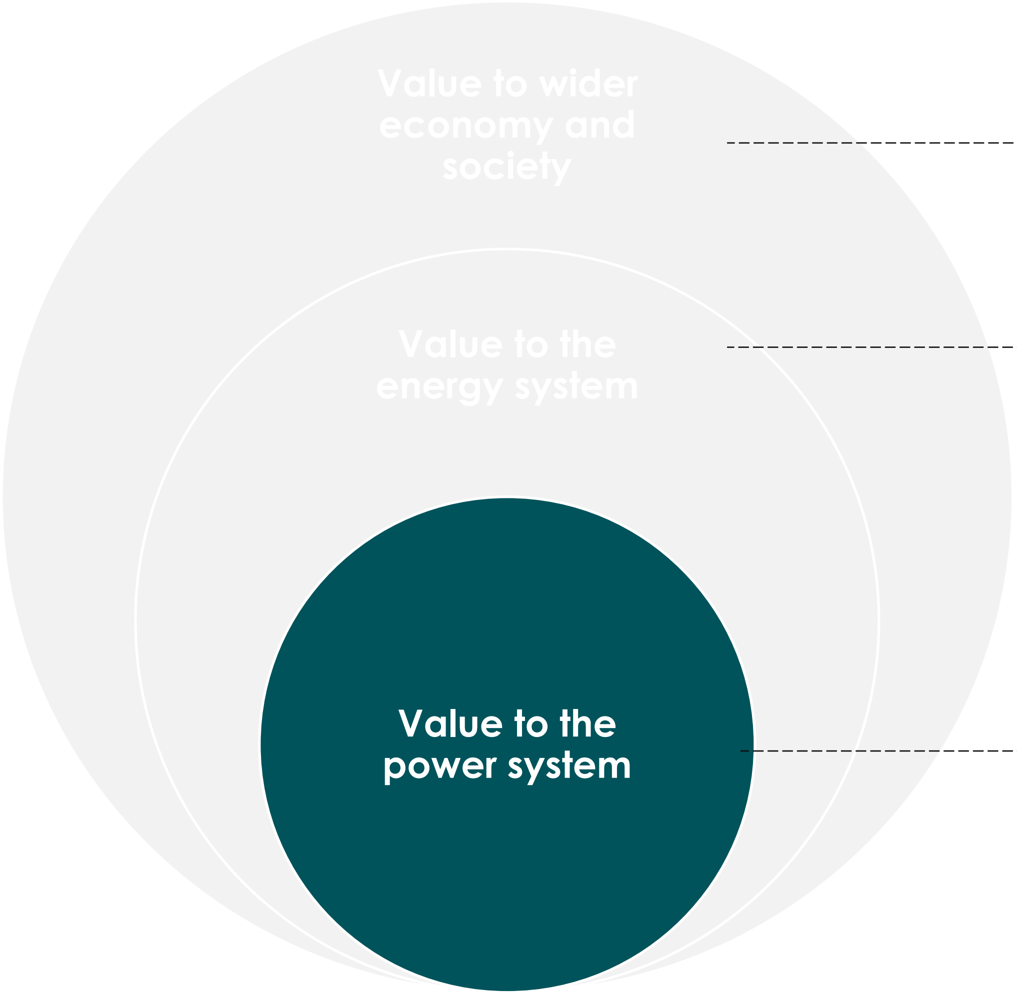

Value to wider economy and society

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★ Considerations around: Economic value-add and jobs; Environmental risks; Energy security

Hybrid applications (E.g. heat, hydrogen, desalination)

★ Total system costs (e.g. LCOE, balancing, grid expansion & grid stability costs)

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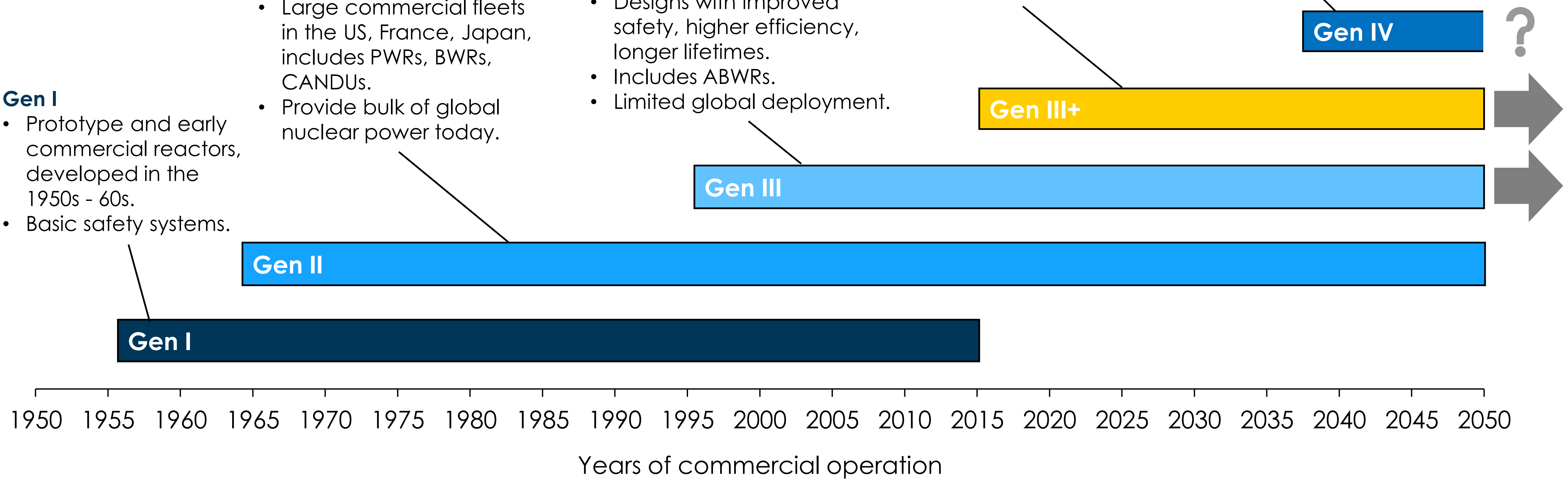
Nuclear power generation: technologies

Generation III+ reactors have been deployed at scale in the last decade, while Gen IV reactors remain at demonstration stage

Nuclear reactor generations in operation over time (indicative)



Gen I
- Prototype and early commercial reactors, developed in the 1950s - 60s.
- Basic safety systems.

Gen II
- Large commercial fleets in the US, France, Japan, includes PWRs, BWRs, CANDUs.
- Provide bulk of global nuclear power today.

Gen III
- Designs with improved safety, higher efficiency, longer lifetimes.
- Includes ABWRs.
- Limited global deployment.

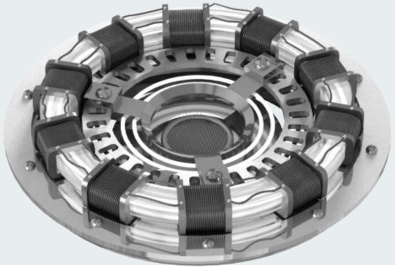
Gen III+
- Evolution of Gen III with passive safety, simplified designs to reduce costs.
- Higher efficiency.
- Includes LWRs: EPR, AP1000, VVER-1200, APR1400.

Gen IV
- Future concepts under development with different neutron spectra, coolants, and fuels.
- Aim for high efficiency, improved safety, proliferation resistance, and low waste.

Notes: PWR = Pressurised Water Reactor, BWR = Boiling Water Reactor, CANDU = Canada Deuterium Uranium, ABWR = Advanced Boiling Water Reactors, LWR = Light Water Reactor (moderated and cooled by water), EPR = European Pressurised Reactor.
Source: World Nuclear Association (2021), *Advanced Nuclear Power Reactors*

Generations 1 to III+ are mature reactor technologies, while Gen IV fission and fusion are still low-maturity

Decreasing Maturity

				TRL (Technology readiness level)	FOAK (1st commercial deployment)	NOAK (Large-scale deployment)
Gen I- III	**Conventional large-scale reactors**		- Global standard for commercial nuclear energy since the 1960s. - The main types are Pressurised Water Reactors (PWRs) and Boiling Water Reactors (BWRs).	TRL 9	1956	1956
Gen III+	**Small Modular Reactors (SMR)**		• SMRs are compact reactors (10 – 500 MW) built in factories and shipped for assembly • Growing commercial interest due to scalability and flexibility	TRL 2-8	2029 +	2035 +
Gen IV	**Next-generation reactors**		Next generation of nuclear fission technologies which use novel coolants including: - High-temperature gas reactors - Liquid metal reactors - Molten salt reactors - Fast breeder reactors	TRL 2-8	2030 +	2035 +
	Fusion		- Fusion joins light atomic nuclei like hydrogen into heavier ones to release energy - Massive clean energy potential with minimal long-lived radioactive waste - Remains in early-stage R&D	TRL 2-5	2040 +	2050 +

Notes: FOAK first of a kind TRL 9+ deployment; NOAK = n^{th} of a kind deployment. Assumed TRL scale: TRL 1-3 = Research to Proof of Concept; TRL 4-6 = Lab to Pilot Demonstration; TRL 7-9 = Prototype Demonstration to FOAK / Full Commercial Deployment. Sources: US DoE (2024), *Pathways to Commercial Liftoff: Advanced Nuclear*; Mycle Schneider Consulting (2024), *The World Nuclear Industry Status Report 2024*; Third Way (2024), *The Global Race for Advanced Nuclear Is On*; Ben James (2024), *The Big Guide to Fusion*; Nuclear Innovation Alliance (2025), *Advanced Reactor Deployment Map*

Nuclear reactor efficiency and safety improvements can be achieved via a mix of design options

<table>
<tr>
<th></th>
<th>Neutron Spectrum
The range of neutron energies that dominate within the reactor core</th>
<th>Fuel Type
The chemical and physical form of the nuclear fuel</th>
<th>Coolant Type
The substance used to transfer heat away from the reactor core</th>
<th>Modularity
The size and construction approach</th>
</tr>
<tr>
<td>Key design options</td>
<td>Thermal
Fast
Thermal or fast</td>
<td>LEU[1]
Molten Salt Fuel
HALEU[2]
Metallic fuel
MOX / Pu / UC + PuC [3]
Thorium</td>
<td>Water-cooled
Lead-cooled
Gas-cooled
Sodium-cooled
Molten Salt-cooled</td>
<td>Large Reactor 900 MW +
SMR 50 – 500 MW
Microreactor 1- 20 MW</td>
</tr>
<tr>
<td>Efficiency impacts of leading options</td>
<td>• Thermal: lower as limited by water/steam cycles
• Fast: higher due to higher outlet temperatures</td>
<td>• LEU: efficiency limited by reactor core and coolant; typically 32–37%
• HALEU: allows higher burnup and advanced designs with higher efficiency
• MOX / Pu: increased fuel utilisation and burn-up but similar efficiency to LEU</td>
<td>Higher temp. = higher efficiency
<table>
<tr><th>Coolant Type</th><th>Outlet Temp. (°C)</th><th>Efficiency (%)</th></tr>
<tr><td>Water</td><td>~300</td><td>32-37</td></tr>
<tr><td>Sodium</td><td>500-550</td><td>38-42</td></tr>
<tr><td>Lead</td><td>480-570</td><td>38-44</td></tr>
<tr><td>Molten Salt</td><td>~750</td><td>40-50</td></tr>
<tr><td>Gas</td><td>650-950</td><td>40-50</td></tr>
</table>
</td>
<td>• Large: economies of scale, optimised for high capacity factor
• SMR: efficiency penalty due to scaling (but advanced reactors make up for this)
• Micro: lower efficiency due to size and heat rejection</td>
</tr>
<tr>
<td>Safety considerations of leading options</td>
<td>• Thermal: mature, well-understood operational safety
• Fast: more challenging control with less experience</td>
<td>• LEU: safety is proven through long-term use
• HALEU: higher enrichment means a smaller mass for criticality. Closer to weapons-grade enrichment, so diversion risks are higher.
• MOX / Pu: requires careful handling due to plutonium radiotoxicity and potential weaponization.</td>
<td>• Water: Mature, well-understood
• Lead & molten salt: corrosion risk
• Gas: robust passive safety features
• Sodium: chemical reactivity with water</td>
<td>• Large: Stringent safety standards (55 GDCs) required but with higher economies of scale
• SMR: Similar safety standards but with diseconomies of scale; passive safety features
• Micro: designed for passive safety and minimal oversight</td>
</tr>
</table>

Notes: [1] LEU = Low Enriched Uranium (<5% U-235); [2] HALEU = High-Assay Low-Enriched Uranium (5-20% U-235); [3] MOX = Mixed Oxide Fuel (UO_2 + PuO_2) ; UC + PuC = mixed uranium-plutonium carbide; GDC = General Design Criteria. Thermal reactors also have variations in moderators, which are typically water or graphite. Fast reactors have no moderator.

Source: Systemiq analysis for the ETC (2025); GEN IV International Forum (2025), Generation IV Criteria and Technologies

Gen III+ & Gen IV reactors: several permutations of temperature, coolant, moderator. Only large-scale Gen III+ commercially deployed today

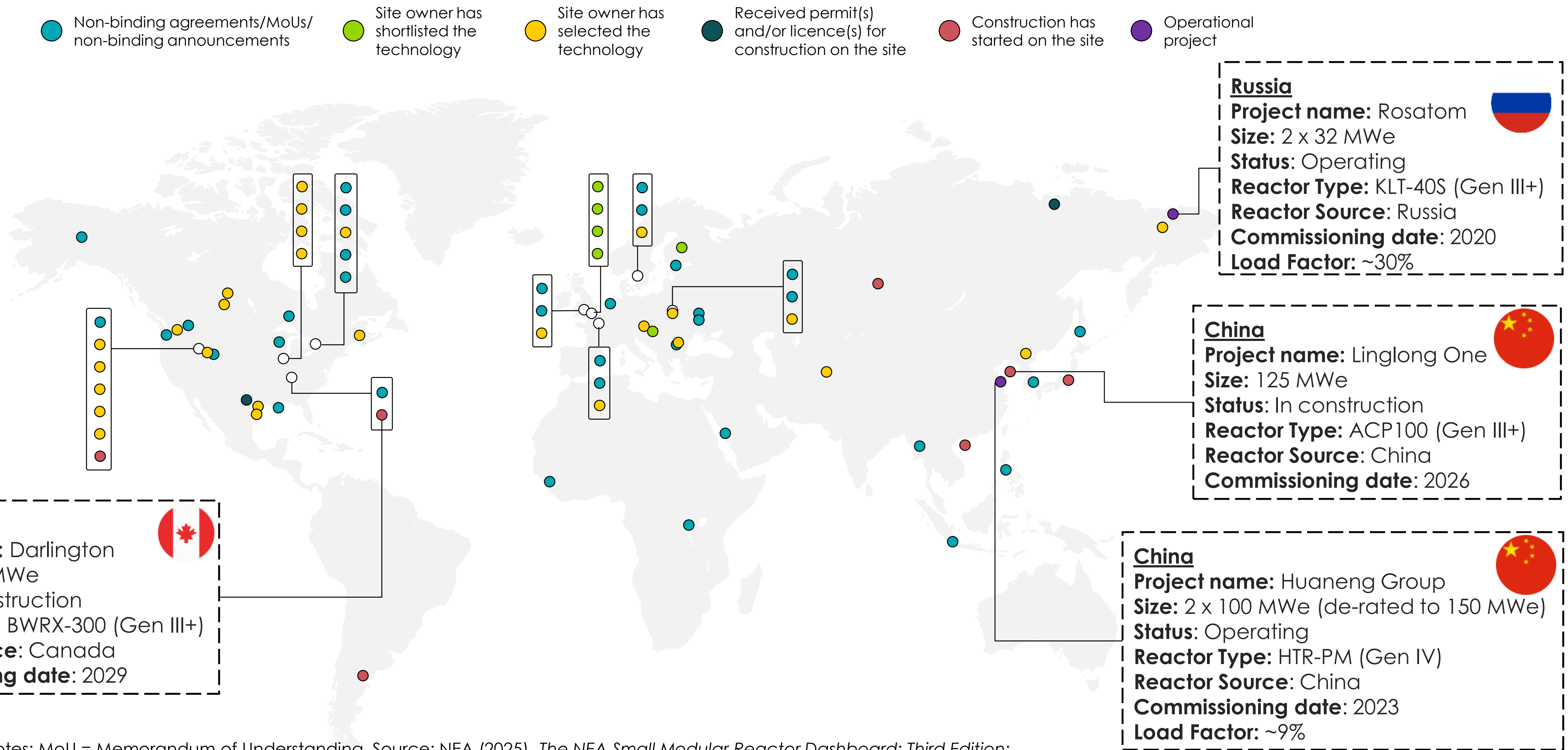
Only Gen III+ are commercially deployed today

	Gen III+	Gen IV					
	Light water reactor, thermal*	**Very-high-temperature, thermal**	**Gas-cooled, fast***	**Sodium-cooled, fast / thermal***	**Lead-cooled, fast**	**Molten salt/molten chloride, thermal***	**Super Critical Water, fast / thermal**
Neutron spectrum	Thermal	Thermal	Fast	Fast / Thermal	Fast	Thermal	Fast / Thermal
Fuel type	LEU	HALEU	UC + PuC	HALEU	MOX (UO_2 + PuO_2)	HALEU/LEU	UO_2/MOX
Coolant	Water	Helium	Helium	Liquid sodium	Lead	Fluoride salts	Water
Moderator	Water	Graphite	None	None / Graphite	None	Graphite	None / D_20 / H_20
Outlet temperature	~300C	~750-1000C	~850C	500-550C	480-570C	~750C	~850C
Benefits	Mature and well-understood technology that has been widely deployed worldwide	Gas-cooled technology provides high temperature ideal for industrial process heat	High thermal efficiency and high temperature heat for industrial applications	Safety advantages and greater fuel burn up reduces spent fuel waste	Enhanced safety, high efficiency (~42%)	Operation at 1 bar provides efficiency and safety benefits	High efficiency (44-48%) and design simplicity
Shortcomings	Heavily water-dependent	Poor performance in the past	Challenges with high temperature, high power density fuels and core structural materials	Sodium management challenges	Lead's high melting point means high coolant temperatures are needed	Molten-salt corrosion issues	Structural material lifetimes (esp. fuel cladding) in harsh SCW environment
Technology developers	DEEP FISSION eDF ROLLS ROYCE LAST ENERGY Westinghouse NUSCALE HITACHI GE VERNOVA	X energy RADIANT	ALLEGRO GENERAL ATOMICS	arc clean technology OKLO Aalo TerraPower	Blykalla Westinghouse	Kairos Power Natura Resources TERRESTRIAL ENERGY TerraPower	HITACHI GE VERNOVA AECL EACL

Notes: *indicate designs most commonly being developed. These advanced reactor designs can be large-scale or SMR-scale. LEU = Low Enriched Uranium (<5% U-235); HALEU = High-Assay Low-Enriched Uranium (5-20% U-235); MOX = Mixed Oxide Fuel (UO_2 + PuO_2) ; UC + PuC = mixed uranium-plutonium carbide; SCW = super critical water.
Source: adapted from BNEF (2025), *US Advanced Nuclear Reactors: Startups Race to Be First*, GEN IV International Forum (2025), Generation IV Criteria and Technologies

SMRs: Gen III+ SMRs are starting to be built in North America and Asia; Gen IV SMRs are in earlier stages of development

Global SMR deployment map



- ● Non-binding agreements/MoUs/ non-binding announcements
- ● Site owner has shortlisted the technology
- ● Site owner has selected the technology
- ● Received permit(s) and/or licence(s) for construction on the site
- ● Construction has started on the site
- ● Operational project

Russia
Project name: Rosatom
Size: 2 x 32 MWe
Status: Operating
Reactor Type: KLT-40S (Gen III+)
Reactor Source: Russia
Commissioning date: 2020
Load Factor: ~30%

China
Project name: Linglong One
Size: 125 MWe
Status: In construction
Reactor Type: ACP100 (Gen III+)
Reactor Source: China
Commissioning date: 2026

China
Project name: Huaneng Group
Size: 2 x 100 MWe (de-rated to 150 MWe)
Status: Operating
Reactor Type: HTR-PM (Gen IV)
Reactor Source: China
Commissioning date: 2023
Load Factor: ~9%

Canada
Project name: Darlington
Size: 4 x 300 MWe
Status: In construction
Reactor Type: BWRX-300 (Gen III+)
Reactor Source: Canada
Commissioning date: 2029

Notes: MoU = Memorandum of Understanding. Source: NEA (2025), *The NEA Small Modular Reactor Dashboard: Third Edition;* US DoE (2024), *Pathways to Commercial Liftoff: Advanced Nuclear*; Mycle Schneider Consulting (2024), *The World Nuclear Industry Status Report 2024*; Third Way (2024), *The Global Race for Advanced Nuclear Is On*; Nuclear Innovation Alliance (2025), *Advanced Reactor Deployment Map*

Gen IV: reactor concepts have not progressed beyond demonstration stages despite decades of research & development

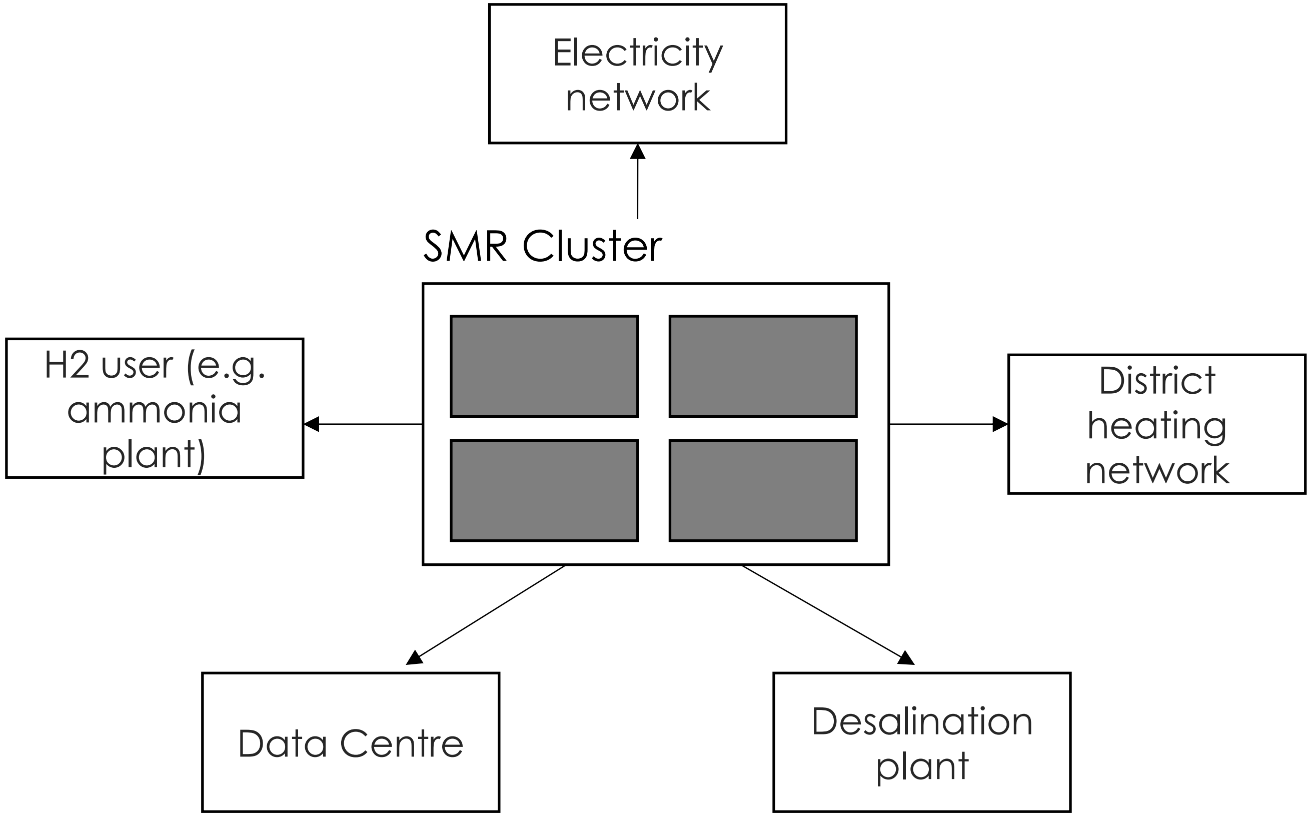
Barrier	Evidence
1. Technical Complexity *Novel materials, fuels, and coolants require decades of R&D and testing.*	Sodium coolant fires at Monju (Japan); corrosion at MSRE (US); slow TRISO fuel qualification.
2. High Costs and Economic Risk *First-of-a-kind (FOAK) projects face cost overruns and uncertain returns, issues with prototypes have limited investor confidence. Mature LWRs and renewables remain cheaper.*	Fast breeder reactors* have been extensively yet unsuccessfully tested (e.g., Superphénix in France from 1985 – 1998); TerraPower's Natrium delayed to 2030s; Monju (Japan) operational for <1 year in 20; US EBR-II ended in 1994; US MSR program halted
3. Regulatory, Policy & Permitting Hurdles *Slow, uncertain licensing processes, shifting government priorities, and lack of public support delay deployment.*	NRC slow to license non-LWRs; US fast reactor demos delayed; UK Dounreay closures.
4. Industry and Supply Chain Lock-in *Existing supply chains and skills are optimised for conventional reactors, not advanced types.*	Westinghouse & EDF focus on LWRs; many vendors left fast reactor market after 1980s

Notes: *Fast breeder reactors (FBRs) are a subcategory of fast neutron reactors that are designed not just to generate power but also to produce more fissile material than they consume

Source: World Nuclear Association (2021), *Advanced Nuclear Power Reactors*; EBSCO (2024), *Superphénix nuclear reactor*

SMRs: Hybrid applications could unlock privately funded, behind-the-meter SMR deployment

Industrial cluster hybrid applications concept



- **Key hybrid nuclear applications** include desalination, district heat, process heat, hydrogen production
- Privately-funded SMRs could be co-located with industrial demand clusters:
  - Option to flex offtake to grid when prices are high could enable the SMR to operate as a baseload asset while also providing flex to the grid
  - Dynamic operation could enable 40% lower hydrogen production according to one study, through electricity cost reductions
- Seasonal offtake flexing can also allow heat to be used for district heating in winter

Source: ULC Energy (2024), *Study reveals low cost of nuclear H2*

Fusion: Nuclear fusion has various technology options

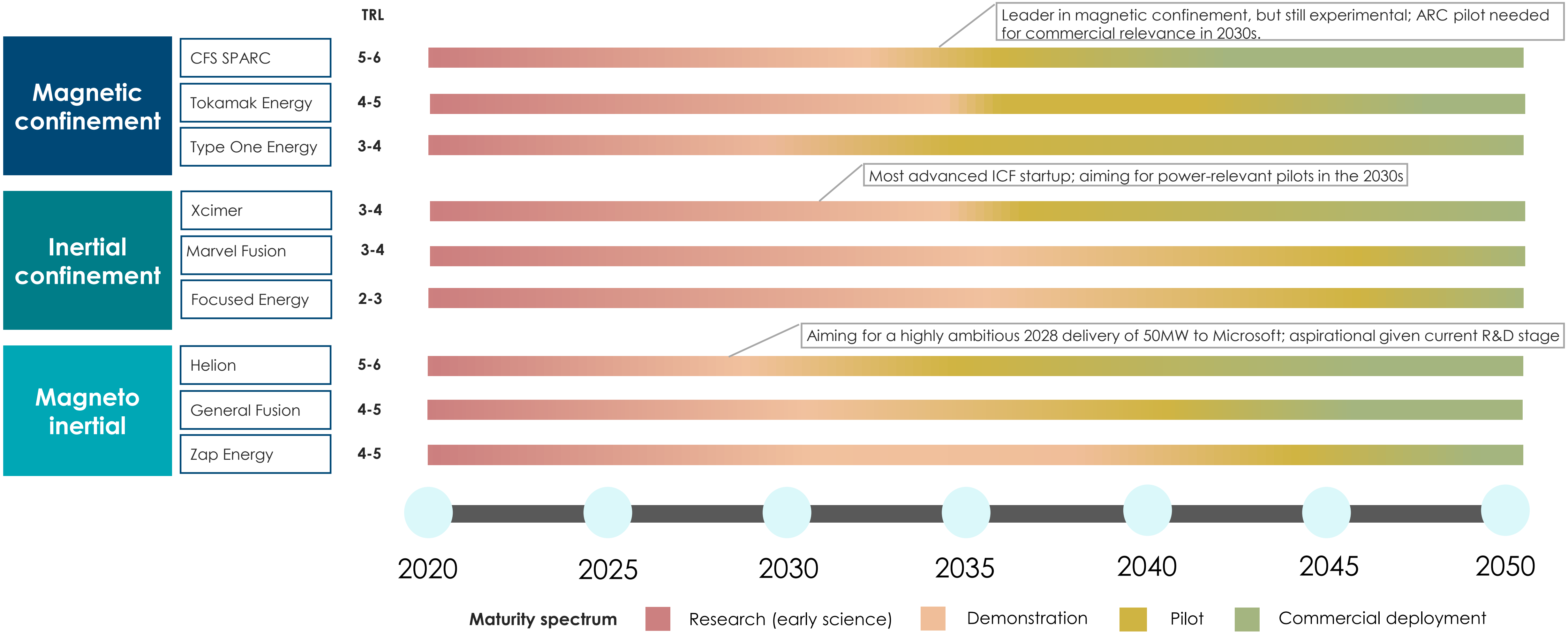
Nuclear fusion is the process of joining light atoms (like hydrogen) together to release huge amounts of clean energy, the same reaction that powers the sun.

There are three different types of technology options to achieve fusion energy:

Magnetic confinement	Inertial confinement	Magneto inertial
Uses strong magnetic fields to confine hot plasma for long durations	Uses ultra-powerful lasers or projectiles to rapidly compress tiny fuel pellets until they fuse	Combines short bursts of compression with magnetic fields to make fusion more efficient
e.g. Tokamaks (CFS SPARC, Tokamak Energy, ITER), Stellarators (Type One Energy, Wendelstein 7-X)	e.g. NIF, Xcimer and Marvel Fusion, First Light Fusion (projectile impact with separate ignition step)	e.g. Helion, General Fusion, Zap Energy
Most advanced	*Emerging*	*Emerging*

Fusion: Most advanced players unlikely to achieve commercial deployment until late 2030’s, with the 2040’s more likely

Maturity spectrum for nuclear fusion technologies (2020-2050)



Leader in magnetic confinement, but still experimental; ARC pilot needed for commercial relevance in 2030s.

Most advanced ICF startup; aiming for power-relevant pilots in the 2030s

Aiming for a highly ambitious 2028 delivery of 50MW to Microsoft; aspirational given current R&D stage

Fusion: progress is real, but commercial viability before the 2040s is improbable due to four key barriers

Four barriers are preventing the rapid development of nuclear fusion:

1

Sustained operation

No device yet maintains stable plasma at grid-relevant uptime

2

Materials

Extreme neutron flux degrades chamber walls: no proven long-life solutions

3

Fuel cycle

Tritium breeding at scale remains untested

4

Economics

FOAK pilots will be expensive, and long-term OPEX is uncertain

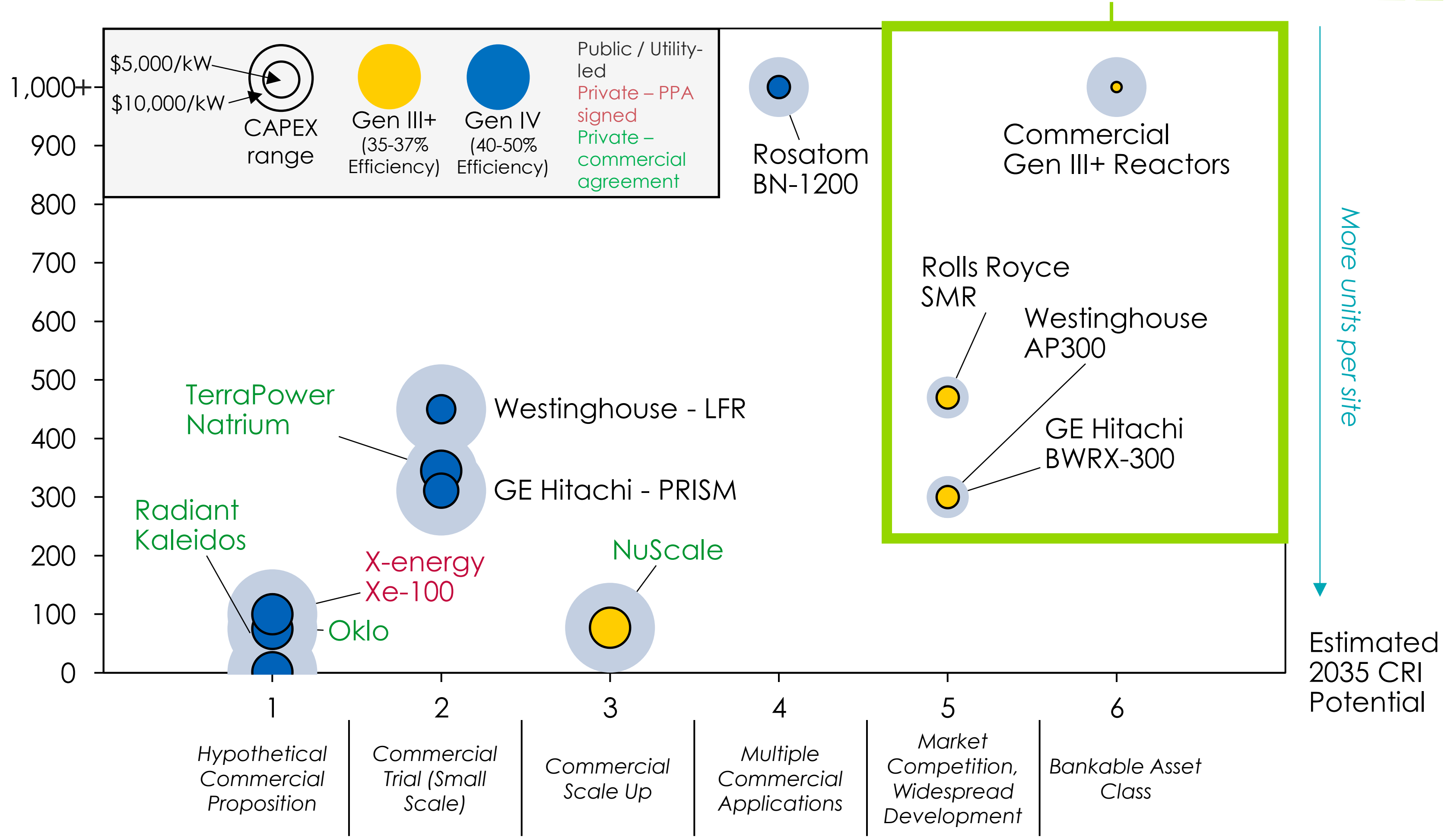
Fusion has shifted from science to engineering, but commercial relevance before the 2040s is improbable.

Its long-term role hinges on solving fuel, materials, and cost challenges in the next 10–15 years.

Conclusion: Next-decade nuclear deployment will be dominated by large Gen III+ fission reactors, while Gen IV remain lower-readiness and higher-risk

Illustrative diagram of the unit size and Commercial Readiness Index (CRI) of selected designs

Unit Size (MWe)



Deployment in the next decade will be dominated by designs using:

1. **Conventional technology** (e.g., Gen III+) with a more certain pathway to cost reduction / regulatory approval
2. **Large unit sizes** (e.g., 300+ MW) to capture plant-level economies of scale
3. **Standardisation and modularisation** to offer a route to low-cost via:
    - Manufacturing efficiencies
    - FOAK to NOAK learning

The impact / scalability of innovations to improve efficiency (e.g. via new fuels and designs) and modularisation both **remain largely unproved in practice**

Notes: Circle diameter represents CAPEX scale. CRI 1 = TRL 2-8; CRI 2 = TRL 9. Commercial Gen III+ Reactors include reactors such as AP1000, EPR, APR-1400, HPR-1000. FOAK = first of a kind, NOAK = nth of a kind. Source: Systemiq analysis for the ETC (2025); ARENA (2014), *Commercial Readiness Index for Renewable Energy Sectors*

Nuclear power generation: costs

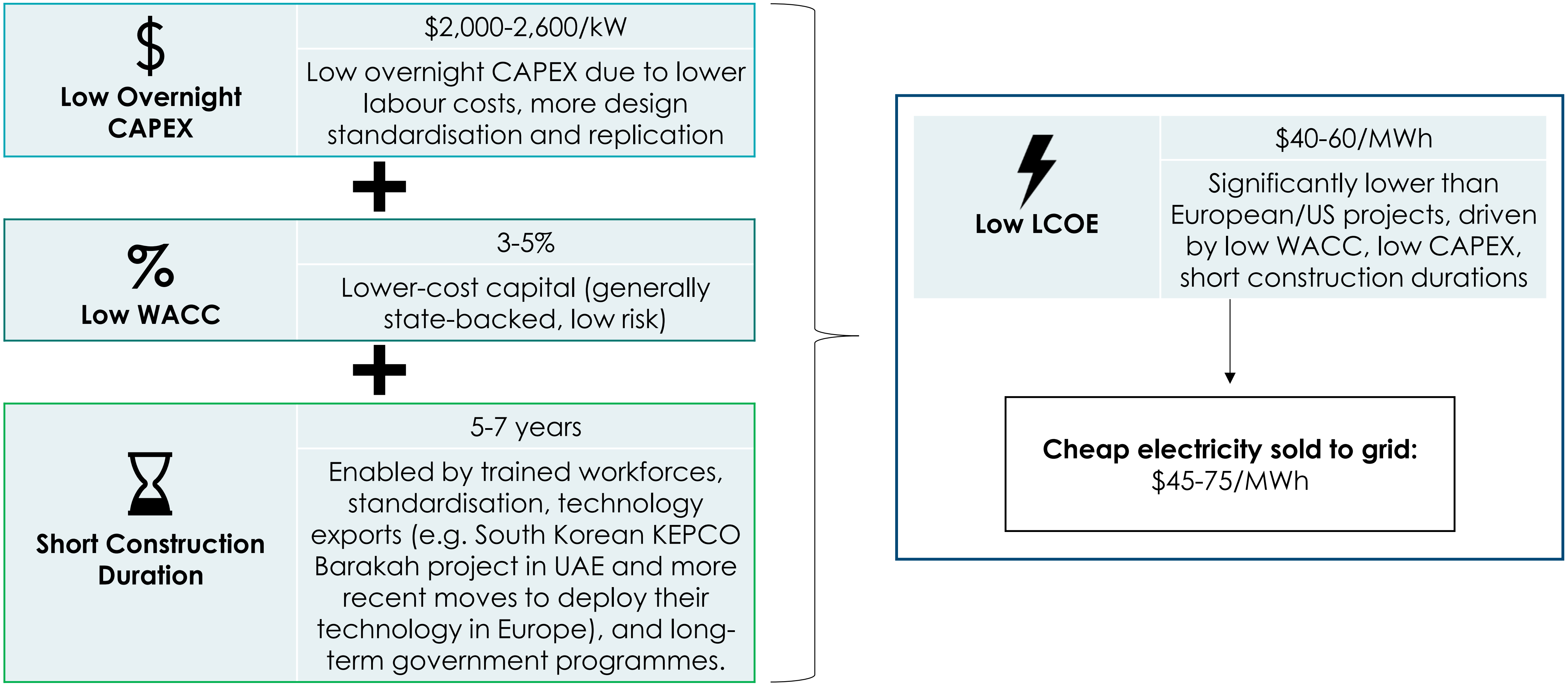
Nuclear project costs made up of several key categories

Capital Expenditure (CAPEX)	Overnight CAPEX	Plant construction expenses including site preparation, equipment and materials, labour, project management, training, and the initial fuel load.
	Financing costs	Interest during construction (IDC) and other costs of capital linked to project duration and risk
Operating Expenditure (OPEX)	Fuel costs	Uranium procurement, enrichment, fabrication, and ongoing spent fuel handling during operation
	O&M costs	Staffing, maintenance, security, insurance, regulatory compliance Contributions to waste and decommissioning funds
Decommissioning Expenditure (DECEX)	Decomm-issioning	Plant decommissioning expenses accounting for the full dismantling of the facilities at end-of-life.
	Waste management	Waste management expenses include activities related to handling all radioactive materials.

LCOE / Sold power price

Source: Energy Technologies Institute (2020), *The ETI Nuclear Cost Drivers Project*

Key drivers of successful Gen III+ nuclear deployment in China and South Korea: low capital expenditure (CAPEX), low cost of capital (WACC), and short construction durations



Low Overnight CAPEX

$2,000-2,600/kW

Low overnight CAPEX due to lower labour costs, more design standardisation and replication

+

Low WACC

3-5%

Lower-cost capital (generally state-backed, low risk)

+

Short Construction Duration

5-7 years

Enabled by trained workforces, standardisation, technology exports (e.g. South Korean KEPCO Barakah project in UAE and more recent moves to deploy their technology in Europe), and long-term government programmes.

Low LCOE

$40-60/MWh

Significantly lower than European/US projects, driven by low WACC, low CAPEX, short construction durations

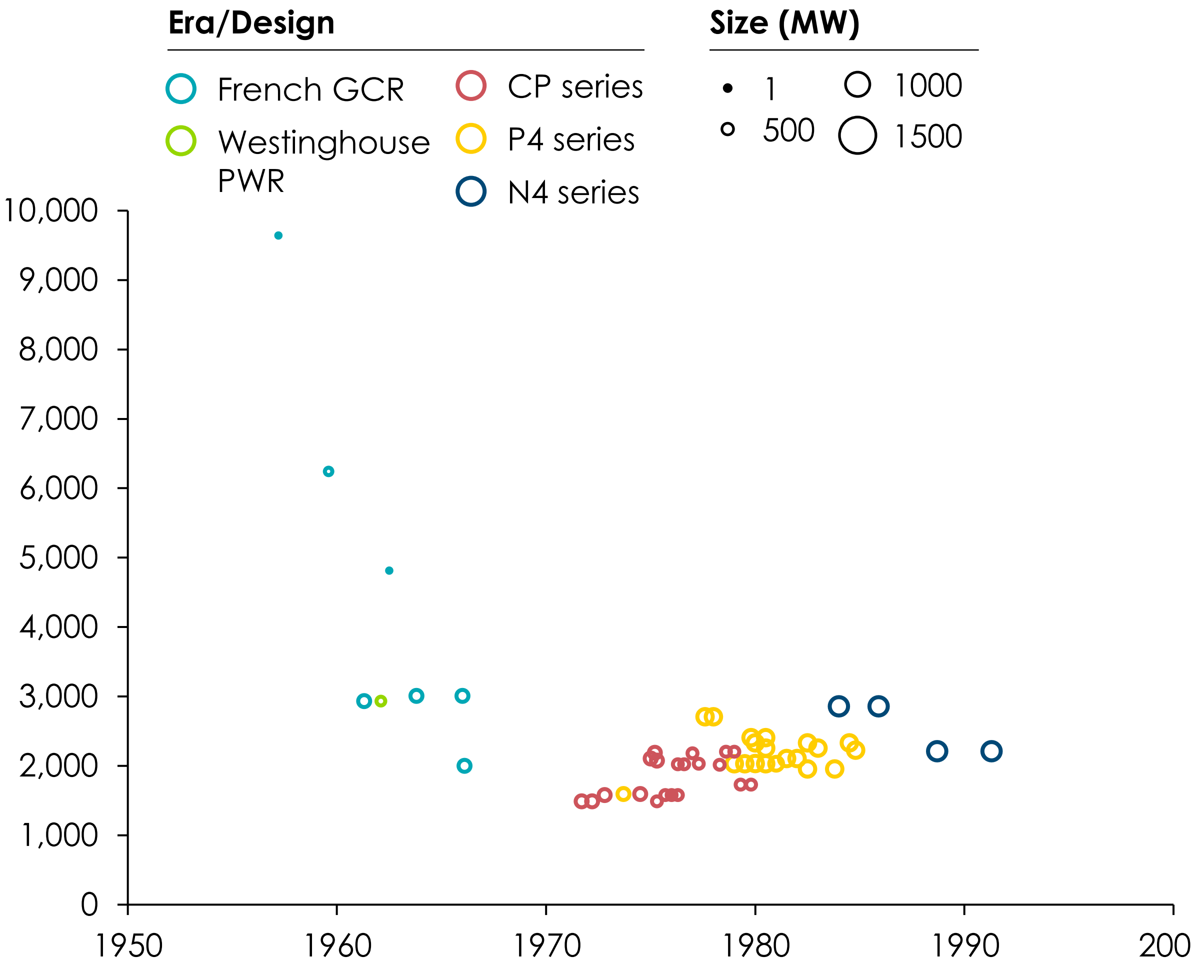
Cheap electricity sold to grid:
$45-75/MWh

Sources: GreenPrizm (2023), *Summary of 2023 Report on Chinese Nuclear Power Generation and Costs Analysis*; Y. Rong et al. (2021), *Discount Rate of China's New Energy Power Industry*; IAEA (2016), *Nuclear Contracting Toolkit - Discount Rate*; Breakthrough Institute (2024), *China's Impressive Rate of Nuclear Construction*; Ritchie; Our World in Data (2020), *Nuclear Energy*; Financial Times (2024), *South Korea pushes to export nuclear reactors to Europe*; KEI (2022), *South Korea's Economic Rationale for Nuclear Energy*; World Nuclear Association (2025), *Nuclear Power in China*.

France’s large-scale nuclear programme in the 1970s and 1980s helped to slash power prices, with government intervention

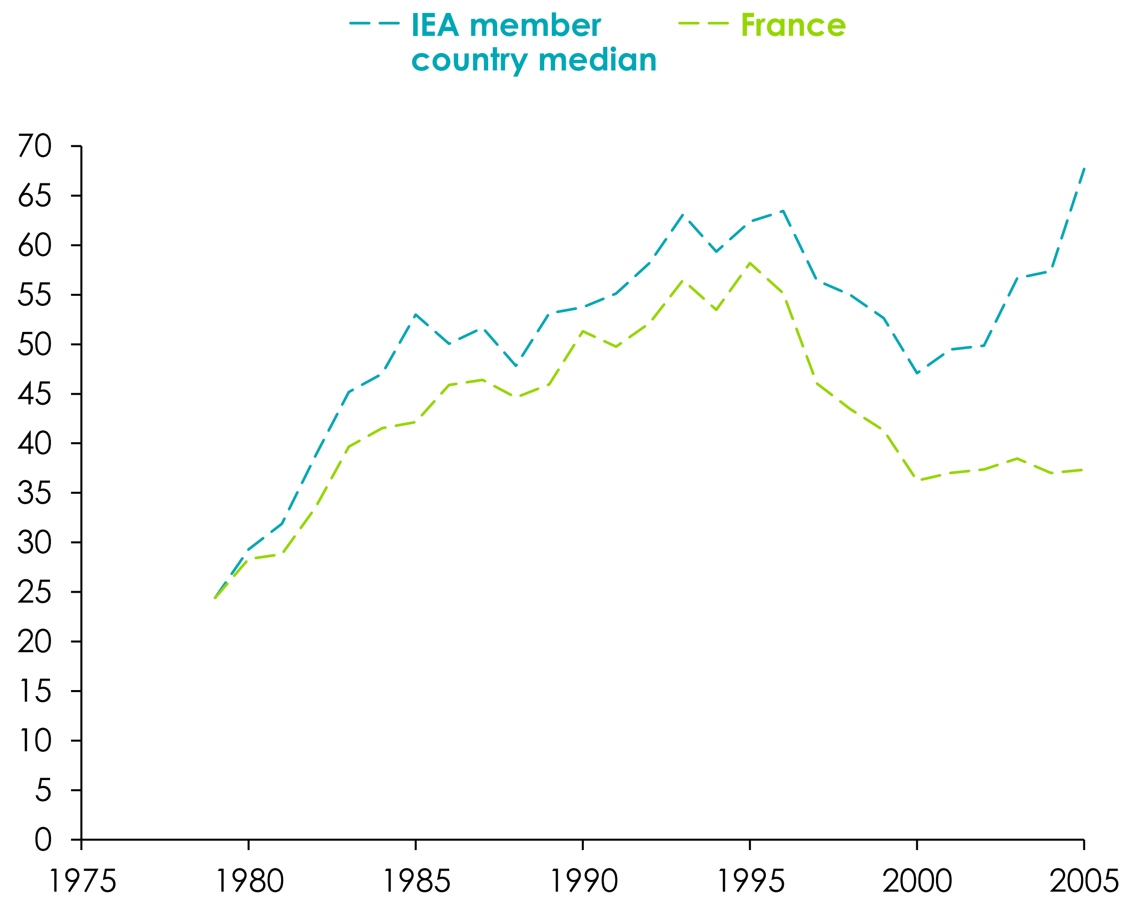
Overnight CAPEX for French nuclear fleet

$/kW, real 2024



France vs other countries industrial electricity prices

$/MWh, real 2024

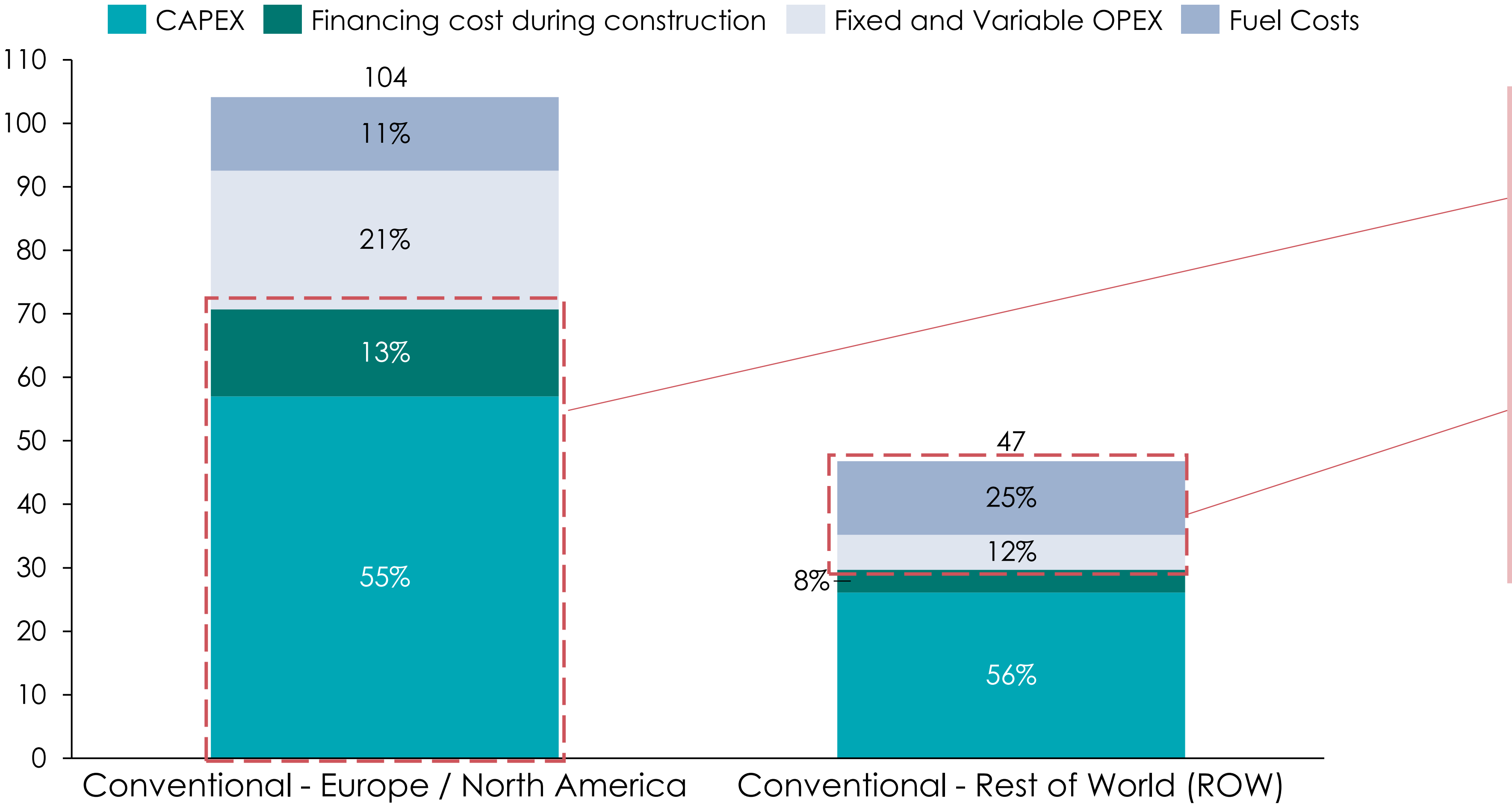


Notes: All nuclear power stations in France are pressurized water reactors (PWR). French GCR refers to gas-cooled reactors, CP, P4, and N4 refer to specific types of PWR designs. Source: J. R. Lovering (2016) *Historical construction costs of global nuclear power reactors*; UK Department for Energy Security and Net Zero (2024) *Energy Prices International Comparisons*

Upfront costs drive levelised costs of energy (LCOE), but operating costs have a higher relative influence outside of Europe / North America

Conventional nuclear LCOE breakdowns for Europe/North America vs Rest of World

$/MWh, real 2024



In Europe and North America, higher construction costs and financing dominate

OPEX plays larger relative role in **ROW** due to lower capital costs from shorter build times and standardised designs

Source: Energy Technologies Institute (2020), *The ETI Nuclear Cost Drivers Project*

Overall, key levelized cost driver is CAPEX, including financing

- **Overall, CAPEX, including financing cost, is the key driver of LCOE**
  - Build costs (equipment, labour, materials, indirect services) and financing costs are the largest components
  - Construction schedule length and risk management critical to avoid cost escalation
    - Financing costs, especially interest during construction, are highly sensitive to construction time and risk. Longer build durations sharply increase cost
    - Standardisation, modularisation, and repeat builds (fleet effects) could enable learning, supply chain efficiency, and shorter build times

- **Fuel costs contribute relatively little to overall levelized cost**
  - Efficiency improvements in fuel use (e.g. from advanced reactor designs) will have limited overall impact

All nuclear project costs made up of several key categories

Capital Expenditure (CAPEX)	Overnight CAPEX	Plant construction expenses including site preparation, equipment and materials, labour, project management, training, and the initial fuel load.
	Financing costs	Interest during construction (IDC) and other costs of capital linked to project duration and risk
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LCOE / Sold power price

Source: Energy Technologies Institute (2020), *The ETI Nuclear Cost Drivers Project*

Nuclear CAPEX is mainly driven by indirect services (site management), interest during construction and equipment costs

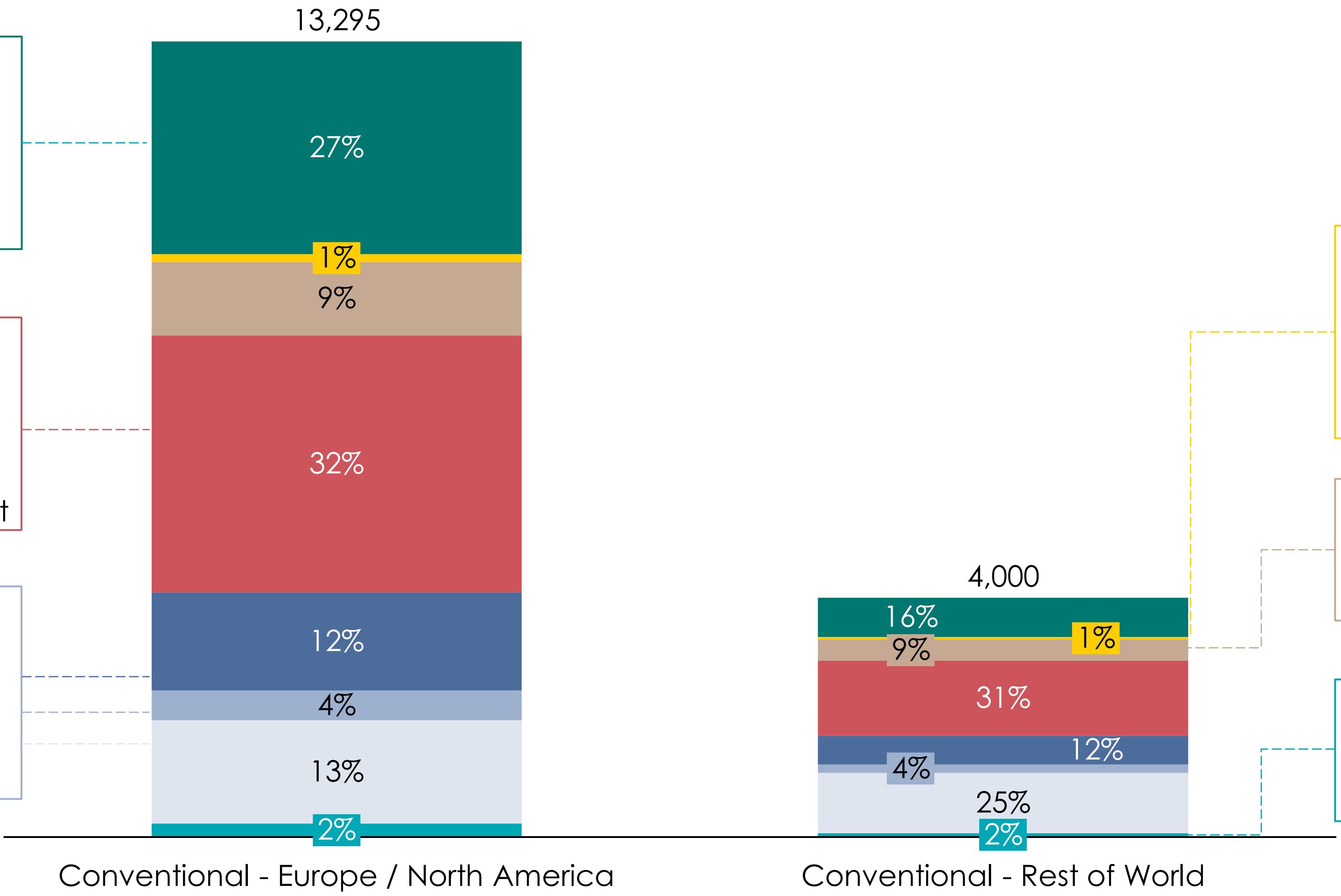
Conventional nuclear CAPEX breakdowns for Europe/North America vs Rest of World

$/kW, real 2024

Financial cost
Escalation; fees; interest during construction (IDC); contingency on financial costs

Indirect services (site management) costs
Field indirect, supervision, commissioning, project management

Direct construction costs, including;
- Labour
- Materials
- Equipment



Supplementary costs
Includes shipping and transportation costs, spare parts, taxes, insurance, decommissioning

Owner's costs
Staff, training, housing, other owner's costs

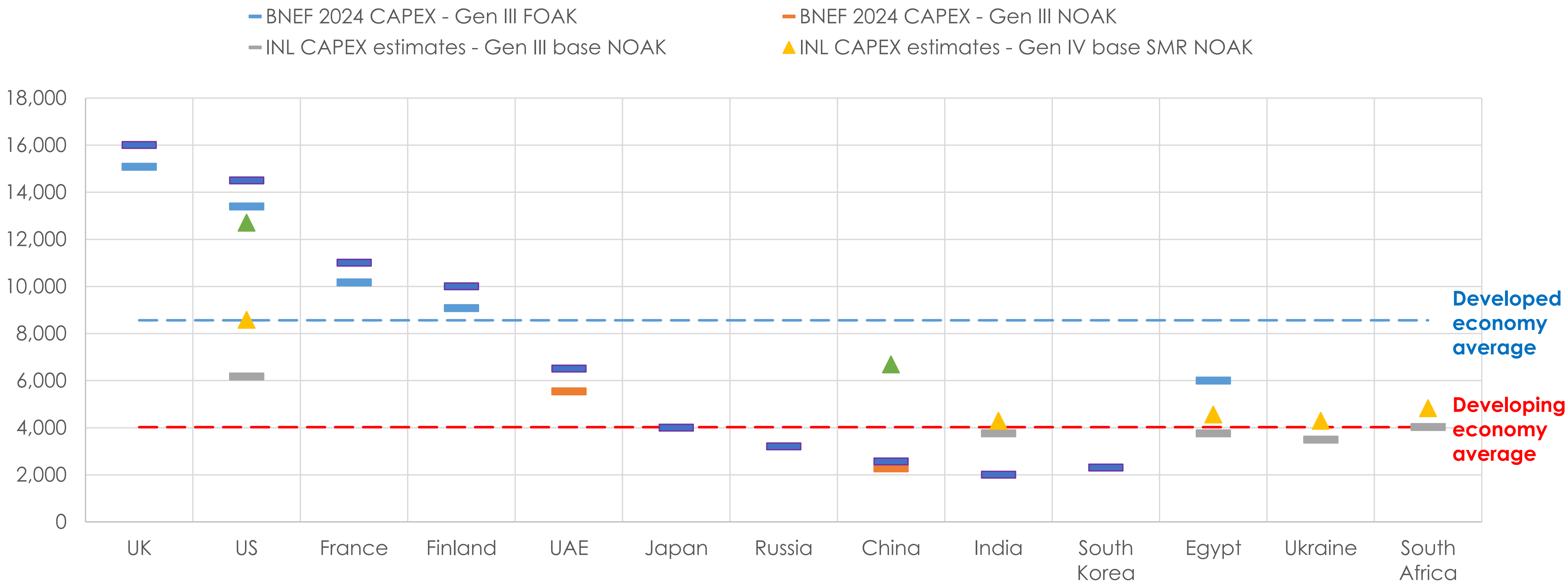
Pre-construction costs
Includes land, licensing, permits, studies

Note: Assumptions on financing costs: 7% WACC (real, pre-tax) assumed for all plants; assumed quicker build schedule for 'Rest of World' category, which reduces the interest during construction. Lower-cost financing would result from a more predictable construction schedule and state-backed financing or state-run Export-Import (EXIM) banks (that typically have lower interest rates). Source: Energy Technologies Institute (2020), *The ETI Nuclear Cost Drivers Project*

CAPEX varies significantly by country, driven by regulation complexity and supply chain readiness / costs

CAPEX estimates by country, FOAK vs NOAK; Gen III vs Gen IV

$/kW, real 2024

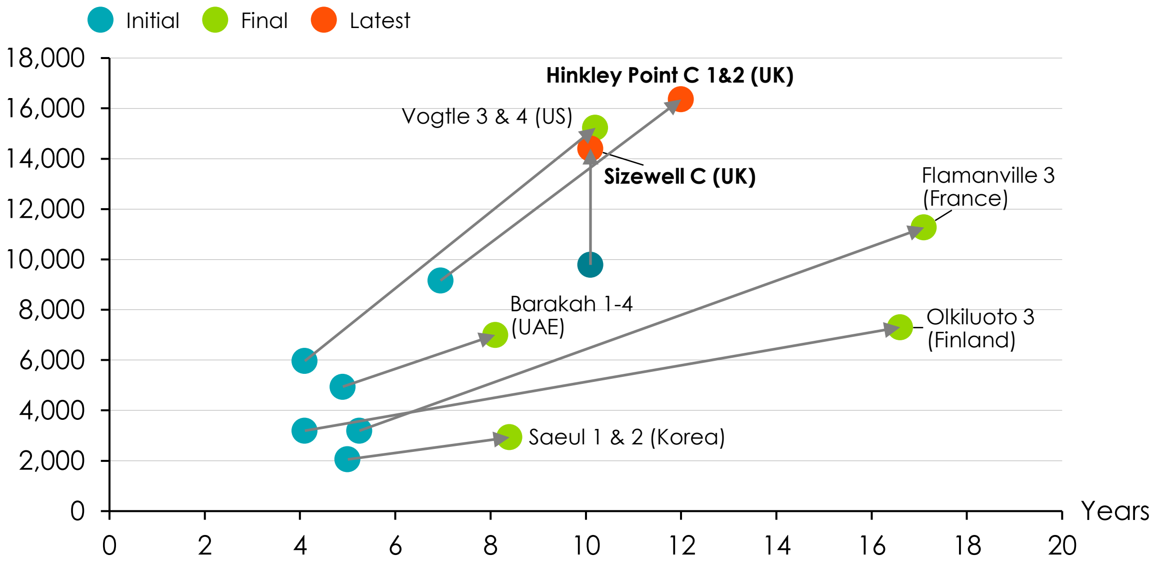


Notes: FOAK = 1st of a kind; NOAK = nth of a kind.
Source: BNEF (2025), *LCOE Data Viewer*; INL (2024), *Nuclear Energy Cost Estimates for Net Zero World Initiative – 2024 Update*; Financial Times (2025), *Cost of Sizewell C nuclear project expected to reach close to £40bn*; Green Prizm (2024), *2023 Report on Chinese Nuclear Power Generation and Costs Analysis*

Recent UK projects show first of a kind (FOAK) reactor construction increasing in cost and duration; degree of detailed design completion is critical

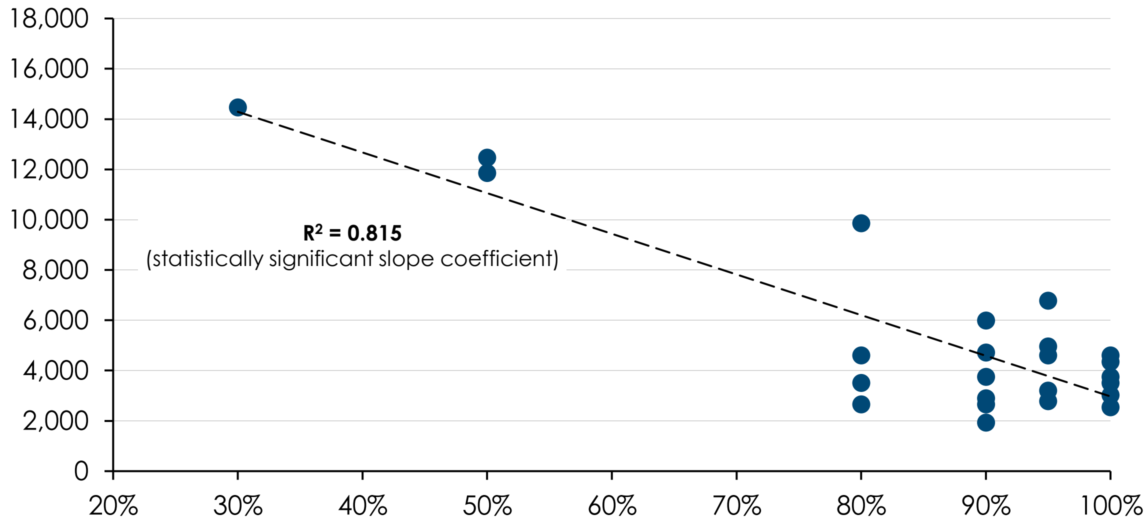
Initial and latest CAPEX estimates and construction times

$/kW, real 2024



CAPEX vs detailed design completion percentage at construction start

$/kW, real 2024



Increases driven by:

1. **Lack of replication due to FOAK project design in UK**, limiting learning-by-doing and productivity gains
2. **Long construction timeline**, increasing exposure to long-tail risks (e.g. geopolitical, financial, regulatory)
3. **Safety-driven overengineering**, adding complexity, cost, and regulatory burden
4. **High capital costs**, delayed returns, increasing cost of capital and investment risk

- Level of plant design detail required by the regulator during the licensing/certification process is lower than the design detail required for actual construction.

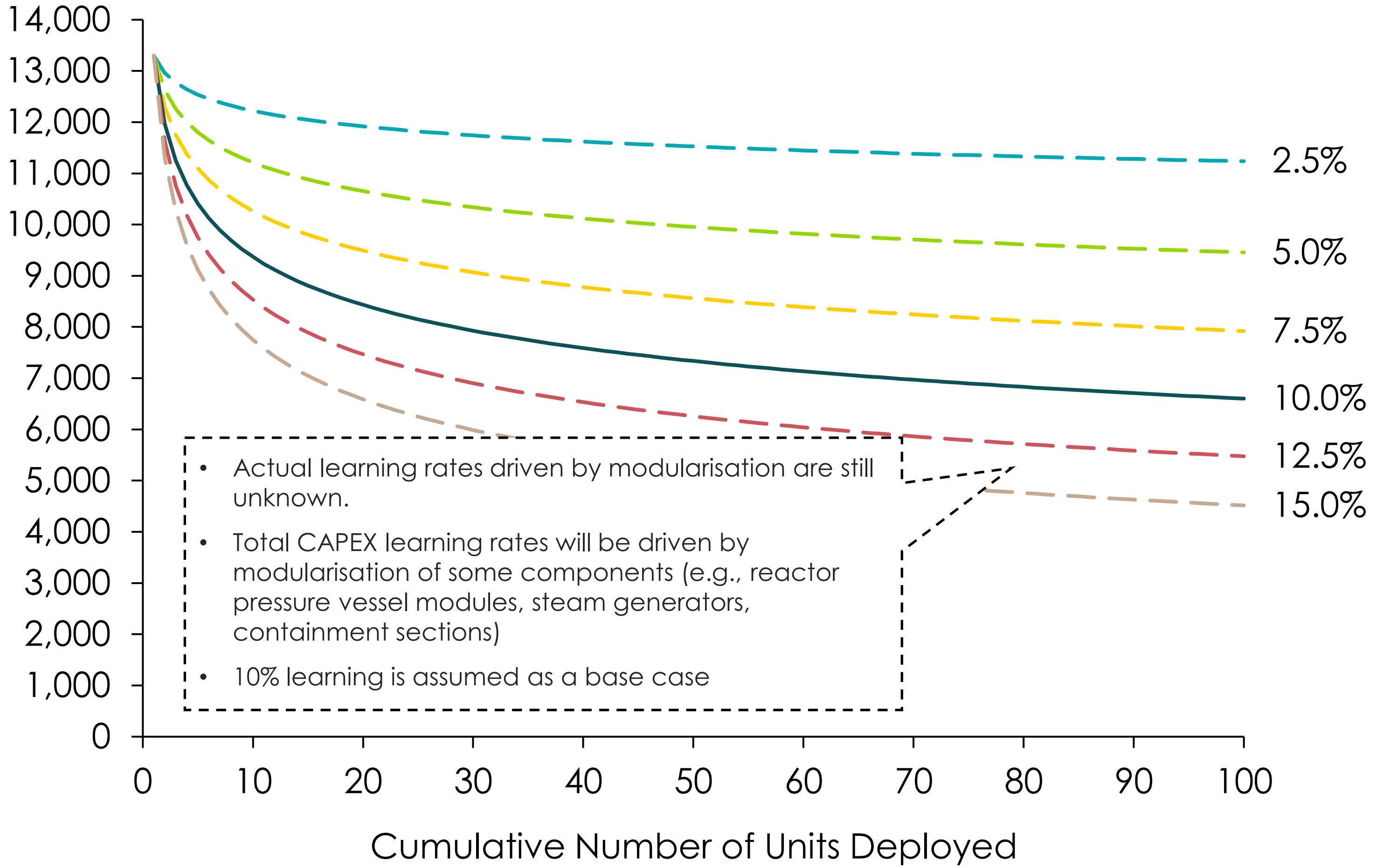
- **The higher the design completion at construction start, the higher the chance of staying within budget**, showing the important of completing design work prior to starting construction.

Notes: This figure captures the range of projects in the ETI Cost Database, spanning Europe, North America, and RoW.
Source: Financial Times (2025), *Can the nuclear industry find a better way to build?;* Energy Technologies Institute (2020), *The ETI Nuclear Cost Drivers Project*

Commercial-scale SMR and advanced reactor CAPEX are still unknown; reductions will depend on standardisation and economies of scale in manufacturing processes

Theoretical impacts of modularisation on learning rates and CAPEX (Conventional - Europe / US)

$/kW, real 2024



- Actual learning rates driven by modularisation are still unknown.
- Total CAPEX learning rates will be driven by modularisation of some components (e.g., reactor pressure vessel modules, steam generators, containment sections)
- 10% learning is assumed as a base case

SMR and advanced reactor vendors aim to cut construction costs through:

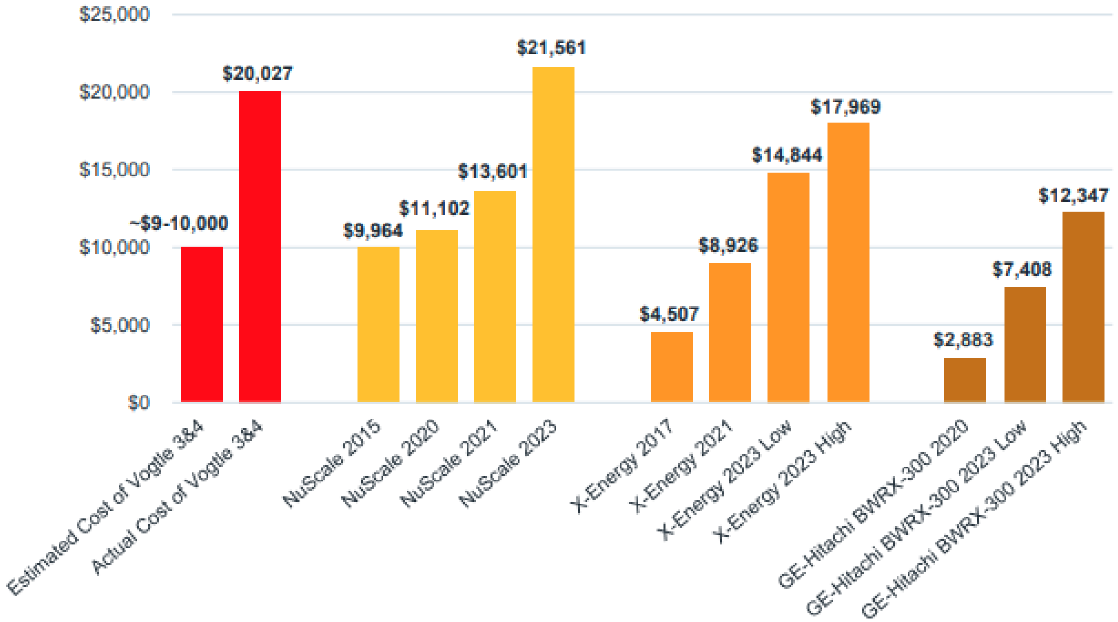
- Reduced on-site scope, duration, and labour via simpler designs, fewer buildings, and fewer safety systems.
- High factory fabrication of modules and components, enabling faster, higher-quality, and lower-risk construction.
- Standardised, modular designs that minimise site-specific engineering, leverage repeatable manufacturing, and use commercial components.
- Design for reuse and constructability, including seismic isolation to cut site-specific costs.
- Lower operating staff needs due to inherent safety and potential for remote/virtual operation.

Notes: High Temp Gas Reactors includes very-high-temperature and gas-cooled reactors; Liquid Metal Fast Reactors includes Sodium-cooled and lead-cooled reactors. SCWRs are excluded from this analysis due to lower design maturity and data availability.
Source: Energy Technologies Institute (2020), *The ETI Nuclear Cost Drivers Project;* Thunder Said Energy (2025), *Nuclear SMRs: grown ups?*

SMR cost projections increasing; diversity of designs barrier to standardisation

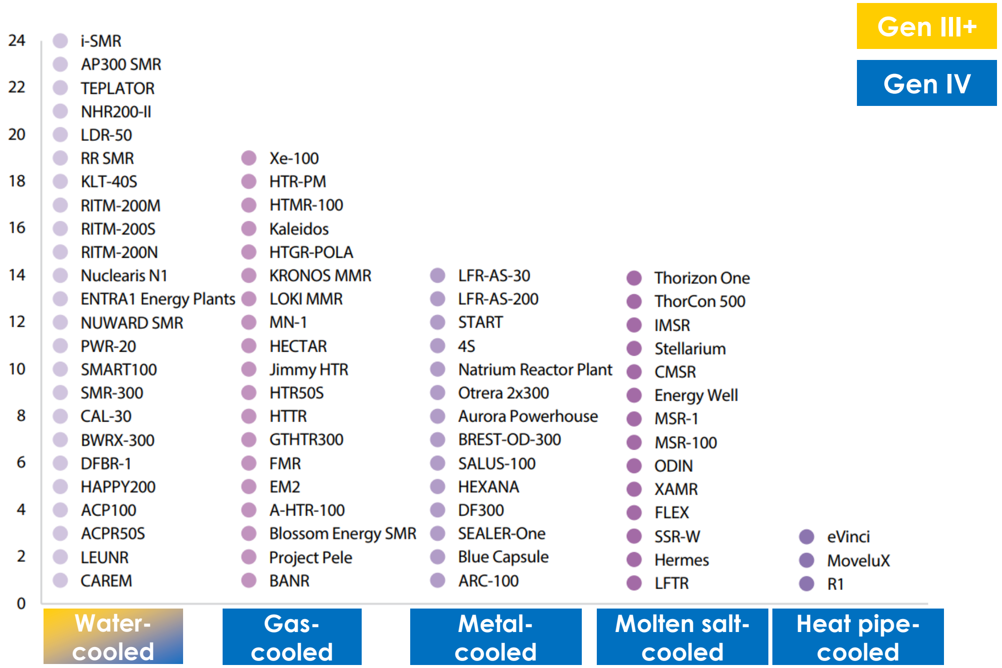
Projected cost increases for proposed US SMR's

$/kW, real 2023



SMR concepts in development by reactor type

Number of concepts in development



SMR vendors in the US have cited an increase in the following factors as cause behind rising costs;

- Inflationary pressures for construction materials
- Higher labour costs
- Increased interest rates
- Supply chain constraints for equipment

Key barrier:

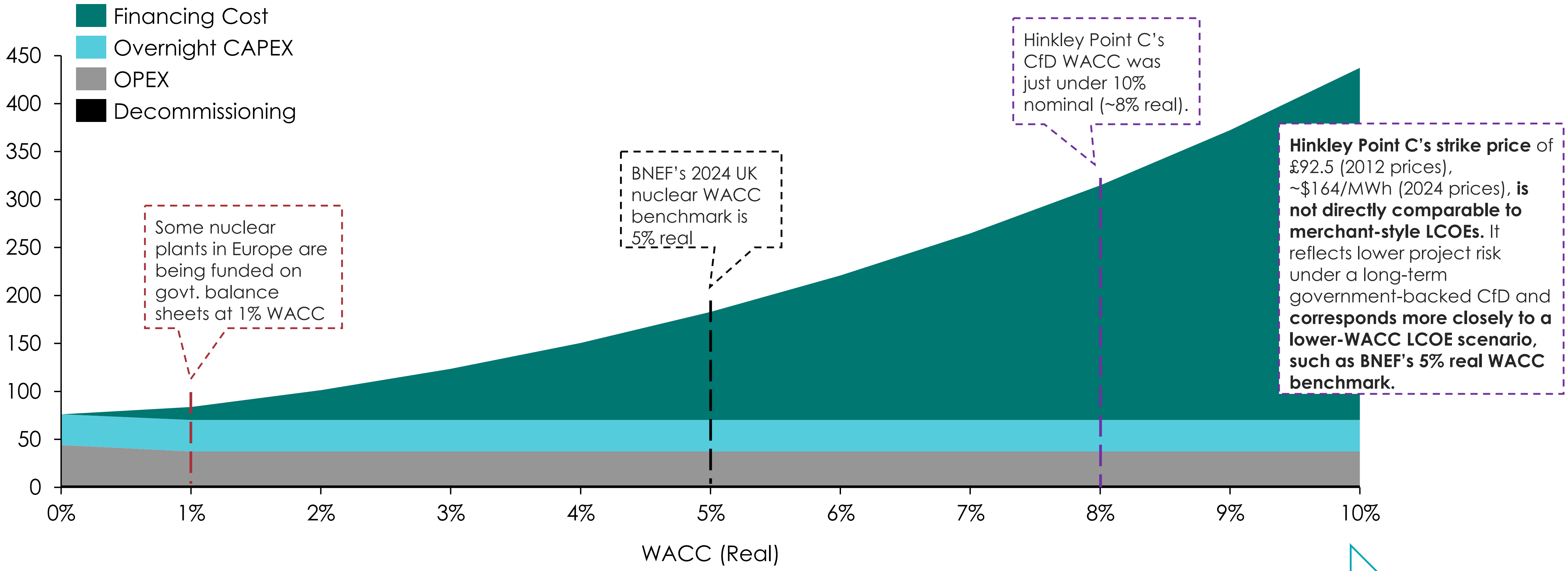
- Consolidation is needed to unlock the standardisation and economies of scale that all SMR developers promise
- However, standardisation cannot happen with >100 designs competing for market share

Source: IEEFA (2023) Small Modular Reactors; Still Too Expensive, Too Slow and Too Risky; Source: NEA (2025), *The NEA Small Modular Reactor Dashboard: Third Edition*.

The weighted average cost of capital (WACC) is a key nuclear LCOE sensitivity

UK conventional nuclear 2024 sensitivity to WACC

$/MWh, real 2024



Some nuclear plants in Europe are being funded on govt. balance sheets at 1% WACC

BNEF's 2024 UK nuclear WACC benchmark is 5% real

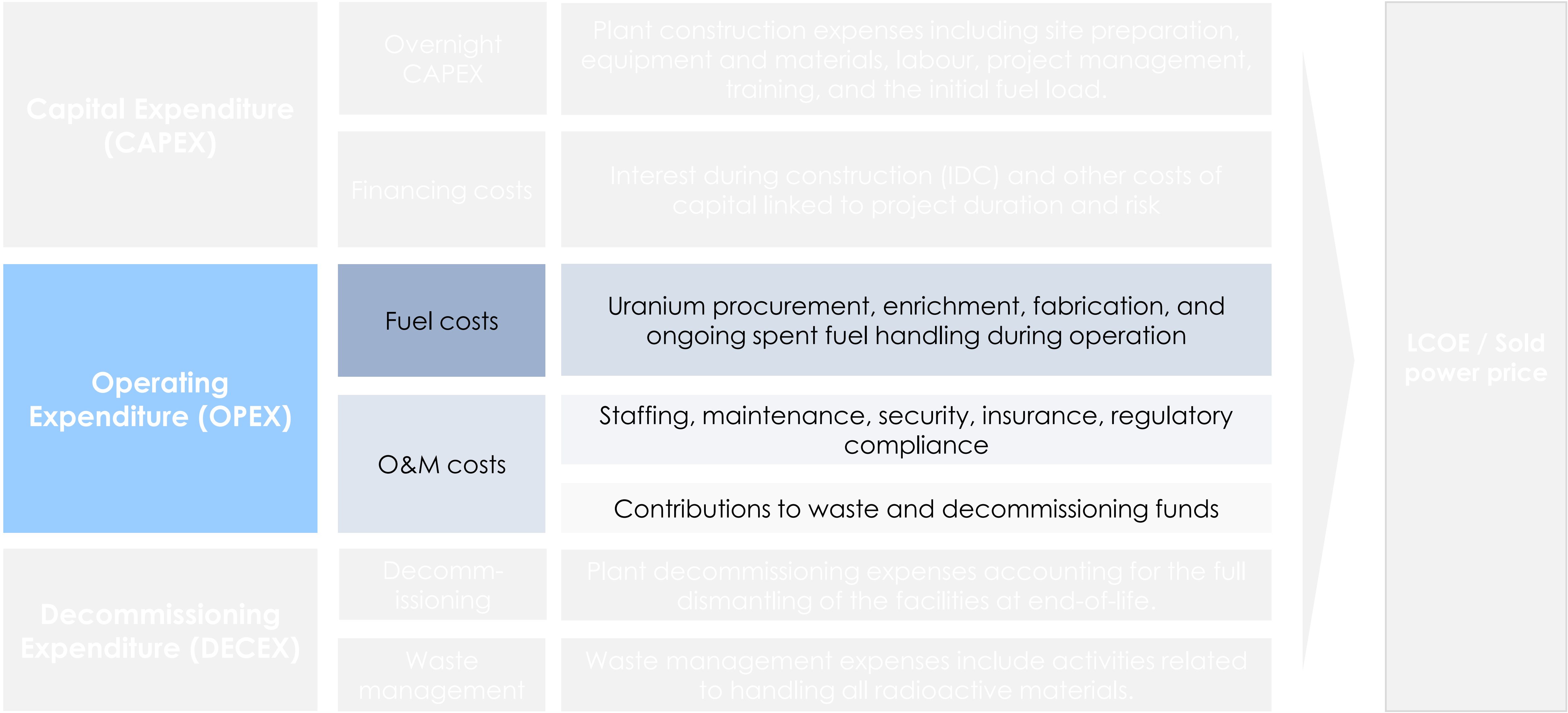
Hinkley Point C's CfD WACC was just under 10% nominal (~8% real).

Hinkley Point C's strike price of £92.5 (2012 prices), ~$164/MWh (2024 prices), **is not directly comparable to merchant-style LCOEs.** It reflects lower project risk under a long-term government-backed CfD and **corresponds more closely to a lower-WACC LCOE scenario, such as BNEF's 5% real WACC benchmark.**

Higher risk = higher investor returns = higher WACC = higher LCOE

Notes: CfD = Contracts for Difference, CAPEX = Capital Expenditure, OPEX = Operating Expenditure (incl. fueling), DECEX = Decommissioning Expenditure. Overnight CAPEX is the total CAPEX excluding financing costs. Only WACC varies as a sensitivity.
Source: BNEF (2025), *LCOE Data Viewer*, INL (2024), *Nuclear Energy Cost Estimates for Net Zero World Initiative*

All nuclear project costs made up of several key categories



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LCOE / Sold power price

Source: Energy Technologies Institute (2020), *The ETI Nuclear Cost Drivers Project*

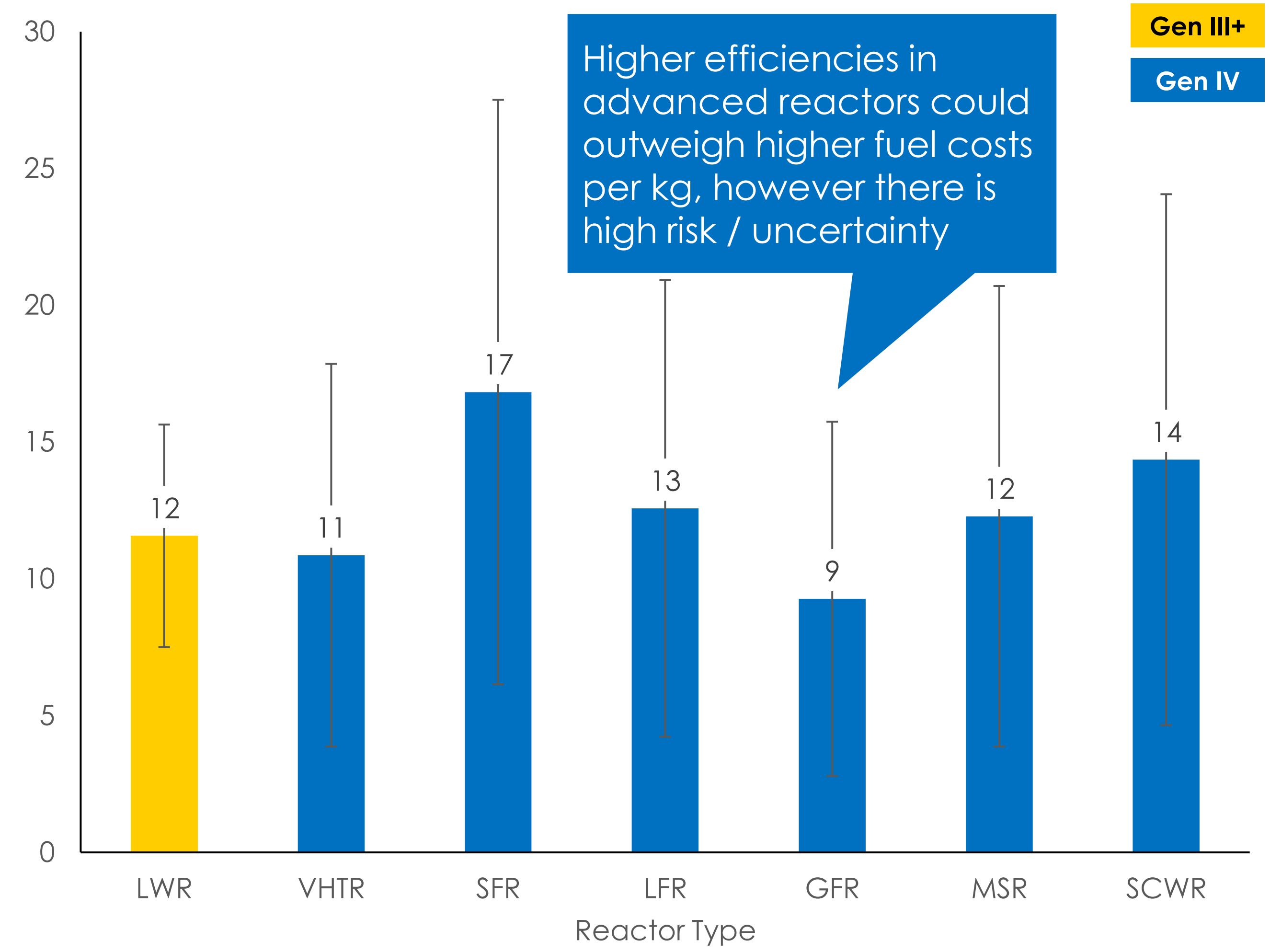
Fuel costs per unit electricity output are in a similar range across Gen III+ and Gen IV designs, despite variations across fuel costs, burnup, and efficiency

Fuel costs (per MWh electricity) can be calculated using fuel costs (per kg), reactor burnup (thermal energy per tonne of fuel), and efficiency (of thermal to electrical conversion) as follows:

$$\text{Fuel cost } (\$/\text{MWh}_e) = \frac{\text{Fuel cost } (\$/\text{kg})}{\text{Burnup } (\text{MWd}_{th} / \text{kg}) \times 24 \text{ (h per day)} \times \text{Efficiency } (\%)}$$

Estimated fuel cost per unit electricity output by reactor design

$/MWh, real 2024



Higher efficiencies in advanced reactors could outweigh higher fuel costs per kg, however there is high risk / uncertainty

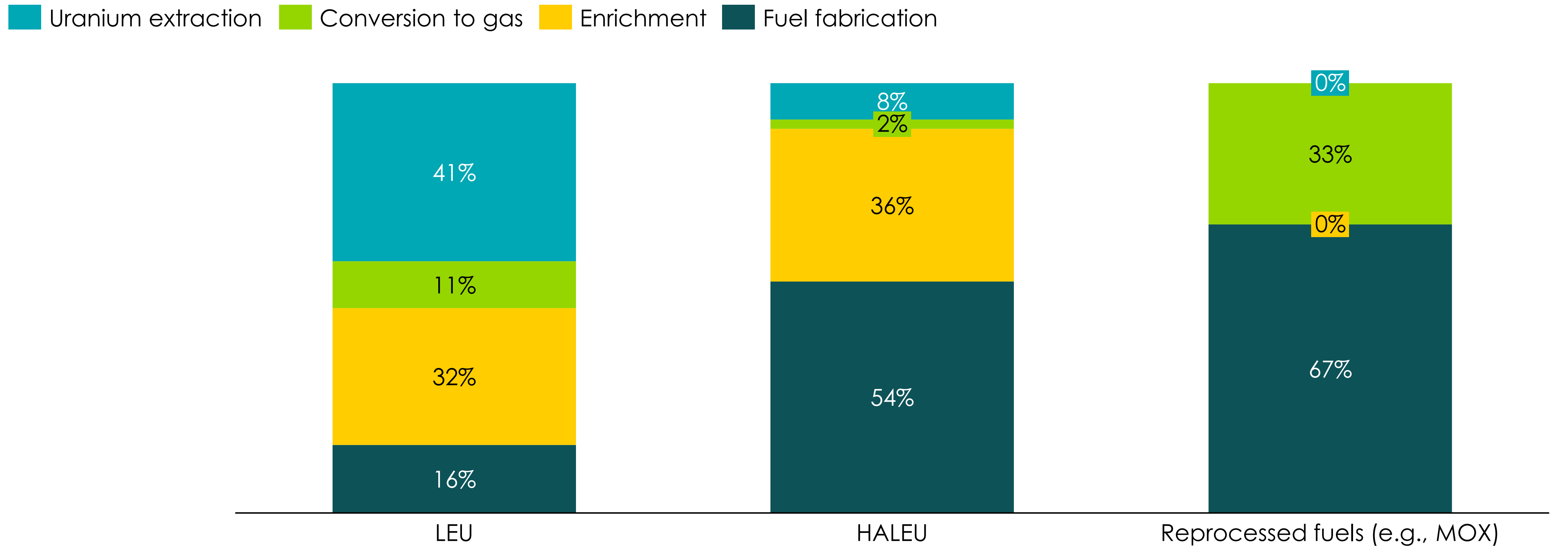
Notes: $\text{MWd}_{th}/\text{kg} = \text{GWd}/\text{t}_{th}$; LWR = Conventional Light Water Reactor; VHTR = Very High Temperature Reactor; SFR = Sodium-cooled Fast Reactor; LFR = Lead-cooled Fast Reactor; GFR = Gas-cooled Fast Reactor; MSR = Molten Salt Reactor; SCWR Supercritical Water-cooled Reactor

Fuel cycle costs are determined by four main stages: uranium extraction, conversion to gas, enrichment, and fuel fabrication

- Uranium is mined as yellowcake (U_3O_8), converted to UF_6 gas, and enriched in centrifuges.
- Conventional reactors use 3-5% low enriched uranium (LEU), while some Gen IV reactors need 5-20% high-assay low enriched uranium (HALEU).
- Weapons-grade uranium is ~90% U-235.

Estimated front end fuel cycle costs per kg of UO_2 fuel

%

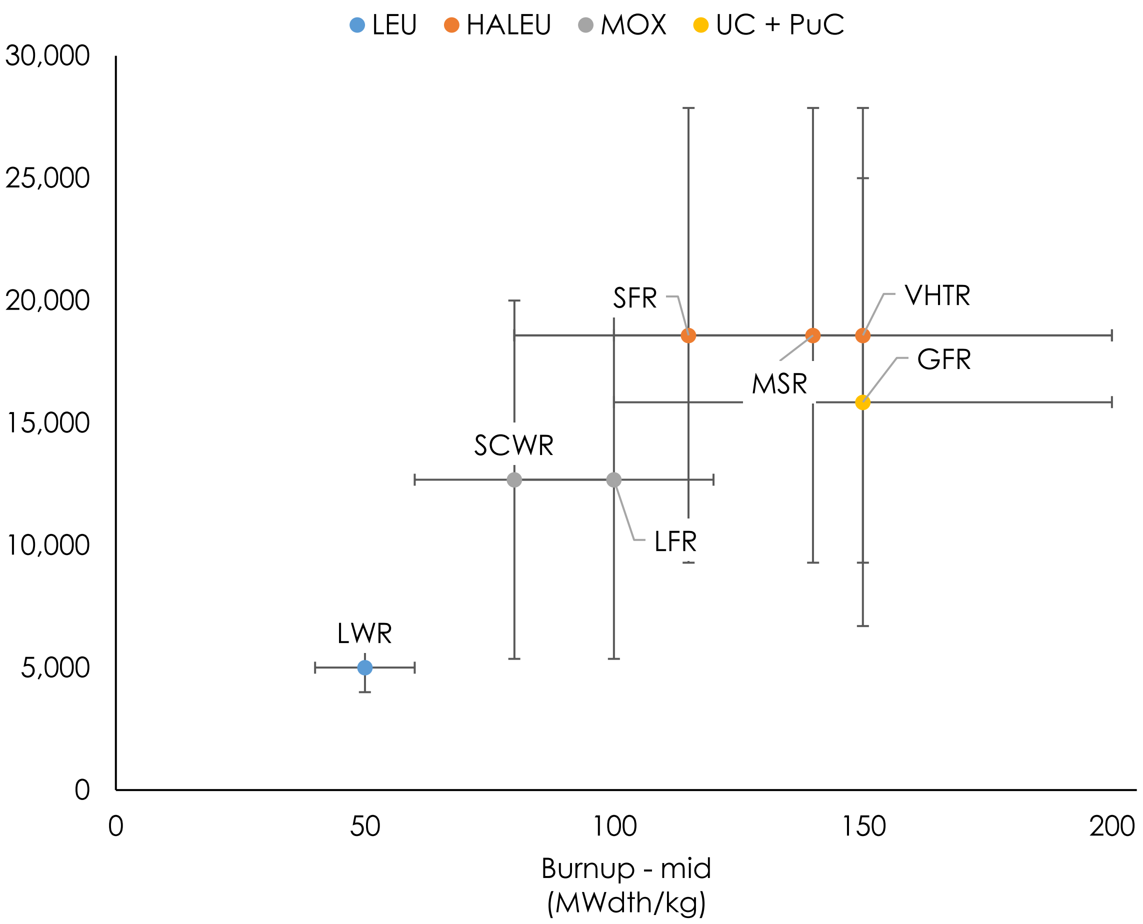


Notes: MOX = Mixed Oxide Fuel (UO_2 + PuO_2)
Source: UxC (2025), *Market Outlooks*, David Turner (2024), *The Looming Uranium Shortage*

Fuel costs, reactor burnup, and thermal to electrical efficiency vary significantly by reactor design

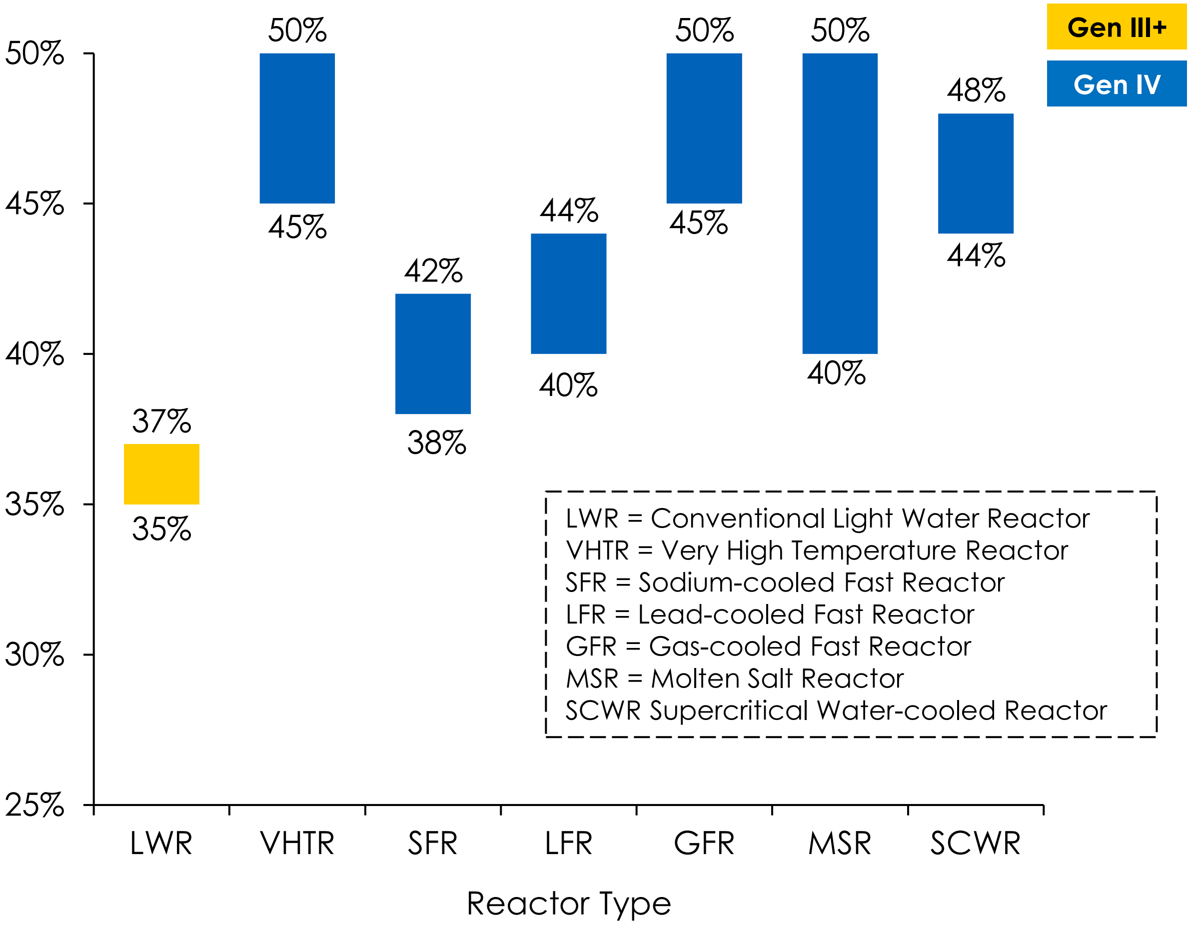
Approximate fuel cost vs burnup rate ranges by fuel type

$/kg (range of estimates shown by error bars)



Estimated thermal to electrical conversion efficiency by reactor design

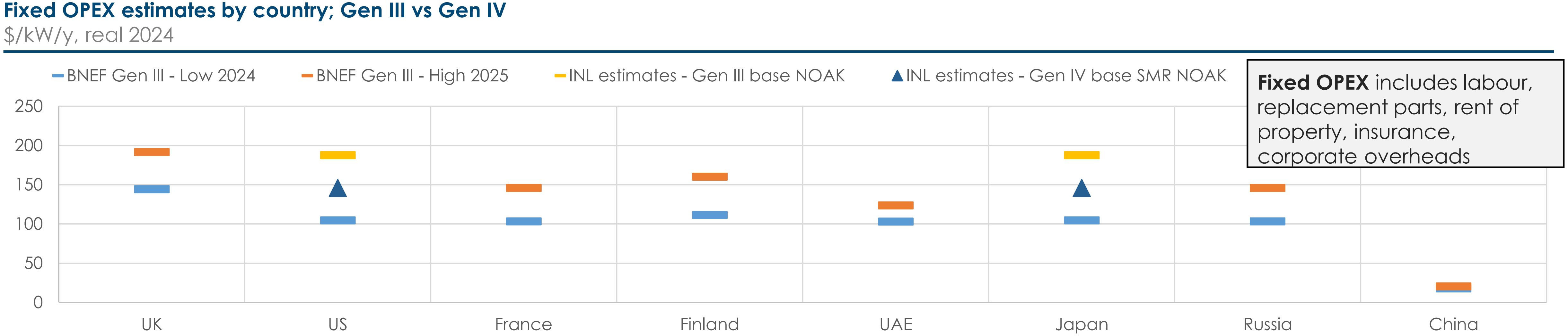
% range



LWR = Conventional Light Water Reactor
VHTR = Very High Temperature Reactor
SFR = Sodium-cooled Fast Reactor
LFR = Lead-cooled Fast Reactor
GFR = Gas-cooled Fast Reactor
MSR = Molten Salt Reactor
SCWR Supercritical Water-cooled Reactor

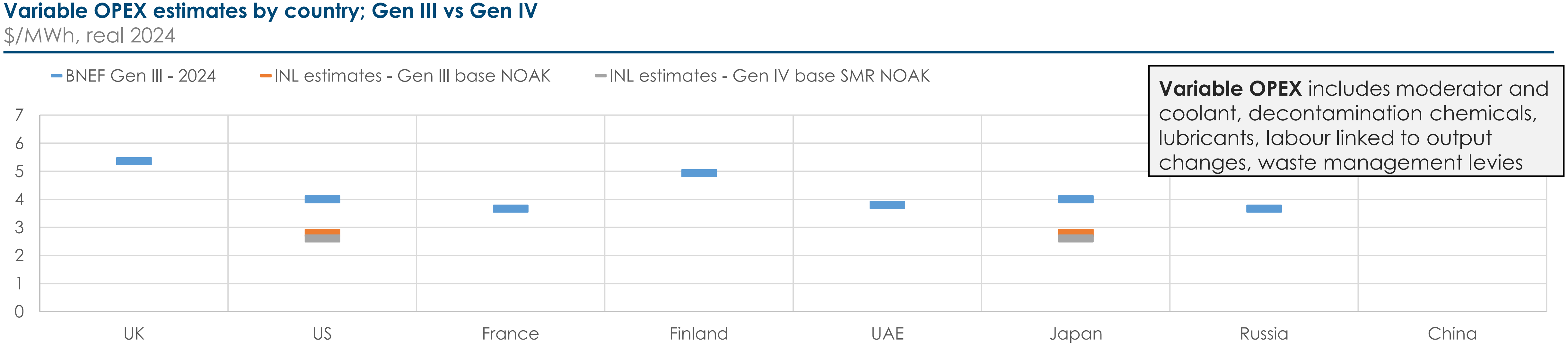
Notes: LEU = Low Enriched Uranium (<5% U-235); HALEU = High-Assay Low-Enriched Uranium (5-20% U-235); MOX = Mixed Oxide Fuel (UO_2 + PuO_2); UC + PuC = mixed uranium-plutonium carbide; Burnup is the thermal energy output (MWd_{th}) per unit mass of fuel burned. Source: World Nuclear Association (2023), Economics of Nuclear Power; Michael Hewitt (2025), *Investment in a Nuclear Startup – Fuel Decision Tree*

Fixed OPEX varies by reactor design and by country, whereas variable OPEX is consistent


Fixed OPEX estimates by country; Gen III vs Gen IV

$/kW/y, real 2024

Fixed OPEX includes labour, replacement parts, rent of property, insurance, corporate overheads


Variable OPEX estimates by country; Gen III vs Gen IV

$/MWh, real 2024

Variable OPEX includes moderator and coolant, decontamination chemicals, lubricants, labour linked to output changes, waste management levies

Source: BNEF (2025), *LCOE Data Viewer*; INL (2024), *Nuclear Energy Cost Estimates for Net Zero World Initiative – 2024 Update*

All nuclear project costs made up of several key categories

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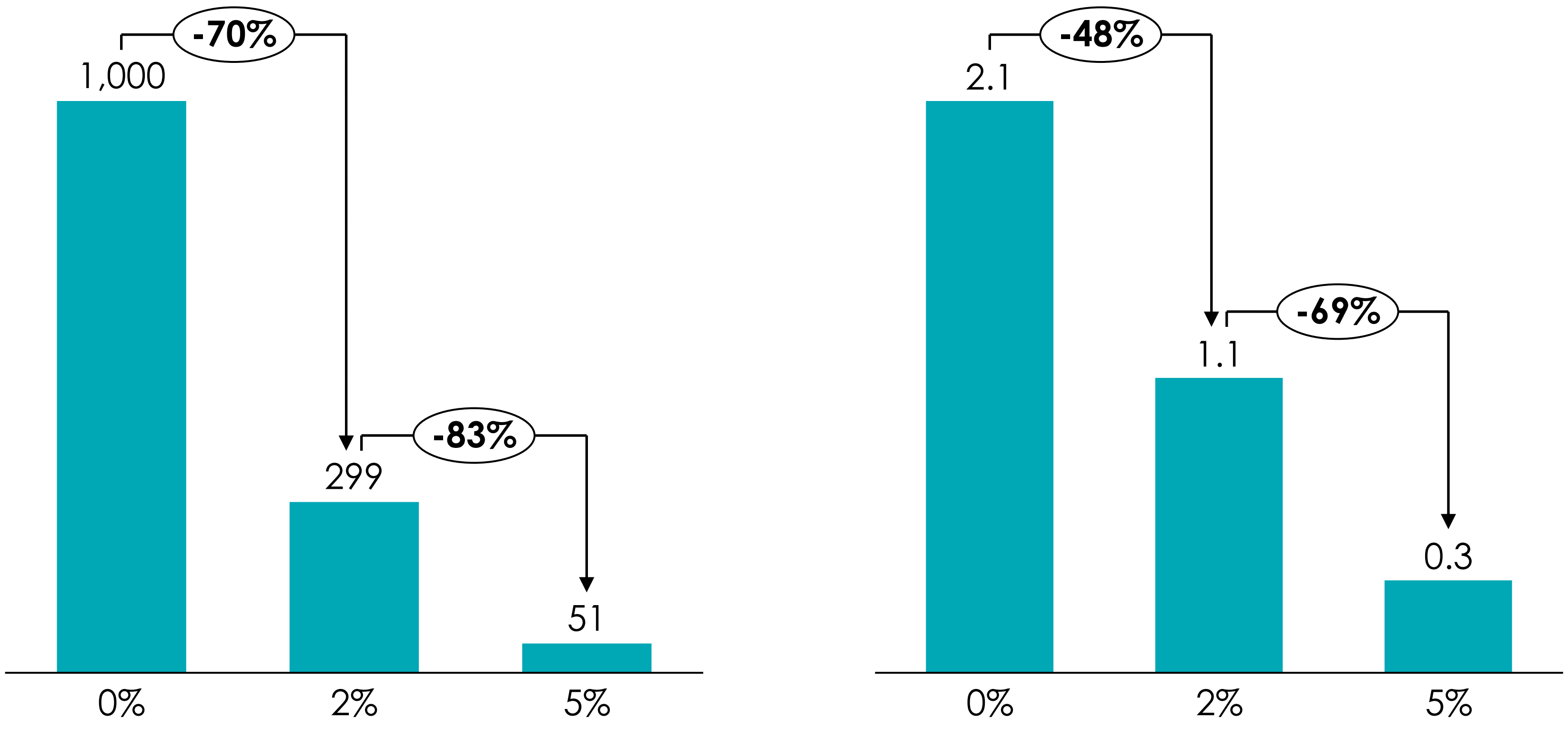
LCOE / Sold power price

Source: Energy Technologies Institute (2020), *The ETI Nuclear Cost Drivers Project*

The 'present value' of decommissioning and waste disposal costs are relatively low, regardless of discount rate

Net present value of DECEX for a 1 GW project
$m, real 2024

LCOE contribution of DECEX for a 1 GW project
RHS - $/MWh, real 2024



Discount Rate
(1 GW project, 60-year life, 90% capacity factor)

- Decommissioning (including waste disposal) costs ~$1m/MW in today's money
- For a 1 GW project, this would add ~$1b to the project cost but only $2/MWh to LCOE (at a 0% discount rate)
- Contributing 1.5% of revenue per year over the project life builds up sufficient funds to pay off DECEX at end-of-life[1].
- Despite discounting, decommissioning activities will incur long-term costs in the future so should be accounted for in project design / programme planning

Notes: [1]Assuming $60/MWh average revenue and 3% (real) average annual returns.
Source: INL (2024), *Nuclear Energy Cost Estimates for Net Zero World Initiative*

All nuclear project costs made up of several key categories

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LCOE / Sold power price

Source: Energy Technologies Institute (2020), *The ETI Nuclear Cost Drivers Project*

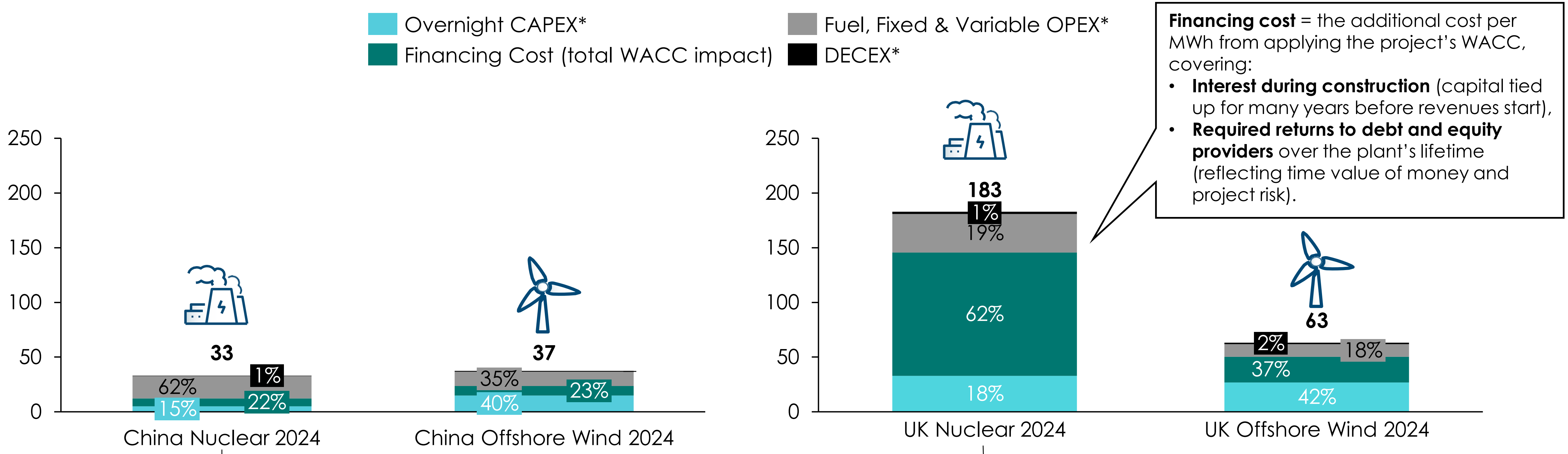
Estimates of levelised cost of energy (LCOE) are diverging across regions and alternative technologies

China: Nuclear and offshore wind indicative LCOE breakdown

$/MWh, real 2024

UK: Nuclear and offshore wind indicative LCOE breakdown

$/MWh, real 2024



Financing cost = the additional cost per MWh from applying the project's WACC, covering:

- **Interest during construction** (capital tied up for many years before revenues start),
- **Required returns to debt and equity providers** over the plant's lifetime (reflecting time value of money and project risk).

China Nuclear 2024:

- **WACC:** 3%, real
- **Overnight CAPEX:** $2,400/kW
- **Construction time:** 6 years
- **Capacity factor:** 90%

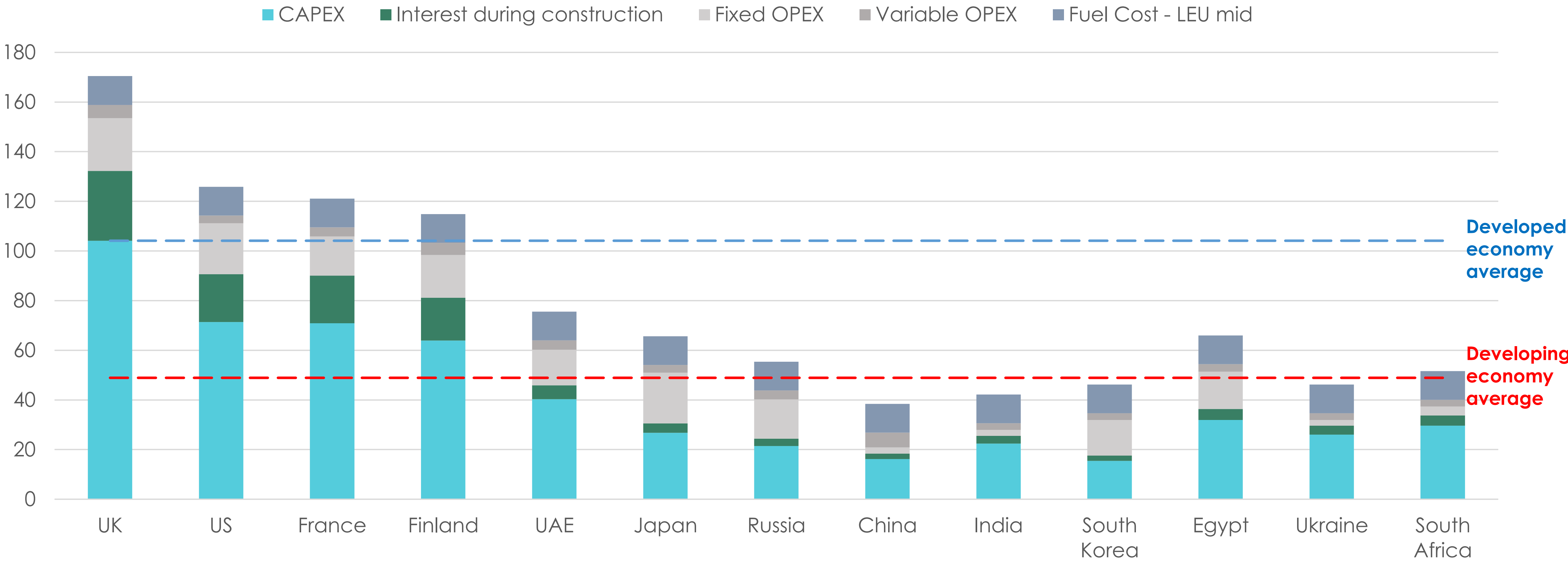
UK Nuclear 2024:

- **WACC:** 5%, real
- **Overnight CAPEX:** $15,500/kW
- **Construction time:** 10 years
- **Capacity factor:** 90%

Notes: CAPEX, OPEX, & DECEX shown with 0% WACC applied to separate WACC impact into Financing Cost. CF = Capacity Factor, WACC = weighted average cost of capital (real), CAPEX = Capital Expenditure, OPEX = Operating Expenditure (incl. fueling), DECEX = Decommissioning Expenditure. Overnight CAPEX is the total CAPEX excluding financing costs. Source: *BNEF LCOE Data Viewer,* INL (2024), *Nuclear Energy Cost Estimates for Net Zero World Initiative*, ORE Catapult (2021), *End-of-life planning in offshore wind*

There is a clear LCOE divergence between US / Europe and RoW, mainly driven by CAPEX and interest during construction

Current LCOE estimates by country, Gen III
$/MWh, real 2024



Notes: 5% WACC (real) assumed for all countries, to reflect likely government-backed loans/revenue models. Construction duration assumed to be 10y for US / Europe and 5y for RoW. Interest during construction (IDC) assumed CAPEX is spent evenly over construction duration (n), so the average interest accrues at WACC for n/2 years.
Source: Source: Energy Technologies Institute (2020), *The ETI Nuclear Cost Drivers Project; BNEF LCOE Data Viewer,* INL (2024), *Nuclear Energy Cost Estimates for Net Zero World Initiative*

Understanding “system value”

Understanding power “system value” requires accounting for full system costs

“System value” of power generation technology requires understanding full implications across total system costs

Definitions

System Cost Component	Definition
Generation costs (LCOE)	Generation asset costs (CAPEX & OPEX), including of wind, solar, nuclear, geothermal, hydro, gas
Curtailment costs	Costs associated with curtailing generation assets
Balancing costs	Costs of assets to provide balancing/flexibility/storage (CAPEX & OPEX), including batteries, pumped hydro, compressed air, gas peaking plants
Grid stability costs	Ancillary service costs to maintain grid stability across voltage (e.g., reactive power support, voltage control) and frequency (e.g., through reserves, inertia, fast frequency response)
Grid expansion costs	Additional grid build costs to connect generation assets to demand centres

Curtailment can be classified as either a generation or balancing cost

Studies on "system value" of nuclear don't include full suite of "total system costs", and often exclude full techno-economic detail…

Gap analysis of nuclear system cost impact studies

	System Value Assessment Criteria								
Study	**System cost inclusions**	**Recent (<2y)**	**Clean power system**	**Multiple weather years modelled**	**Geographical range (>1 continent)**	**Techno-economic detail (cost pathways, advanced tech considerations)**	**Modelling detail (nodal / dispatch analysis, DSF, storage etc)**	**Cross-sector analysis (H2, heat)**	**Optimistic on nuclear prospects?**
Sepulveda / Jenkins et al.	Generation, balancing	X	✓	X	X	X	✓	X	✓
Carbon Free Europe	Generation, balancing	X	✓	X	X	X	✓	✓	X
Göke et al.	Generation, balancing, grid expansion	✓	✓	X	X	X	✓	✓	X
Kan et al.	Generation, balancing, grid expansion	X	✓	X	X	X	✓	✓	X
Thellufsen et al.	Generation, balancing, grid expansion	✓	✓	X	X	X	✓	✓	X

There is a gap in the literature for studies which:

1. Incorporate recent techno-economic detail
2. Determine grid cost impacts (incl. stability)
3. Model multiple weather years
4. Span a range of geographies
5. Present results in a simple, digestible format

Sources: Sepulveda / Jenkins et al. (2018), *The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation*; Carbon Free Europe (2022), *Deployment of Nuclear Energy in the EU and UK Under Different Reactor Cost Assumptions*; Göke et al. (2025), *Flexible nuclear power and fluctuating renewables? — An analysis for*; Thellufsen et al. (2024), *Cost and system effects of nuclear power in carbon-neutral energy systems*; Kan et al. (2020), *The cost of a future low-carbon electricity system without nuclear power – the case of Sweden*

…overall they show that nuclear would have to be much cheaper than today’s US and European levels to be competitive

In US and Europe, recent nuclear CAPEX values are > $15,000/kW

Estimated nuclear CAPEX level needed for competitiveness vs clean alternatives by study

Study	Location	Nuclear CAPEX competitiveness threshold[1] ($/kW, real 2024)
Sepulveda / Jenkins et al.	**US**	8,750
Carbon Free Europe	**Europe**	5,045
Göke et al.	**Europe**	5,000
Kan et al.	**Sweden**	4,235
Thellufsen et al.	**Denmark**	1,677

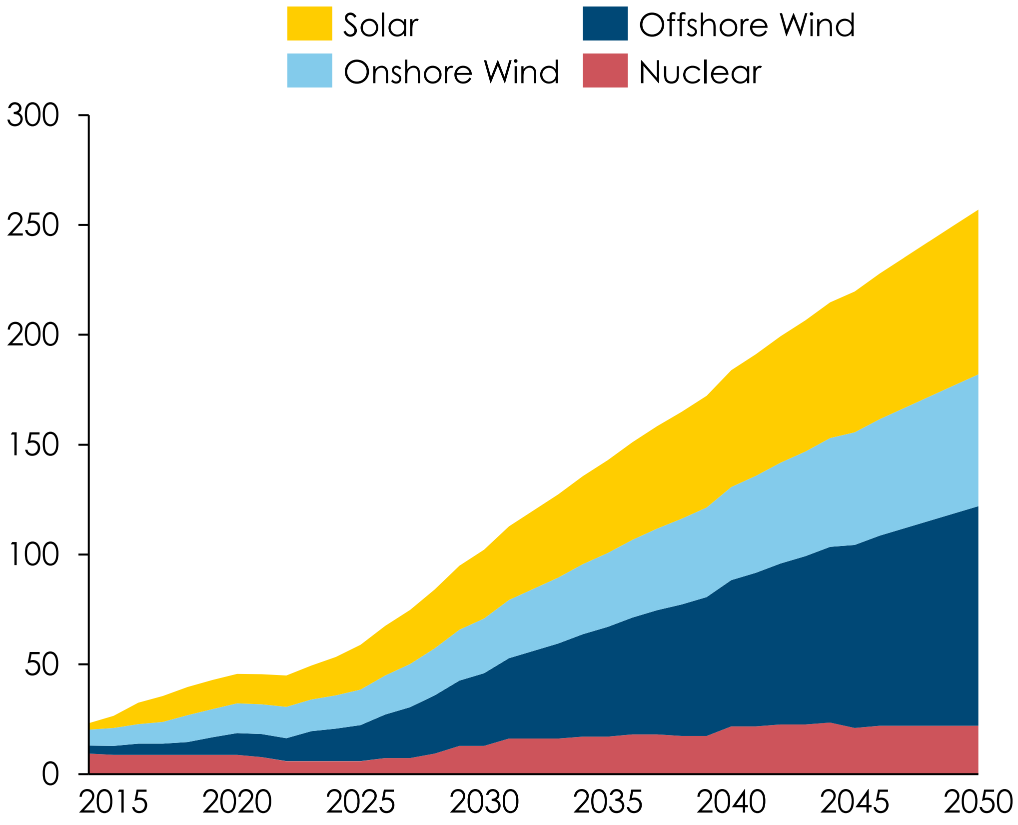
- Wide range of estimates for the competitiveness threshold
- Only the Sepulveda / Jenkins one is close to recent US/Europe CAPEX data points
- Europe and US focus excludes regions which are currently delivering nuclear projects below these thresholds (e.g., in Asia)
- Existing studies lack insights on advanced reactor implications

Notes: [1] The threshold below which nuclear becomes competitive with alternative generation technologies in clean power systems under each study’s assumptions.
Sources: Sepulveda / Jenkins et al. (2018), *The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation*; Carbon Free Europe (2022), *Deployment of Nuclear Energy in the EU and UK Under Different Reactor Cost Assumptions*; Göke et al. (2025), *Flexible nuclear power and fluctuating renewables? — An analysis for*; Thellufsen et al. (2024), *Cost and system effects of nuclear power in carbon-neutral energy systems*; Kan et al. (2020), *The cost of a future low-carbon electricity system without nuclear power – the case of Sweden*

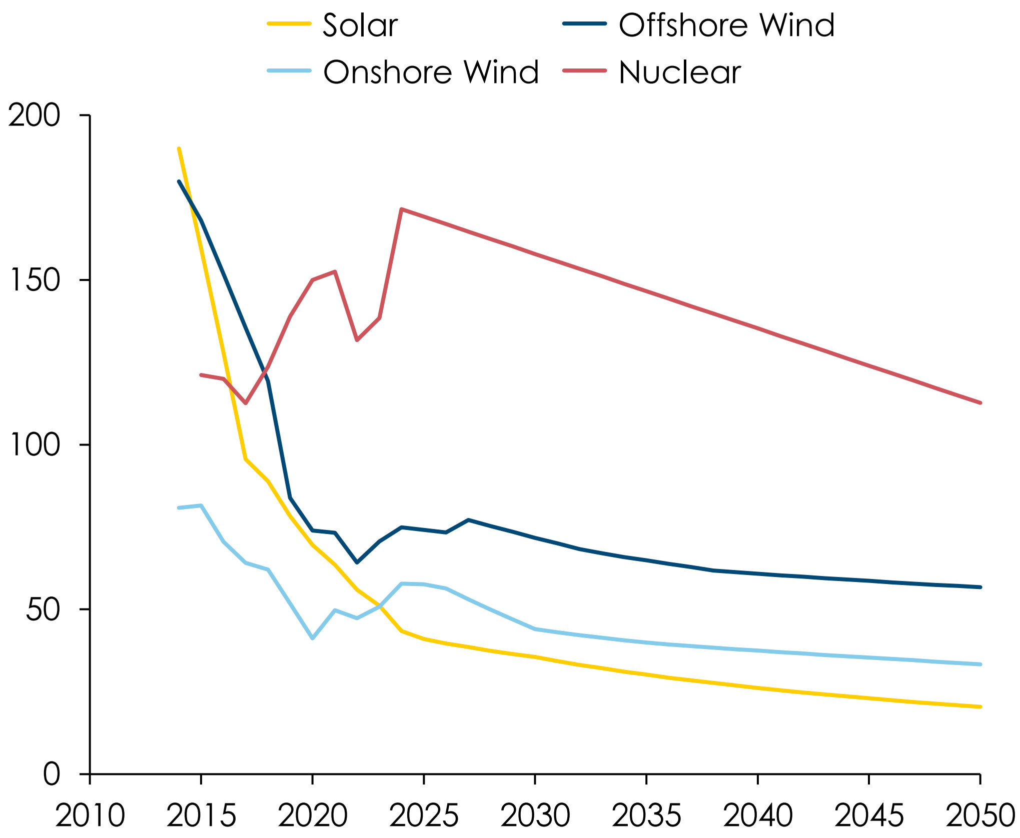
UK System Modelling (Windbelt)

Generation: Costs are set to decrease as installed capacity increases across all generation technologies, particularly onshore wind and solar

Installed capacity by technology over time in the UK in ETC scenarios
GW



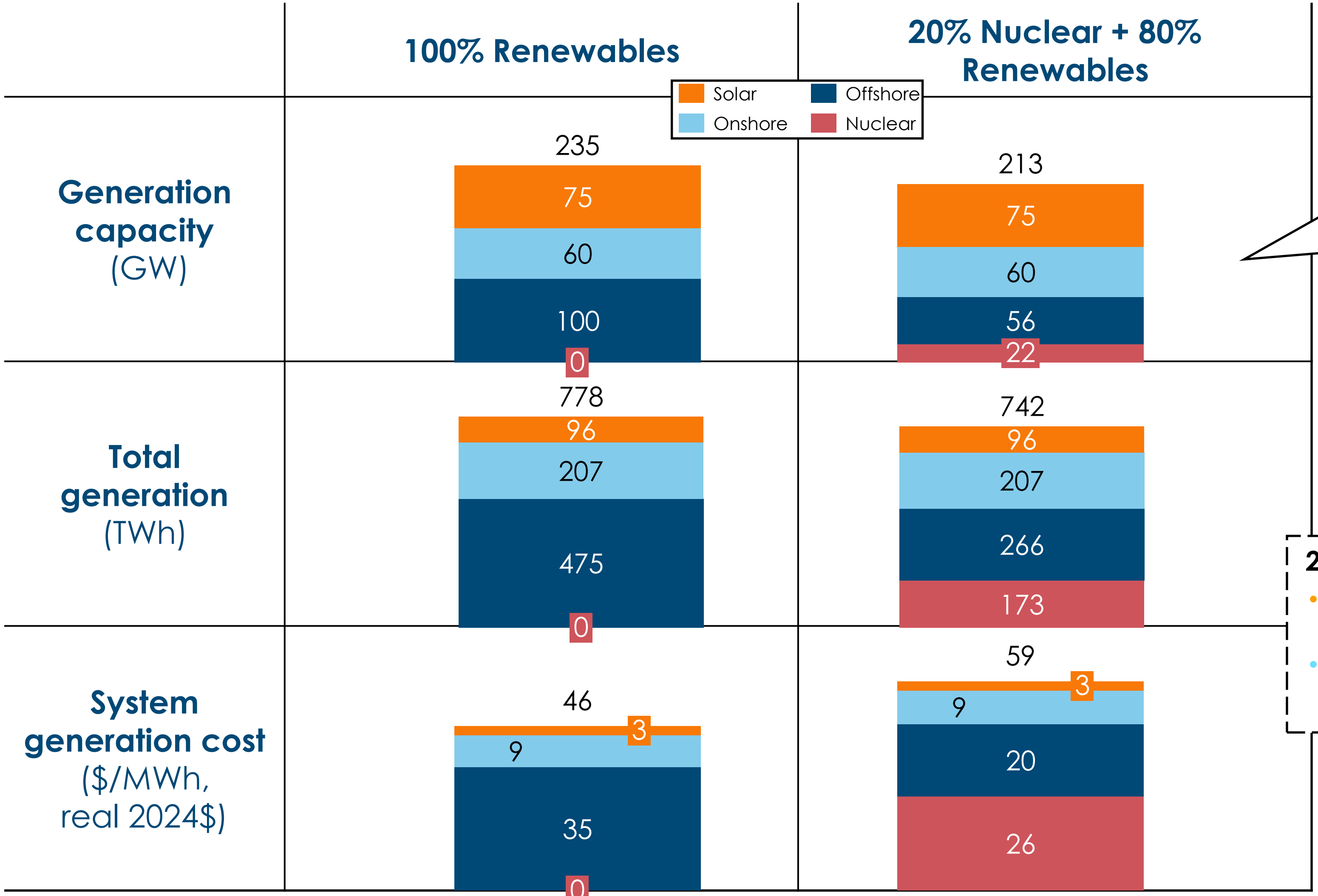
Average LCOE trends by technology over time in the UK - mid
$/MWh, real 2024 – central estimate



Notes: Capacity buildout rates are indicative, as annual increments have not been modelled in detail. The capacities correspond to the maximum buildout by technology in the scenarios outlined in this section.
Sources: Systemiq analysis for the ETC (2025); BNEF (2025), *New Energy Outlook*; BNEF (2025), *LCOE Data Viewer*

Generation: A system with nuclear reduces generation overbuild needs, however system average costs are higher

Generation capacities, annual generation, and system costs for a 2050 system in the UK (minimum weather year)



Nuclear replaces the highest-cost renewable technology, offshore wind

2050 LCOE assumptions (mid):
- **Solar: $20/MWh**
- **Onshore: $31/MWh**
- **Offshore: $56/MWh**
- **Nuclear: $112/MWh**

Notes: The 10% Nuclear + 90% Renewables scenario refers to the percentage of annual generation. 2050 LCOEs assumptions (central scenario): CAPEX: Solar = $290/kW; Onshore = $1.3k/kW; Offshore = $3.6k/kW; Nuclear = $8.6k/kW. Capacity factors: Solar = 15%; Onshore = 46%; Offshore = 60%; Nuclear = 90%.
Sources: Systemiq analysis for the ETC (2025); BNEF (2025), *New Energy Outlook*, BNEF (2025), *LCOE Data Viewer*

Balancing: While nuclear reactors are designed to run as baseload, best in class French reactors can technically operate flexibly…

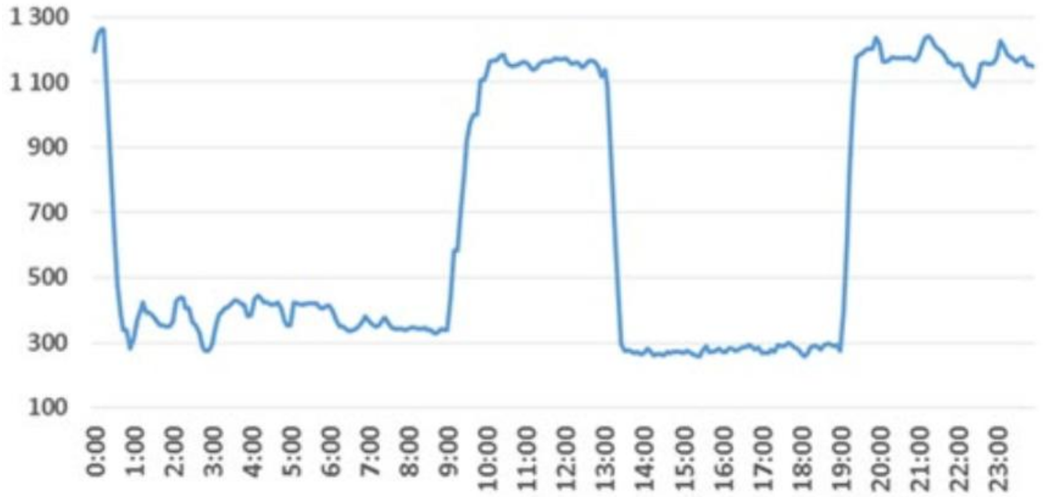
Two technical options for ramping nuclear flexibly:

Core ramping, via control rod movement or modification of boron concentrations in reactor core. BUT:
- Reducing core power results in buildup of neutron absorbing isotopes -> *limits rapid cyclical ramping*
- Changing core power rapidly changes fuel temperatures -> thermal and mechanical stresses that *limit ramping rate*.

Venting steam before it reaches the generating turbine. BUT:
- may result in *decreased operational lifetime of turbine assembly, and not widely practiced*

France case study – the most flexible nuclear
Leaders in flexibility due to use of "grey" control rods which absorb fewer neutrons to modulate chain reactions more precisely. This:
- **Can reduce output from 100% to 20%** (min load) of rated capacity **twice a day** in **under 30 minutes.**
- **Ramp rate ->** 3%/Min, 30-40 MW/min for a typical reactor
- **Hot start** -> Nuclear not designed for this
- **Cold start** -> ~72 hours

Golftech 2 (typical French) nuclear plant power variation over 1 day
MW, 1,300 max capacity



Source: NREL (2020), *Flexible Nuclear for Clean Energy Systems*

Balancing: …however, in reality while some plants react to negative price signals, French nuclear is mostly operated as baseload

Flexibility is amplified by the "fleet effect".

- In 2020 France had 58 nuclear reactors with a combined power of **63 GW** operated by EDF.
- Accounting for maintenance, France can generate **20-55GW** each hour from nuclear in optimal months
- On average these reactors could **ramp up/down at a fleet level by 21 GW within 30 minutes**.

▶ Even in France where plants have been designed for flexibility – most reactors do not cut generation during prolonged negative price periods.

▶ Market mechanisms would be needed to incentivise further flexibility, but also accounting for other technical limitations.

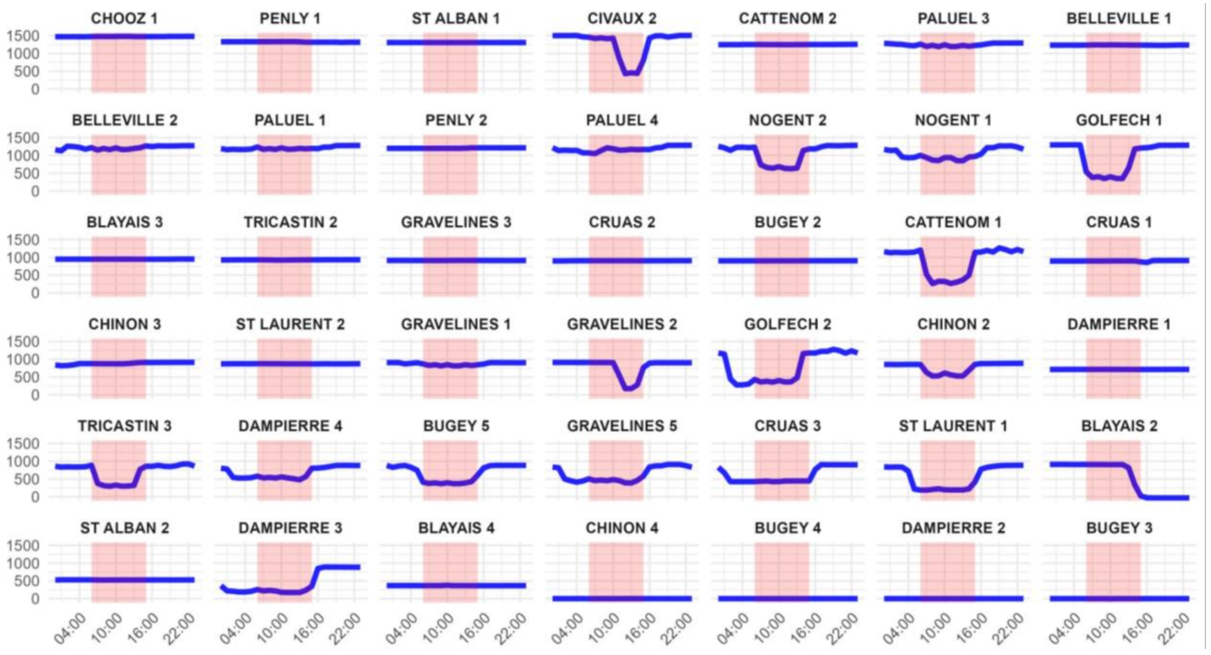
Case study: flexible operation at negative power pricing times

In April 2024, France saw 7 consecutive hours of negative prices, with a minimum of -65 €/MWh and average of -23€/MWh.

14/38 of the running nuclear reactors reacted flexibly to negative price signals, with 11 cutting close to minimum load, saving around 10GW.

Generation by French nuclear fleet during 7 hours of negative prices

MW, April 28th 2024



Notes: 16 reactors omitted due to no generation that day.
Source: ENTSO-E (2024), *transparency platform*

Balancing: If nuclear cannot run flexibly, how would nuclear impact balancing needs in a system alongside wind and solar?

A system with nuclear alongside wind and solar would…

Reduce balancing needs

↓

- **Reduces some need for short and medium-long duration balancing:**
  - Nuclear avoids the need for some balancing (at moments of otherwise low would-be wind/solar production). Some balancing will still be required - needed to meet demand when the "nuclear baseload" + wind/solar is insufficient (see next slide)

↓

- **Reduces need for ultra-long duration balancing / capacity (e.g. dispatchable backup)**
  - Nuclear power on the system would **reduce some of the need for a back-up dispatchable fleet in a zero-carbon "windbelt" system**; demand at times of very low renewable production could be met by a combination of nuclear as well as other short/medium-long duration storage

?

Uncertain effect on curtailment costs, depending on system design

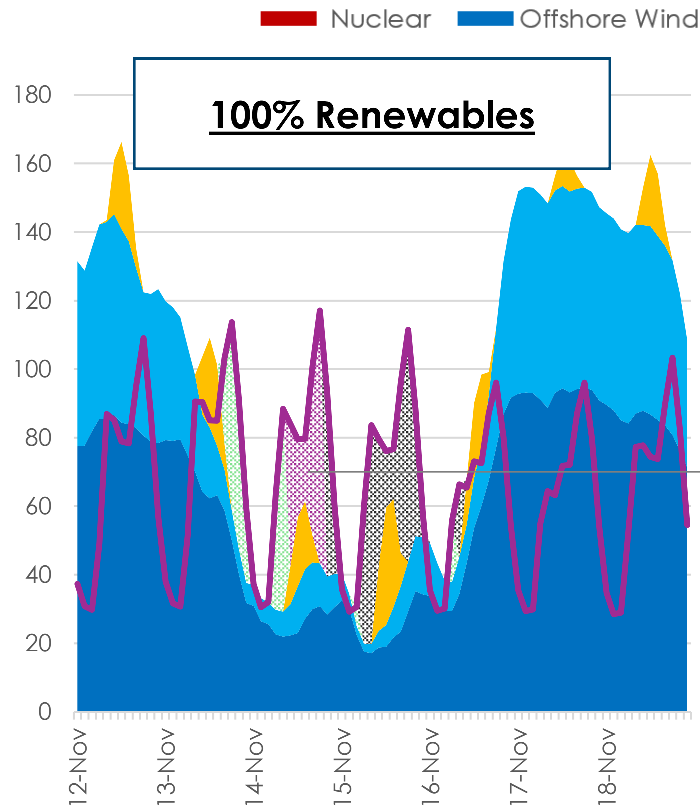
- If nuclear is "must run"/first dispatch, some wind/solar will be curtailed at low demand periods
- If renewables run first (lower SRMC) or sufficient storage is on the system, then curtailment wouldn't be affected

Note: SRMC = short-run marginal cost. Assuming it is not flexible, nuclear capacity deployed should not exceed the baseload demand level, to avoid adding system costs with the need to turn down inflexible nuclear often

Balancing: Storage needs decrease with nuclear in the mix relative to a 100% renewables scenario

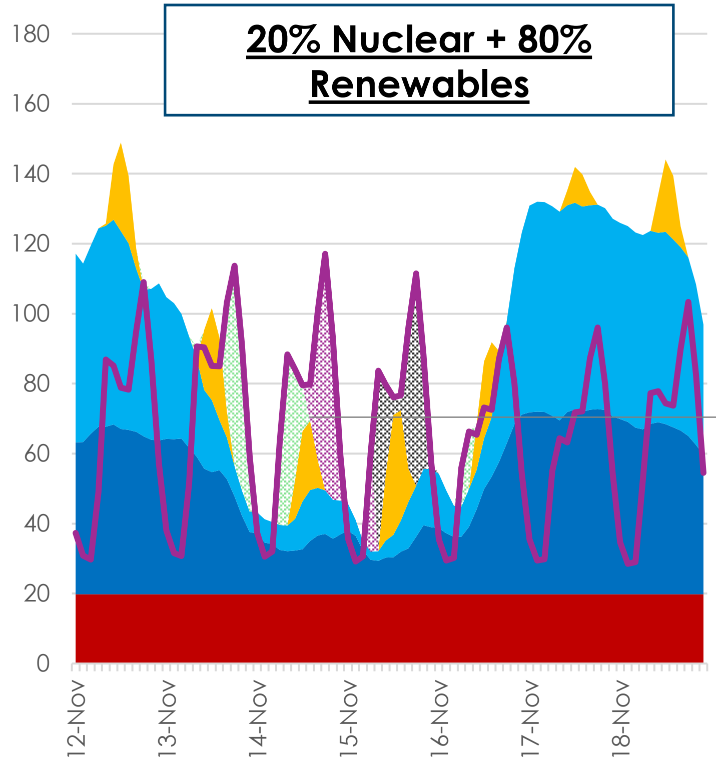
Weekly balancing for selected November period across scenarios (minimum weather year)

GW supply, demand, and balancing for each hour of the period



Short: 0.52 TWh
Medium - Long: 0.41 TWh
Ultra-long: 0.86 TWh
Total: 1.79 TWh

Supply deficit: Short, medium-long, and ultra-long balancing needed to match supply with demand



Short: 0.59 TWh
Medium - Long: 0.42 TWh
Ultra-long: 0.44 TWh
Total: 1.45 TWh

Smaller supply deficit: Less ultra-long duration balancing needed to match supply with demand – **but more still short and medium – long needed**

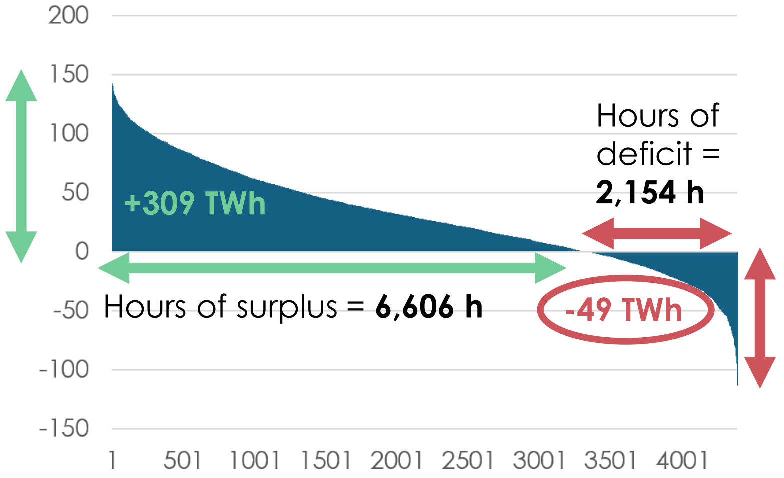
Source: Systemiq analysis for the ETC (2025)

Balancing: Over a year, a system with more nuclear would require 14% less balancing throughput (TWh) and would need to meet a 5% lower peak capacity deficit (GW)

Load duration curves for each wind, solar, and nuclear generation mix scenario – UK 2050 (minimum weather year)

GW surplus and deficit, 2-hourly generation blocks

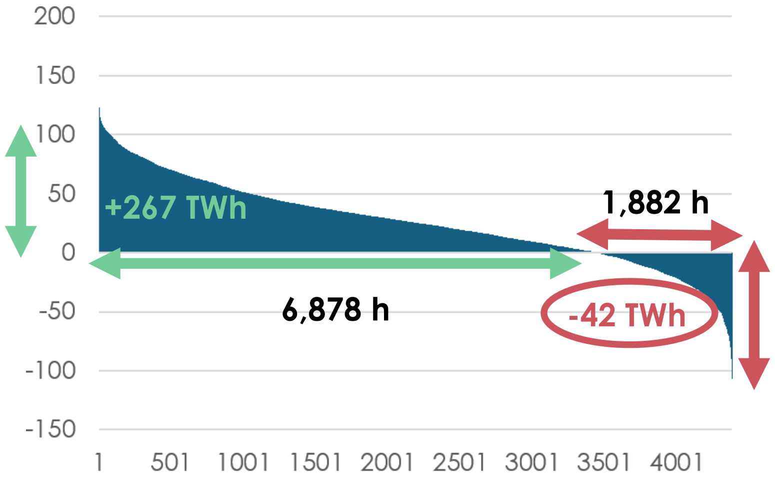
100% Renewables



Max surplus = **142 GW**

Max deficit /storage need = **113 GW**

20% Nuclear + 80% Renewables



Max surplus = **123 GW**

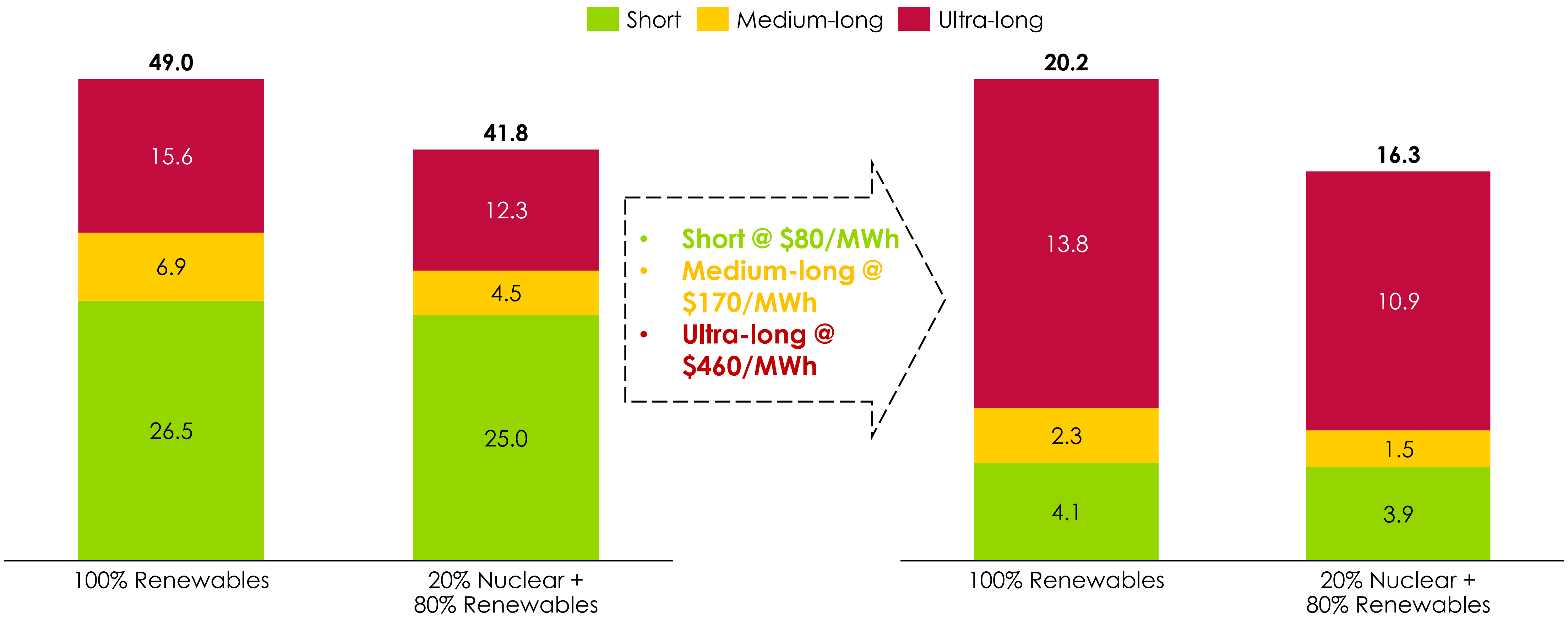
Max deficit /storage need = **107 GW**

Notes: The difference between the "Max deficit /storage need" is higher than the average operational nuclear capacity (90 GW assuming 100 GW running at an average capacity factor of 90%) because the renewables output above zero at the maximum deficit moment.
Source: Systemiq analysis for the ETC (2025)

Balancing: A system with nuclear reduces balancing needs and costs, particularly for longer duration storage

Annual demand met by balancing durations by supply scenario
TWh

Illustrative UK system generation cost by supply scenario
$/MWh, real 2024



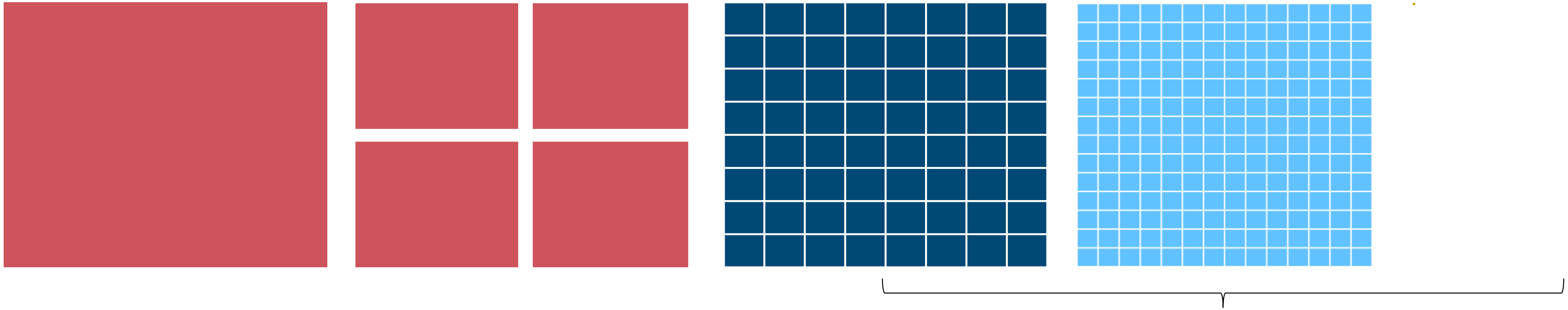
- **Short @ $80/MWh**
- **Medium-long @ $170/MWh**
- **Ultra-long @ $460/MWh**

Notes: Weighted average wind and solar generation cost used as the storage input electricity cost. 2050 Levelised cost of storage estimates (LCOS) ($/MWh): Short = 80 – 131; Medium-long = 173 – 240; Ultra-long = 457. Sources: Systemiq analysis for the ETC (2025); BNEF (2025), *New Energy Outlook*, BNEF (2025), *LCOE Data Viewer*

Balancing / Grid stability: Nuclear power faces periods of planned and unplanned downtime – requiring some additional balancing and grid stability capacity

Comparison of units per GW across clean generation technologies

Number of units per GW (number of squares represents the number of units per GW)



Nuclear (Large Scale)
Unit capacity: ~ 1000 MW

Nuclear (SMR)
Unit capacity: ~ 250 MW

Offshore Wind
Unit capacity: ~ 15 MW

Onshore Wind
Unit capacity: ~ 5 MW

Solar
Unit capacity: ~ 0.0005 MW

Nuclear plants require ~10% downtime for maintenance and refuelling; However, planned downtime is aligned with low supply period and rotate fleet

SMRs reduce this requirement as downtime for each unit can be alternated

Renewables have significantly more units per GW so downtime for each unit can be managed while keeping most capacity online

Source: Systemiq analysis for the ETC (2025)

Grid stability: Nuclear can provide a wider set of grid stability services than variable renewables

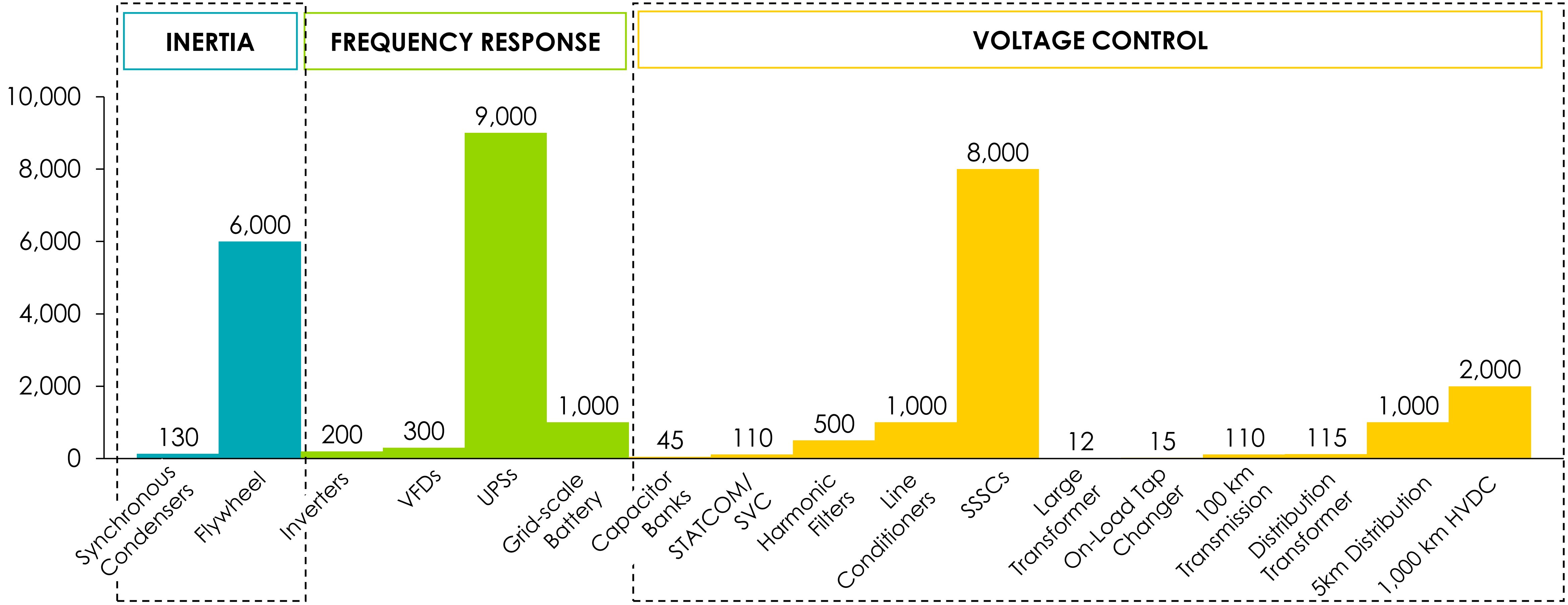
Grid Stability Service	Description	Can wind/solar provide?	Can Nuclear Provide?
Inertia Support	Instantaneous stabilising energy from synchronous mass	**Partially**. Requires additional technology such as synthetic inertia controls or hybrid storage, some can be provided through grid forming inverters	**Yes**. Nuclear plants' large rotating masses provide significant inertia. No additional cost.
Frequency Response	Ability to rapidly adjust power (seconds to minutes) to arrest frequency deviations. Includes FFR (Firm Frequency Response), Dynamic Containment, Dynamic Regulation.	**No**. Cannot inherently adjust output upward on demand. Requires additional technology such as curtailment controls or storage	**Partially**. Nuclear not suited to fast frequency response (slow ramping) so limited role. Some additional cost for faster frequency services.
Voltage Control	Managing voltage through reactive power injection or absorption. Services include reactive power tenders, voltage support	**Yes**. Solar and wind can inherently provide reactive power for voltage support. However, other technologies needed to provide location-specific voltage support and harmonic regulation.	**Yes**. Nuclear synchronous machines provide reactive power like other thermal plants. However, other technologies required to ensure harmonic regulation.
Black Start Capability	Ability to restart grid after a complete blackout without external supply.	**No.** Cannot restart the grid.	**No**. Nuclear requires external power to restart safely. Needs to be contracted separately.

Source: Systemiq analysis (2025); Thunder Said Energy (2025), Renewable-heavy grids: total system costs?

Grid stability: nuclear provides inertia and voltage control services, however alternative technologies can also economically provide these in renewables-dominated systems

Actual mix and level of deployment of grid stability technologies required will depend on system's generation mix and location-specific needs

Cost of grid stability technologies
$/kW



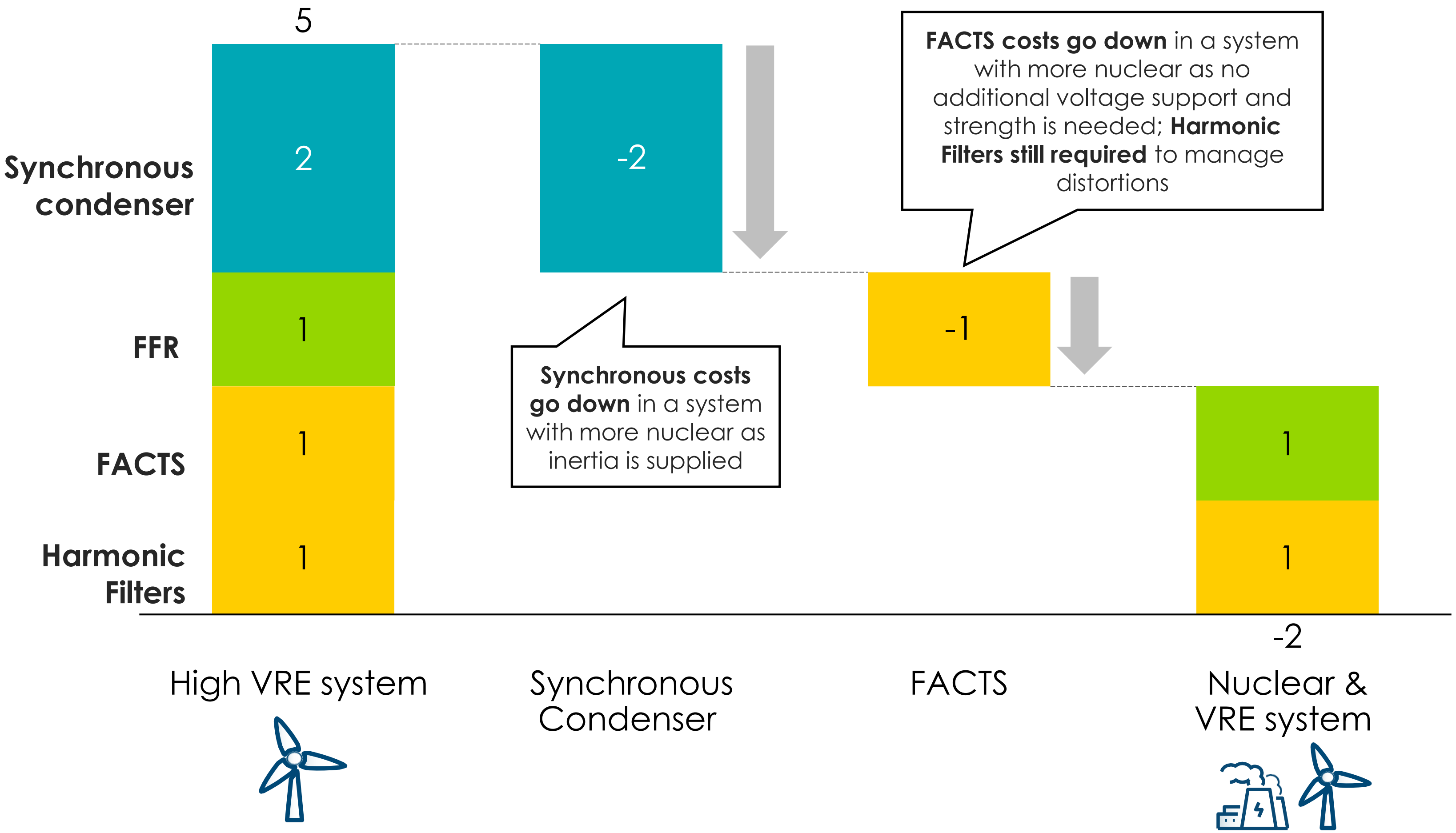
Nuclear inherently provides many of these services, which could partly offset related costs

Source: Thunder Said Energy (2025), *Renewable-heavy grids: total system costs?*

Grid stability: costs are slightly lower in systems with nuclear baseload than in a high-VRE system, but would be dependent on stability technology choices

Estimated costs of grid stability technologies in high-VRE and nuclear + VRE systems

$/MWh (real 2024)



FACTS costs go down in a system with more nuclear as no additional voltage support and strength is needed; **Harmonic Filters still required** to manage distortions

Synchronous costs go down in a system with more nuclear as inertia is supplied

Stability costs higher in high-VRE systems

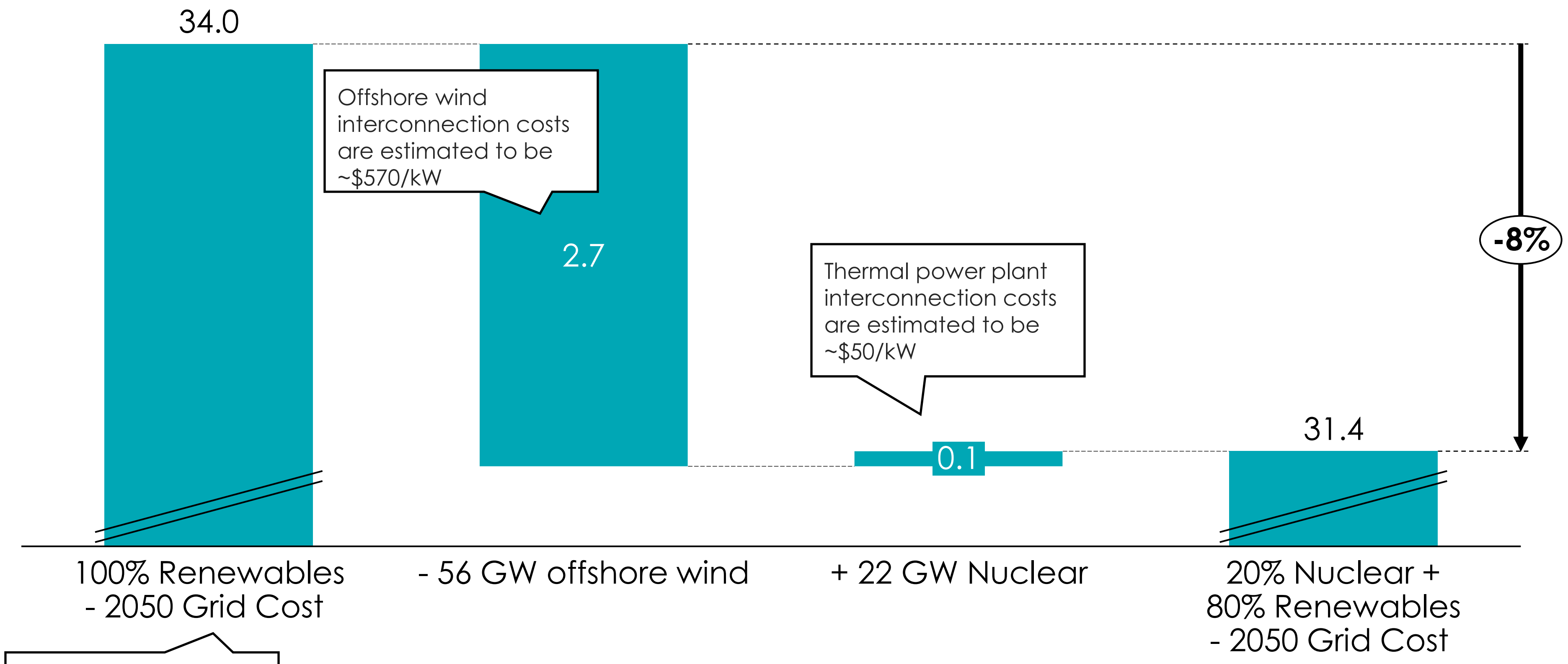
While inverter-based renewables can provide some voltage support, additional technologies such as FACTS and harmonic filters are essential to *ensure* system strength and power quality

FACTS, or Flexible Alternating Current Transmission Systems (FACTS) are technologies that improve grid stability by managing power flows in real time

Note: System modelled by Thunder Said Energy assumed to have a system with 50% wind generation (using a renewables average $2,000/kWe in CAPEX at 25% average capacity factor) to align with ETC modelling of UK case study with a generation system dominated by wind generation. Source: Systemiq analysis for the ETC, Thunder Said Energy (2025), *Renewable-heavy grids: total system costs?*

Transmission & distribution costs: replacing some offshore wind with nuclear decreases total system grid costs by around 10%

Grid cost impacts per unit demand resulting from removing 56 GW of offshore wind and adding 22 GW of nuclear
$/MWh (real 2024)



Offshore wind interconnection costs are estimated to be ~$570/kW

Thermal power plant interconnection costs are estimated to be ~$50/kW

Derived in the ETC's recent Power Systems Transformation report

~10% decrease in system grid costs for the scenario with nuclear, driven by:

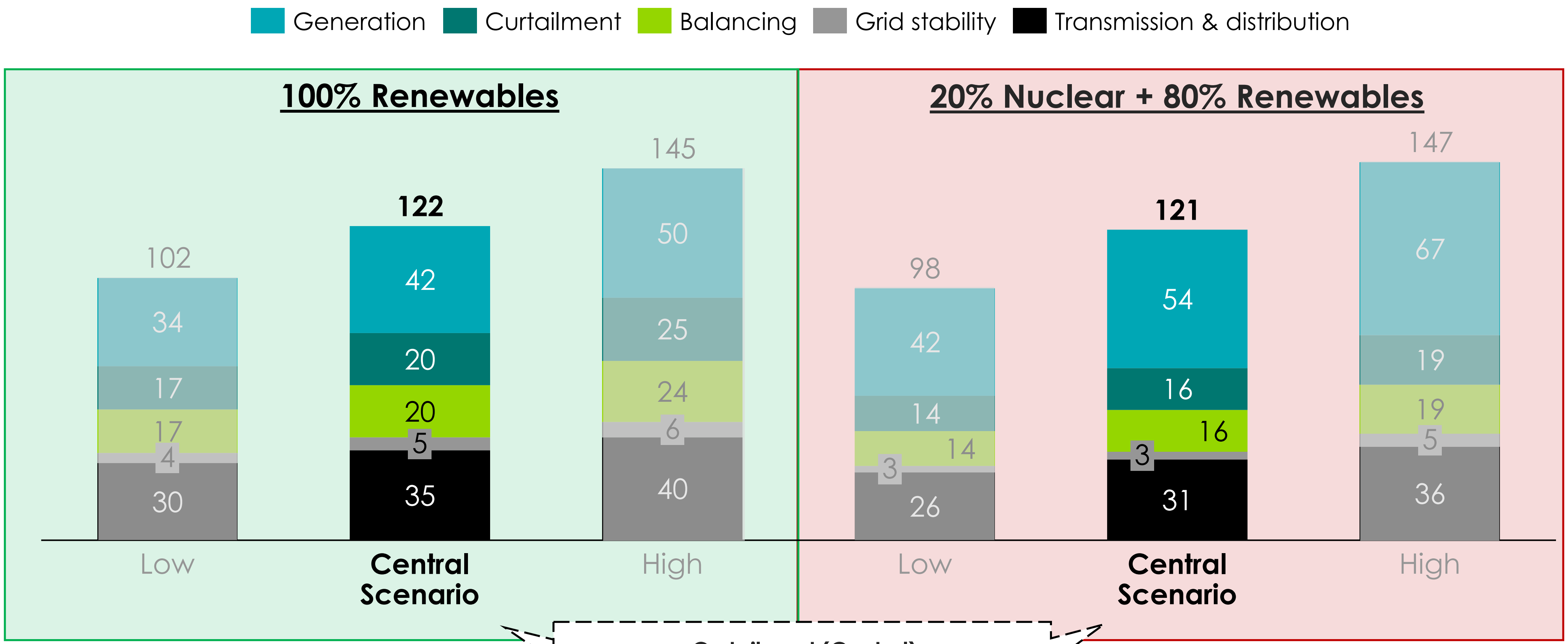
1. Higher use of brownfield sites/connections (e.g., old coal sites)
2. Higher utilisation of connections
3. Closer proximity to demand

Notes: 25% of the interconnection costs are direct costs, while 75% is the requirement to fund network upgrades (therefore 75% of the interconnection costs are accounted for in this calculation). Interconnection upgrade CAPEX is converted to costs per MWh assuming 5% WACC (real) and 40-year asset lifetime.
Source: Thunder Said Energy (2024), *Power grids: the biggest bottleneck in the world?*; Ofgem (2020), *OFTO Tender Round 7*; Ofgem (2025), *Offshore Transmission: Draft Cost Assessment for the Seagreen Wind Energy Limited (SWEL) Offshore Windfarm Transmission Assets*

20% nuclear generation in the UK could result in similar clean power system costs to a 100% renewables scenario, with lower reliance on grid and storage buildout

Illustrative view of components of total system cost and variation by system, UK Case Study in 2050 (minimum weather year)

$/MWh of final electricity demand (real 2024$)



Offshore wind CAPEX:
- Low: $2.8k/kW
- Mid: $3.6k/kW
- High: $4.4k/kW

Nuclear CAPEX:
- Low: $5.1k/kW
- Mid: $8.6k/kW
- High: $12.0k/kW

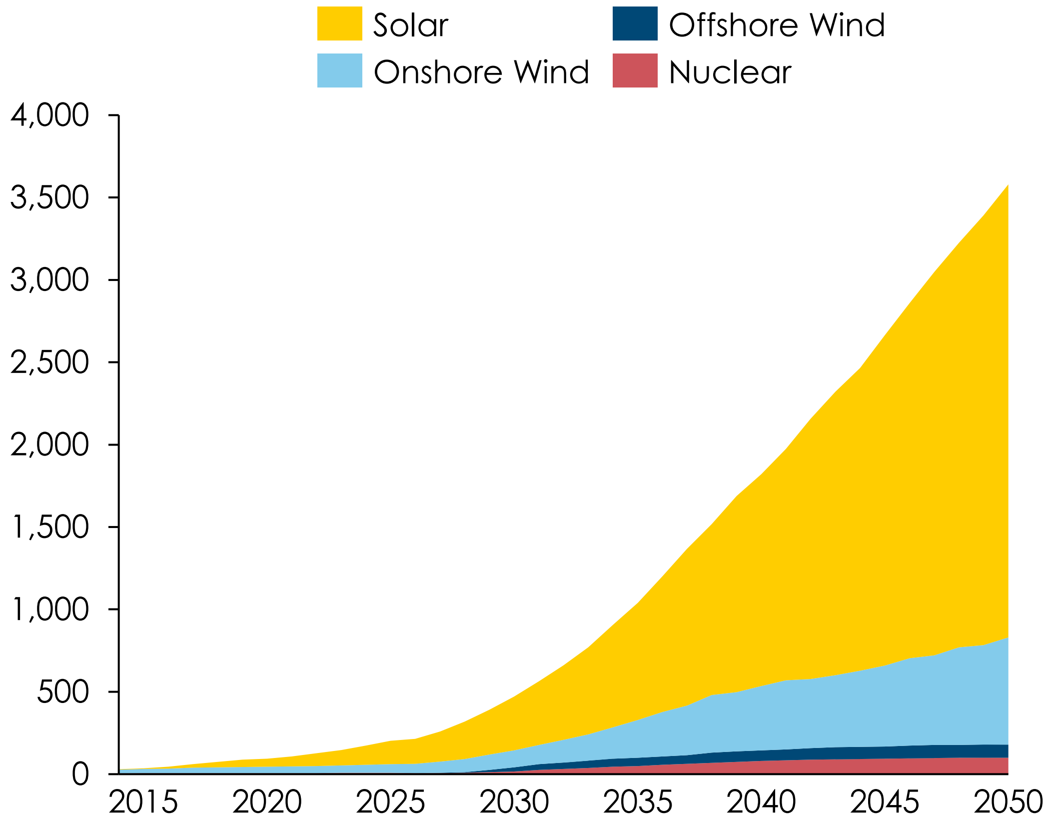
Curtailment (Central):
- 100% Renewables: 230 TWh @ $46/MWh
- 20% Nuclear: 200 TWh @ $42/MWh

Notes: "20% nuclear" refers to the share of generation. Sensitivities: Generation - BNEF's low, medium, and high 2050 CAPEX and OPEX estimates and assumptions for capacity factors, WACC, and lifetimes based on ETC modelling; Curtailment – surplus electricity at the weighted average wind & solar LCOE (assuming no nuclear is curtailed); Balancing – central CAPEX +/- 20% for high/low alongside high/low electricity input costs based on generation; central CAPEX +/- ~$1/MWh for high/low; Transmission & distribution - central CAPEX +/- $5/MWh for high/low. Source: Systemiq analysis for the ETC (2025); BNEF (2025), *LCOE Data Viewer*

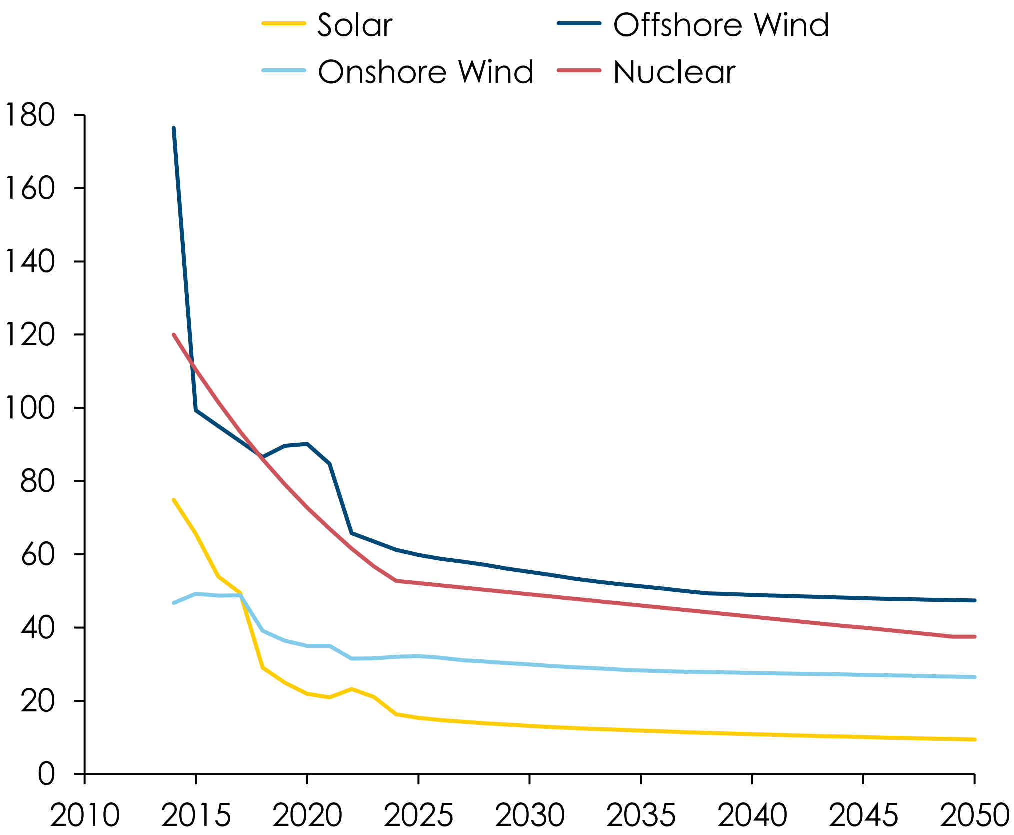
India System Modelling (Sunbelt)

Generation: Costs are set to decrease as installed capacity increases across all generation technologies, particularly onshore wind and solar

Installed capacity by technology over time in India in ETC scenarios
GW



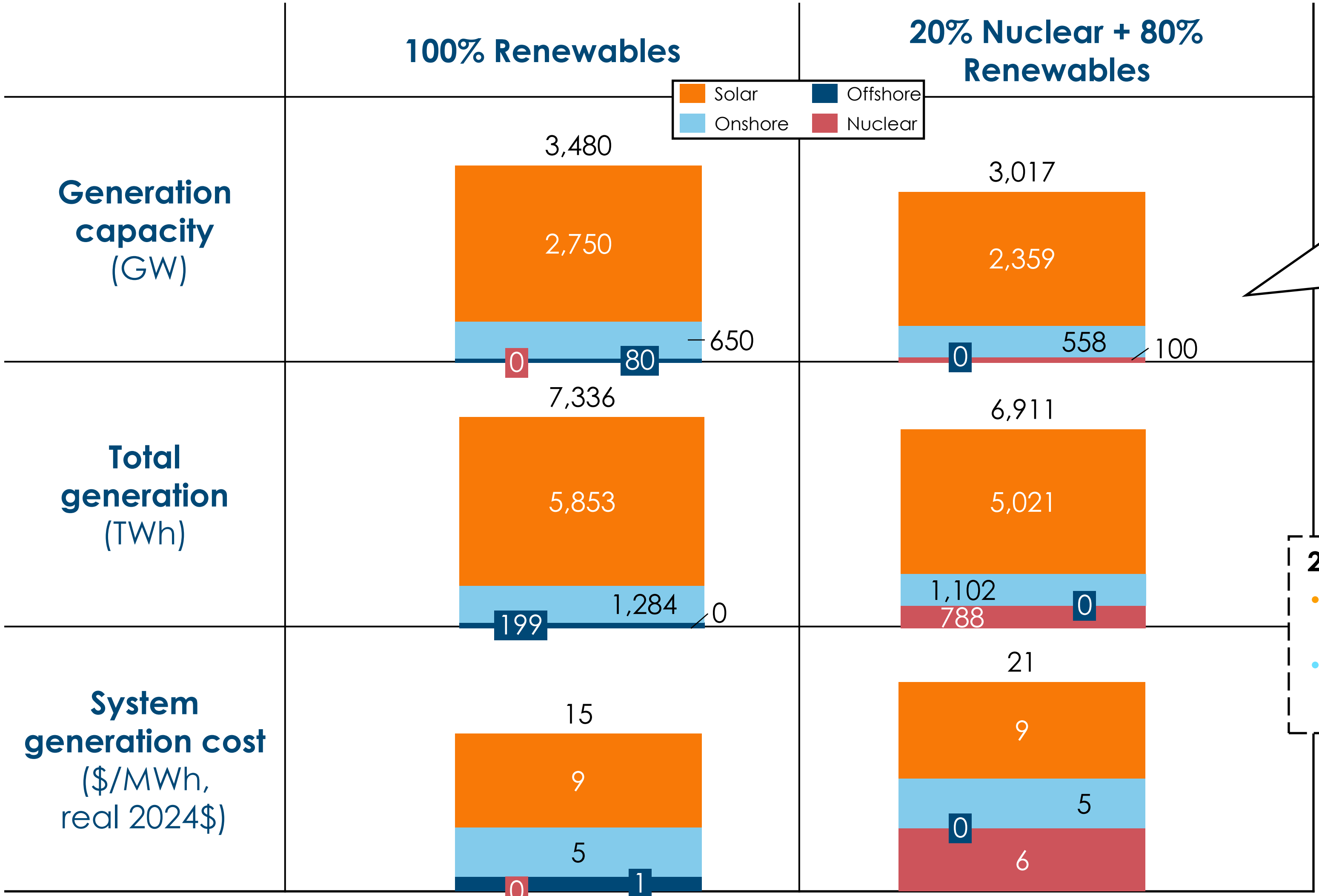
Average LCOE trends by technology over time in India - mid
$/MWh, real 2024 – central estimate



Notes: Capacity buildout rates are indicative, as annual increments have not been modelled in detail. The capacities correspond to the maximum buildout by technology in the scenarios outlined in this section. Offshore wind costs have been aligned with expected trends in China, due to the lack of existing data in India and the assumption that Indian offshore wind projects would rely on imported components. Sources: Systemiq analysis for the ETC (2025); BNEF (2025), *New Energy Outlook;* BNEF (2025), *LCOE Data Viewer*

Generation: A system with nuclear reduces generation overbuild needs, however overall generation costs are higher

Generation capacities, annual generation, and system costs for a 2050 system in India (minimum weather year)



Nuclear replaces the highest-cost renewable technology, offshore wind then solar (due to overbuild)

2050 LCOE assumptions (mid):

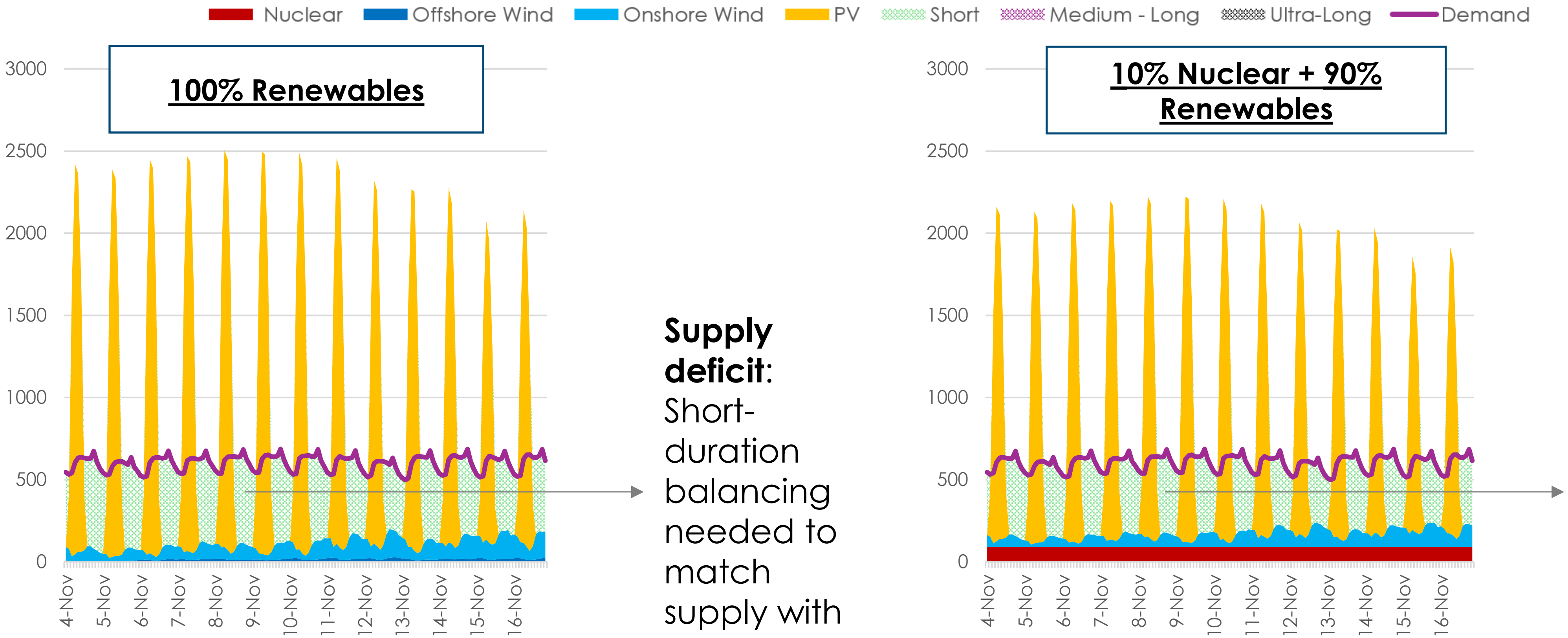
- **Solar: $9/MWh**
- **Onshore: $27/MWh**
- **Offshore: $50/MWh**
- **Nuclear: $38/MWh**

Notes: The 10% Nuclear + 90% Renewables scenario refers to the percentage of annual generation. 2050 LCOEs assumptions (central scenario): CAPEX: Solar = $290/kW; Onshore = $790/kW; Offshore = $3.6k/kW; Nuclear = $8.6k/kW. Capacity factors: Solar = 15%; Onshore = 39%; Offshore = 54%; Nuclear = 90%.
Sources: Systemiq analysis for the ETC (2025); BNEF (2025), *New Energy Outlook*, BNEF (2025), *LCOE Data Viewer*

Balancing: Storage needs decrease with nuclear in the mix relative to a 100% renewables scenario

Weekly balancing for selected November period across scenarios (minimum weather year)

GW supply, demand, and balancing for each hour of the period



Supply deficit: Short-duration balancing needed to match supply with demand

Short: 47.85 TWh
Medium - Long: 0 TWh
Ultra-long: 0 TWh
Total: 47.85 TWh

Smaller supply deficit: ~13% less short-duration balancing needed to match supply with demand

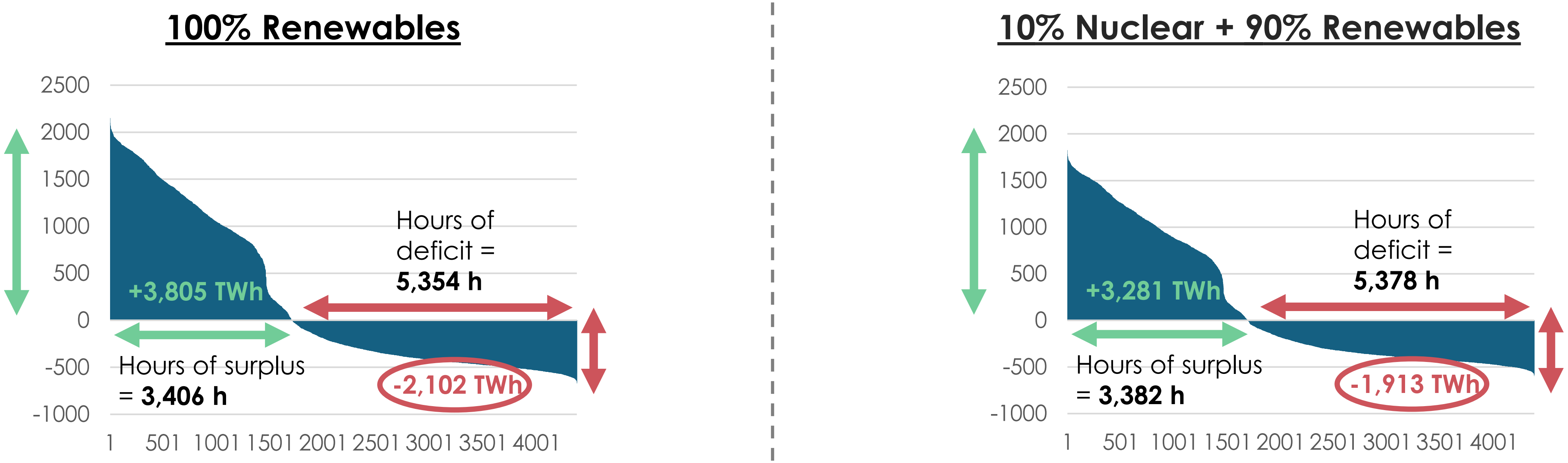
Short: 41.66 TWh
Medium - Long: 0 TWh
Ultra-long: 0 TWh
Total: 41.66 TWh

Notes: The ratio of peak capacity to peak/average demand is aligned with solar and battery system setups published by Ember and the announced 24/7 solar and battery project in the UAE (5.2 GW solar for 1 GW offtake). Sources: Systemiq analysis for the ETC (2025); Ember (2025), *Solar electricity every hour of every day is here and it changes everything;* MASDAR (2025), *UAE President witnesses launch of world's first 24/7 Solar PV, Battery Storage gigascale project to be built in Abu Dhabi*

Balancing: Over a year, a system with more nuclear would require ~10% less balancing throughput (TWh) and would need to meet a ~10% lower peak capacity deficit (GW)

Load duration curves for each wind, solar, and nuclear generation mix scenario - India 2050 (minimum weather year)

GW surplus and deficit, 2-hourly generation blocks



Max surplus = **2,151 GW**

Max deficit /storage need = **672 GW**

Max surplus = **1,826 GW**

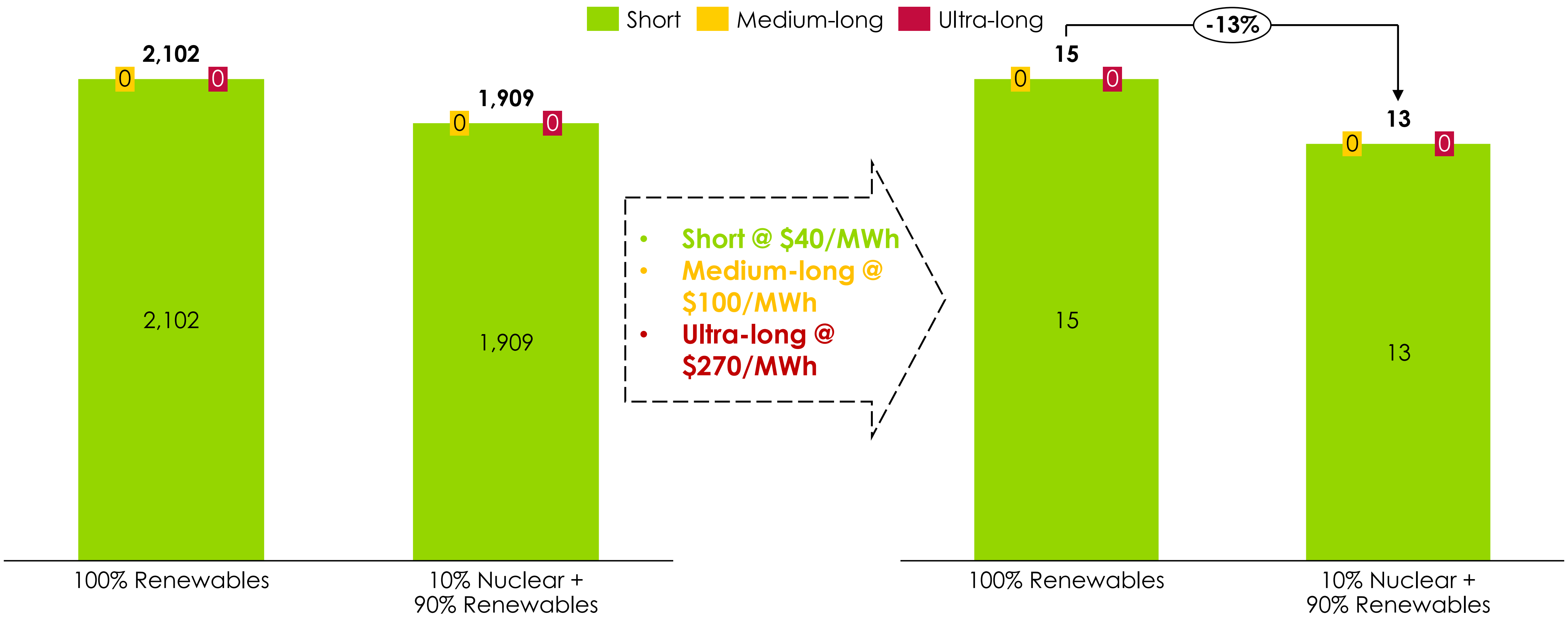
Max deficit /storage need = **599 GW**

Notes: The difference between the "Max deficit /storage need" is higher than the average operational nuclear capacity (90 GW assuming 100 GW running at an average capacity factor of 90%) because the renewables output above zero at the maximum deficit moment.
Source: Systemiq analysis for the ETC (2025)

Balancing: A system with nuclear reduces balancing needs and costs, however this only affects cheaper short-duration storage in Sunbelt scenarios

Annual demand met by balancing durations by supply scenario
TWh

Illustrative India system generation cost by supply scenario
$/MWh, real 2024

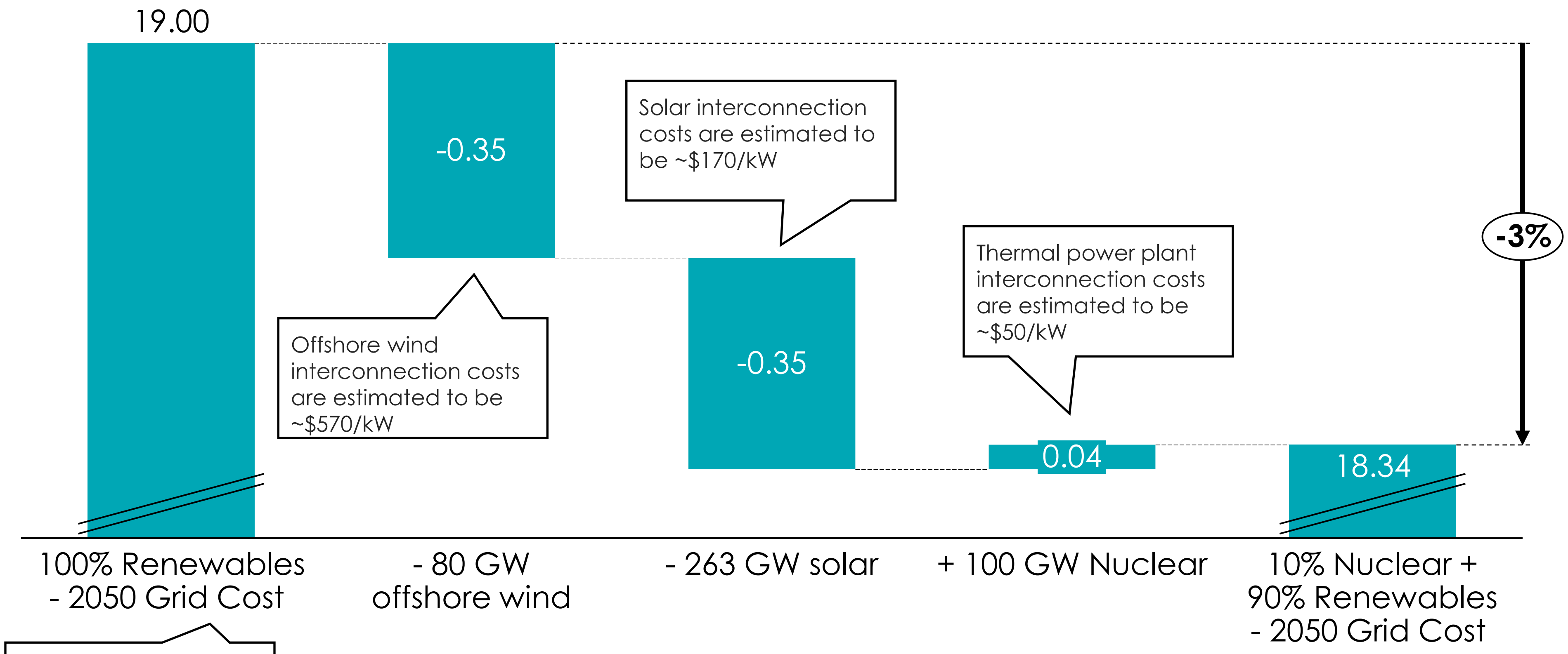


- **Short @ $40/MWh**
- **Medium-long @ $100/MWh**
- **Ultra-long @ $270/MWh**

Notes: Weighted average wind and solar generation cost used as the storage input electricity cost. 2050 LCOSs ($/MWh): Short = 30 – 50; Medium-long = 100 – 130; Ultra-long = 230 – 320. Sources: Systemiq analysis for the ETC (2025); BNEF (2025), *New Energy Outlook*, BNEF (2025), *LCOE Data Viewer*

Transmission & distribution costs: replacing renewables capacity with nuclear slightly decreases total system grid costs

Grid cost impacts per unit demand resulting from removing 56 GW of offshore wind and adding 22 GW of nuclear
$/MWh



Solar interconnection costs are estimated to be ~$170/kW

Offshore wind interconnection costs are estimated to be ~$570/kW

Thermal power plant interconnection costs are estimated to be ~$50/kW

Derived in the ETC's recent Power Systems Transformation report

3% decrease in system grid costs for the scenario with nuclear, driven by:

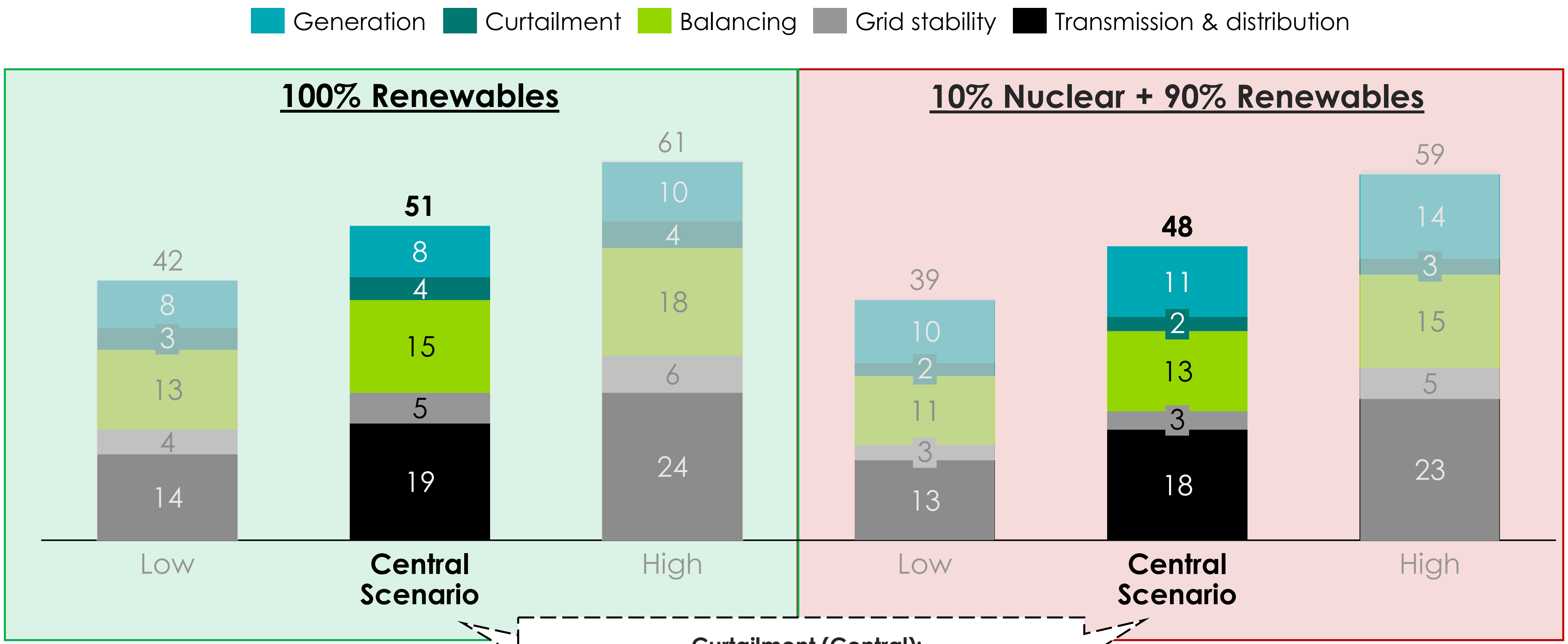
1. Higher use of brownfield sites/connections (e.g., old coal sites)
2. Higher utilisation of connections
3. Closer proximity to demand

Notes: 25% of the interconnection costs are direct costs, while 75% is the requirement to fund network upgrades (therefore 75% of the interconnection costs are accounted for in this calculation). Interconnection upgrade CAPEX is converted to costs per MWh assuming 5% WACC (real) and 40-year asset lifetime.
Source: Thunder Said Energy (2024), *Power grids: the biggest bottleneck in the world?*

10% nuclear generation in India could result in similar clean power system costs to a 100% renewables scenario

Illustrative view of components of total system cost and variation by system, India Case Study in 2050 (minimum weather year)

$/MWh of final electricity demand (real 2024$)



Curtailment (Central):
- 100% Renewables: 1,560 TWh @ $15/MWh
- 10% Nuclear: 1,020 TWh @ $14/MWh

Onshore wind CAPEX:
- Low: $750/kW
- Mid: $790/kW
- High: $840/kW

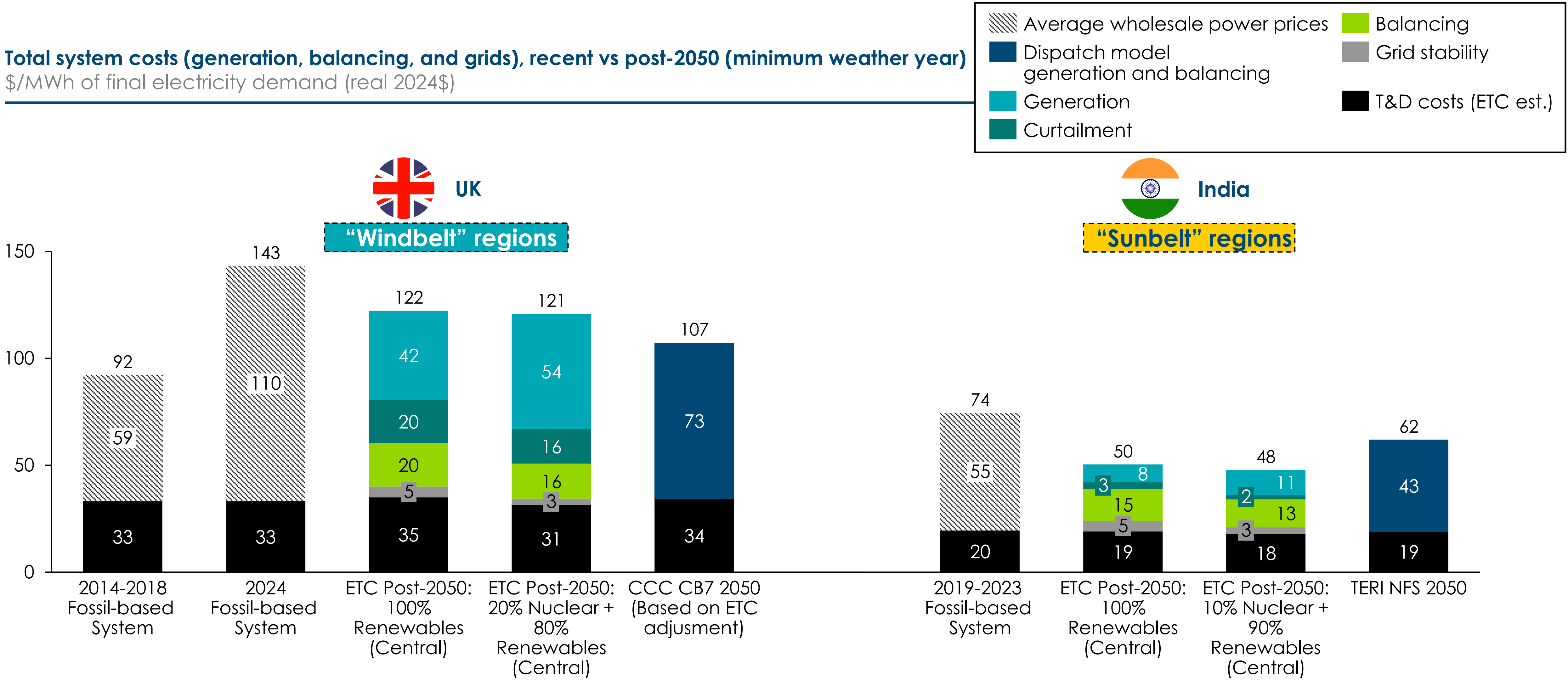
Solar CAPEX:
- Low: $260/kW
- Mid: $290/kW
- High: $320/kW

Nuclear CAPEX:
- Low: $1.5k/kW
- Mid: $2.0k/kW
- High: $2.5k/kW

Notes: "10% nuclear" refers to the share of generation. Sensitivities: Generation - BNEF's low, medium, and high 2050 CAPEX and OPEX estimates and assumptions for capacity factors, WACC, and lifetimes based on ETC modelling; Curtailment – surplus electricity at the weighted average wind & solar LCOE (assuming no nuclear is curtailed); Balancing – central CAPEX +/- 20% for high/low alongside high/low electricity input costs based on generation; central CAPEX +/- ~$1/MWh for high/low; Transmission & distribution - central CAPEX +/- $5/MWh for high/low. Source: Systemiq analysis for the ETC (2025); BNEF (2025), *LCOE Data Viewer*

Total system costs by geography and next steps

Total system costs: Clean power systems, with or without nuclear, could deliver total generation, balancing, and grid costs below today's prices



Total system costs (generation, balancing, and grids), recent vs post-2050 (minimum weather year)

$/MWh of final electricity demand (real 2024$)

Note: T&D = Transmission and distribution. T&D costs per MWh have been assumed based on ETC modelling across all presented here for consistency.

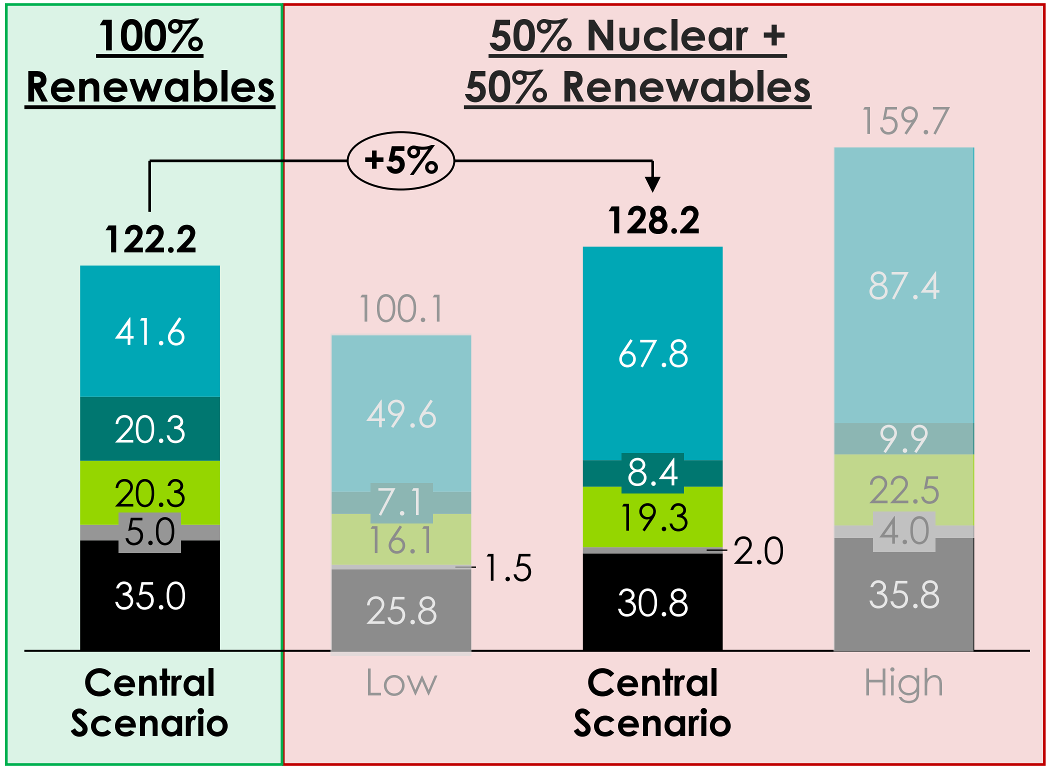
Source: Systemiq analysis for the ETC (2025); BNEF (2025), *LCOE: Data Viewer*; Ofgem (2025), *Wholesale market indicators – Electricity Prices: Forward Delivery Contracts – Weekly Average (GB)*; IEA (2023), *Electricity Market Report – Update 2023*; Statista (2024), *Average electricity prices for enterprises in China from September 2019 to September 2024*; Ember (2025), *Wholesale electricity prices in Europe*; CCC (2025), *The Seventh Carbon Budget*; TERI (2024), *India's Electricity Transition Pathways to 2050: Scenarios and Insights*

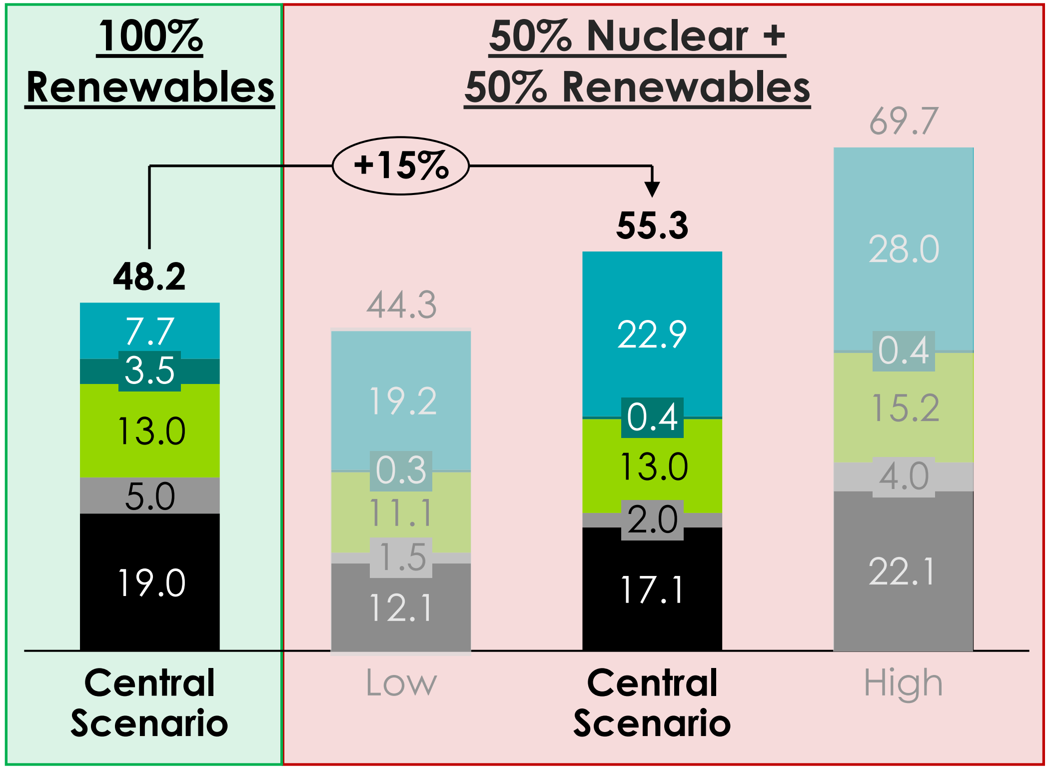
Stretch nuclear scenarios: what happens if we push nuclear beyond current targets to 50% of generation?

100% Renewables vs 50% Nuclear total system costs – UK 2050
$/MWh of final electricity demand (real 2024$)

100% Renewables vs 50% Nuclear total system costs – India 2050
$/MWh of final electricity demand (real 2024$)

🟦 Generation 🟩 Curtailment 🟩 Balancing ⬜ Grid stability ⬛ Transmission & distribution





Notes: "50% nuclear" refers to the share of generation with the following capacities assumed: UK - 75 GW solar, 30 GW onshore wind, 30 GW offshore wind, 40 GW nuclear; India – 1500 GW solar, 400 GW onshore wind, 250 GW nuclear. Sensitivity method is aligned with the other scenarios.
Source: Systemiq analysis for the ETC (2025); BNEF (2025), *LCOE Data Viewer*

Pre-read only

Emerging conclusions: Adding 10-20% nuclear generation to the mix is likely to decrease system costs across all key categories in the UK and India

<table>
<tr><th></th><th>UK</th><th>India</th></tr>
<tr><td>Generation</td><td>- Small proportions of nuclear (e.g., < 20%) can reduce system costs, but this should be kept below the point of minimum demand
- Nuclear CAPEX < $10k/kW is likely to be needed for cost-effective renewables displacement</td><td>- Small proportions of nuclear (e.g., < 10%) can reduce system costs, additions beyond 10% generation are expected to yield diminishing returns
- Nuclear CAPEX < $2.5k/kW is likely to be needed for cost-effective renewables displacement</td></tr>
<tr><td>Curtailment</td><td colspan="2">- Renewable overbuild of 30-40% annual generation is cost-effective to decrease more expensive balancing costs
- However, adding nuclear decreases curtailment volumes and costs (average curtailment cost per MWh decreases by ~10% with the reduction of more expensive renewables generation, e.g., offshore wind)</td></tr>
<tr><td>Balancing</td><td>- Adding 20% nuclear decreases annual storage TWh by 14% – storage needs don't necessarily reduce proportionately
- Largest reductions are across the more expensive medium – long and ultra-long storage durations, decreasing total balancing costs by ~20%</td><td>- Adding 10% nuclear decreases annual storage TWh by ~10%
- Storage needs only decrease across the cheapest short-duration, due to the lack of longer duration storage in either scenario</td></tr>
<tr><td>Grid stability</td><td colspan="2">- Grid stability costs only contribute ~5-10% to total system costs in all scenarios
- These decrease by ~40% in the nuclear scenarios, a 2% decrease to total system costs</td></tr>
<tr><td>Transmission and distribution</td><td>- T&D costs could decrease by 10% as 20% nuclear is added to the generation mix, driven by a lower need for high-cost offshore wind interconnection</td><td>- T&D costs see a 5% decrease as 10% nuclear is added to the generation mix, driven by a lower need for offshore wind and solar interconnection</td></tr>
</table>

Notes: T&D = Transmission and distribution.
Source: Systemiq analysis for the ETC (2025)

Emerging conclusions

1. **Low proportions of nuclear on the system can help achieve similar total system costs to 100% renewables systems;** while nuclear generation is more expensive than clean alternatives, it can save some additional balancing, grid stability and transmission & distribution costs

2. **However, increasing the share of nuclear above a certain level is likely to have diminishing returns**, where the increase in generation costs will outweigh savings in other areas. Furthermore, the share of nuclear generation should generally be below the minimum "baseload" demand to avoid additional costs

3. **Nuclear will reduce but not eliminate balancing needs**; some balancing will still be required - needed to meet demand when the "nuclear baseload" and wind/solar generation is insufficient

4. **Adding some nuclear could reduce system curtailment costs**, as the need to overbuild generation decreases when nuclear is added; **however**, this assumes that renewables are displaced first (due to their lower cost per MWh); if nuclear generation is curtailed before renewables, curtailment costs could rise

Power system mix choices will depend on planning, operation, and public acceptance

System Planning

- **Grid build-out** is a major constraint for renewables; nuclear can help scale clean power with less reliance on transmission expansion.
- **Lead times:** Nuclear projects typically take >10 years to deliver, while renewables+storage can be built within 2-5 years.
- **Deployment speed** favors renewables, but nuclear may still play a role where grid expansion is slow.

System Operation

- **High renewables systems** are technically and economically feasible, though balancing needs grow with penetration
- **Firm output** reduces the scale of long-duration balancing required.
- **System stability** is supported by nuclear's inertia and voltage control.

Public Acceptance

- **Land and population density** constraints increase siting and permitting challenges for renewables.
- **Political dynamics**: Net zero faces pushback in some countries; nuclear often gains stronger centre-right support.
- **Security and safety** considerations restrict where new nuclear projects can be built

- **A diverse generation mix underpins energy security and system resilience**
- **Including some firm power may help in countries where grid, land, or system balancing constraints slow renewable deployment.**

Are there any significant pieces of analysis missing from this work?

Possible extensions to existing system balancing analysis

Modelling other archetypes

- China (mixed climate)
- Spain (Med.)
- Other

Further UK and India scenarios

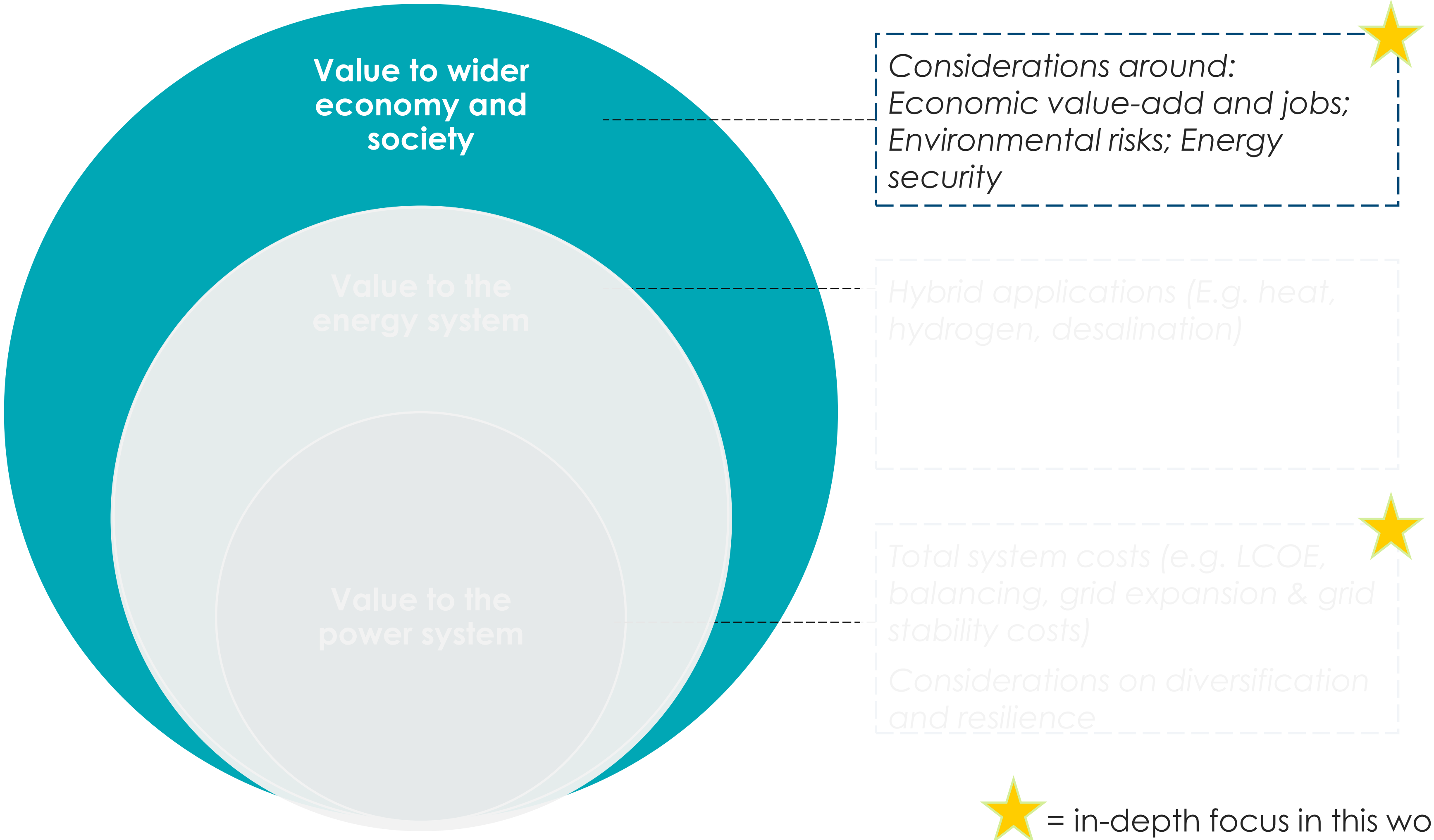
- More generation mix scenarios
- Other time steps (e.g., 2035)
- Scenarios with fossil reliance

Which additions (if any) would be most useful additions to the existing analysis?

Agenda

- Context: the state of play of nuclear
- Techno-economics and understanding “system value”
- **Wider risks and benefits**
- Emerging conclusions

Value of nuclear power should be assessed holistically against alternatives



Value to wider economy and society

Considerations around: Economic value-add and jobs; Environmental risks; Energy security ★

Value to the energy system

Hybrid applications (E.g. heat, hydrogen, desalination)

Value to the power system

★ *Total system costs (e.g. LCOE, balancing, grid expansion & grid stability costs)*

Considerations on diversification and resilience

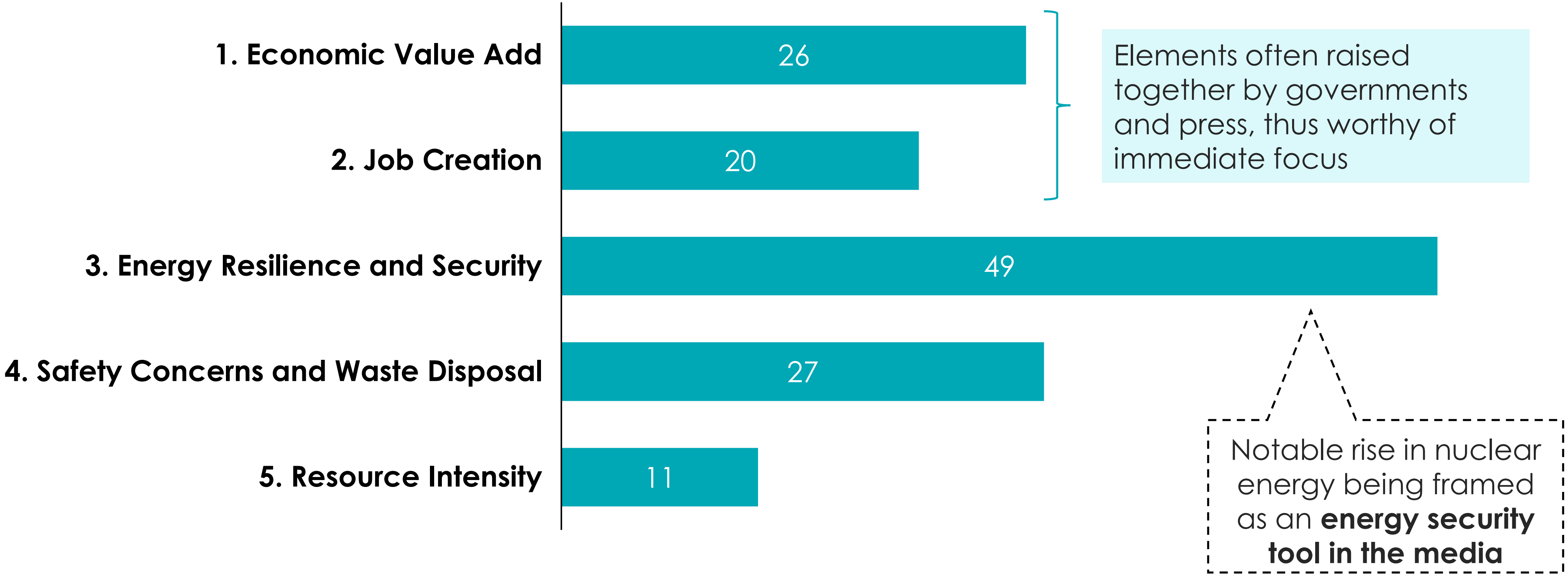
To understand how nuclear can complement a high renewable system

★ = in-depth focus in this workshop

Five risks and benefits are often raised relating to nuclear power

Newspaper headlines relating to risks and benefits of nuclear in 2025, global

units



Elements often raised together by governments and press, thus worthy of immediate focus

Notable rise in nuclear energy being framed as an **energy security tool in the media**

Source: Headline counts are based on distinct 2025 news articles across major international outlets. Sources reviewed include English and non-English media in the US, UK, EU, China (People's Daily, Xinhua, Caixin), South Korea (Korea Herald, Yonhap, Chosun Ilbo), Japan (NHK, Asahi Shimbun, Nikkei), and Scandinavia (SVT, Yle, Dagens Nyheter, Helsingin Sanomat). Each article was assigned to a single primary theme to avoid double counting.

1. Gross Value Added (GVA) is a measure of economic value-add, but directly reflects high capital and operating costs

GVA calculation overview

GVA $/year (GVA should be interpreted relative to physical output or investment cost to judge economic efficiency)

Intermediate Consumption (Cost of inputs)

- Goods and services used in production e.g. fuel, maintenance, imports
- Lower when costs are domestic (e.g. labour, local services) and higher when large shares are imported

GVA = Output – Intermediate Consumption

Output

- Market value of electricity or other goods and services generated
- Includes wages, depreciation and profits created in production

Advantages

- Shows domestic value creation from wages, services and capital returns
- Useful for comparing sectoral contributions to GDP

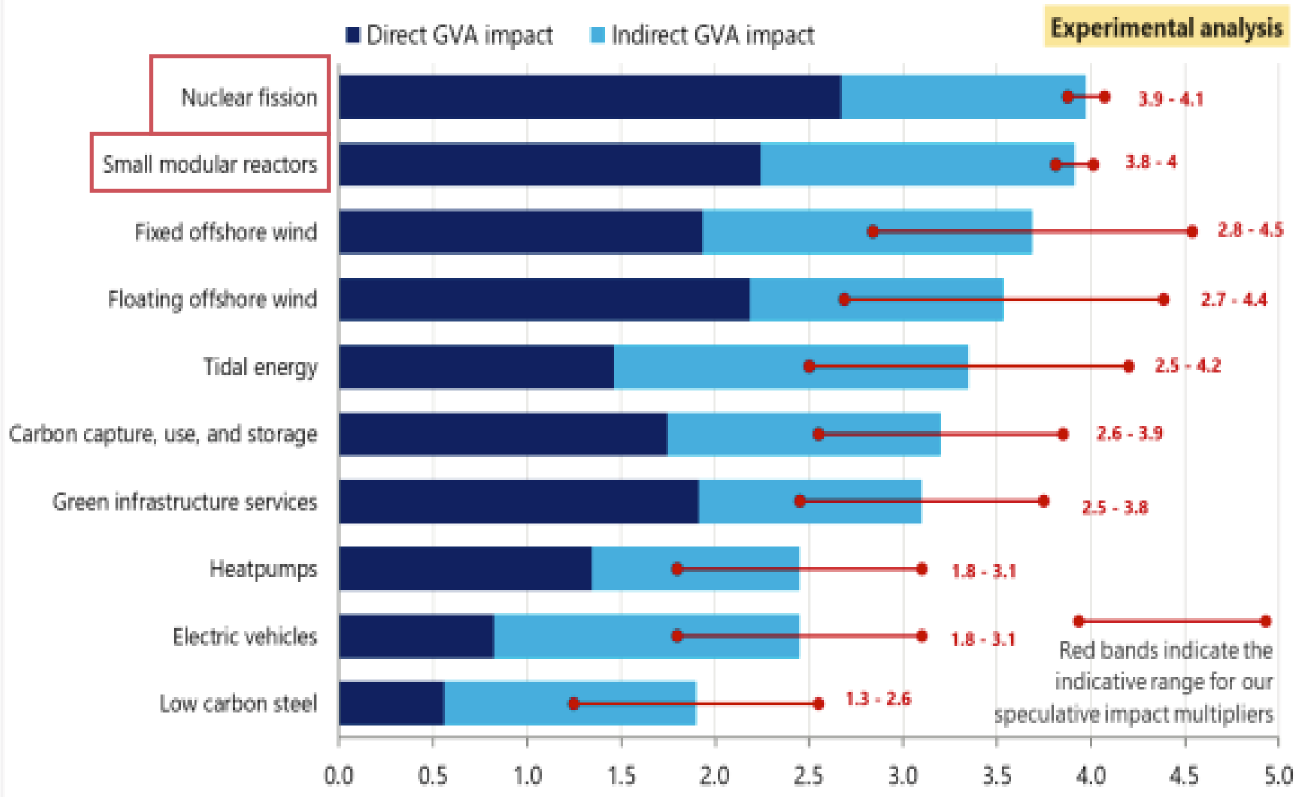
Disadvantages

- High GVA may **reflect high capital and operating costs** rather than economic efficiency or low consumer prices
- Capital-light, low-operating-cost technologies (e.g. solar PV) show lower GVA even when **delivering low-cost clean electricity**
- Does not incorporate consumer welfare or environmental externalities, so is not a full measure of societal benefit

1. Nuclear could generate the highest GVA per £ invested in the UK because of its service intensity

Indicative ranges for annual GDP impact of £1 billion government investment for each innovation, UK

£ billion, 2023 prices



Questions for discussion:

- Do these figures resonate with your experience?

Why does nuclear score highly?

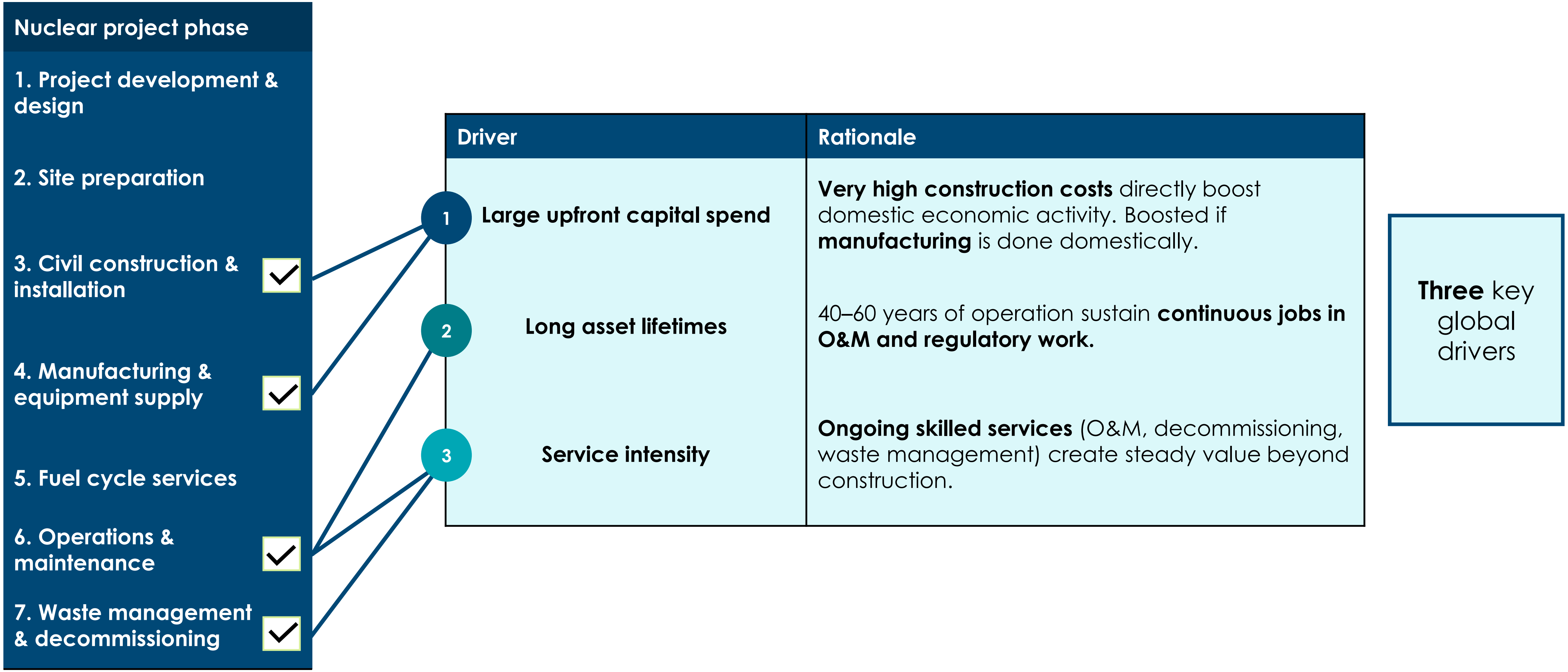
- Nuclear's higher GVA impact **reflects spend concentrated in UK-based services** (operations, maintenance, decommissioning) that have high value-add
- **High civil construction** drives strong direct GVA, while long-term activities extend indirect impacts through UK supply chains
- SMRs also score highly due to UK service intensity and supply chain potential, though maturity risks mean benefits remain uncertain

Model assumptions

- Direct & indirect GVA are built by mapping spend to ONS input–output sectors and applying sector GVA/output ratios; imports are removed (UK-captured spend only)
- Red lines are short-run multiplier ranges from literature (experimental; not UK-calibrated beyond the I-O mapping)

Source: Tony Blair Institute for Global Change & Oxford Economics (2024), *The UK's Competitive Advantage in Green Innovations: Capturing Growth from the Global Green Transition*.

1. Study shows that nuclear's high GVA driven by four key phases in project development



Nuclear project phase

- **1. Project development & design**
- **2. Site preparation**
- **3. Civil construction & installation** ☑
- **4. Manufacturing & equipment supply** ☑
- **5. Fuel cycle services**
- **6. Operations & maintenance** ☑
- **7. Waste management & decommissioning** ☑

Driver	Rationale
① **Large upfront capital spend**	**Very high construction costs** directly boost domestic economic activity. Boosted if **manufacturing** is done domestically.
② **Long asset lifetimes**	40–60 years of operation sustain **continuous jobs in O&M and regulatory work.**
③ **Service intensity**	**Ongoing skilled services** (O&M, decommissioning, waste management) create steady value beyond construction.

Three key global drivers

Source: Tony Blair Institute for Global Change & Oxford Economics (2024), *The UK's Competitive Advantage in Green Innovations: Capturing Growth from the Global Green Transition*.

1. Localising manufacturing a key factor in increasing the GVA of nuclear, benefitting the following countries

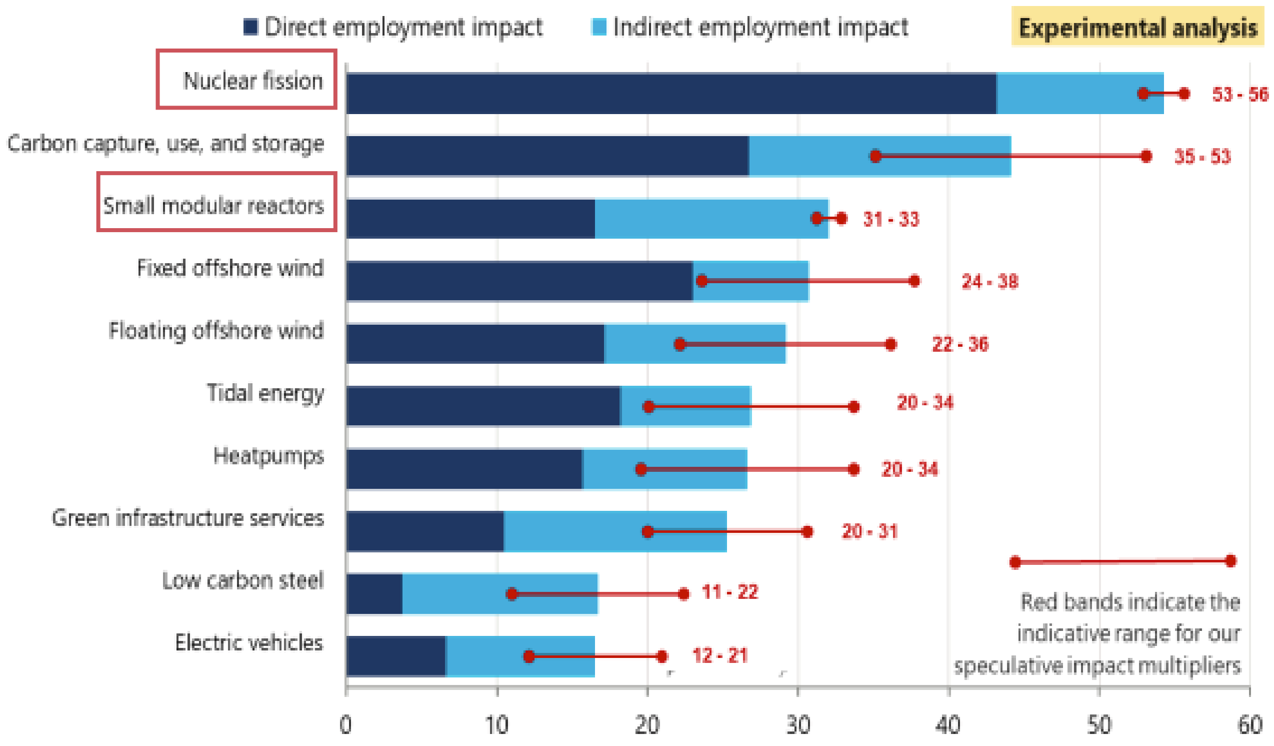
Phase	Activities	Example companies	Countries
1. Project development & design	Feasibility, licensing, permitting, engineering design	EDF, KHNP, Rosatom, Westinghouse Electric Company	🇫🇷 🇰🇷 🇷🇺 🇺🇸
2. Site preparation	Land acquisition, environmental surveys, utilities, access works	Bechtel, Fluor Corporation, China Energy Engineering Group	🇺🇸 🇨🇳
3. Civil construction & installation ☑	Reactor containment, turbine hall, cooling systems, civil works, major equipment	Bouygues Construction, CNNC, Larsen & Toubro	🇫🇷 🇨🇳 🇮🇳
4. Manufacturing & equipment supply ☑	Reactor vessel, turbines, generators, control systems, other components	Doosan Enerbility, GE Hitachi Nuclear Energy, Mitsubishi Heavy Industries, Framatome	🇰🇷 🇯🇵 🇺🇸 🇫🇷
5. Fuel cycle services	Uranium mining, enrichment, fuel fabrication	Cameco, Kazatomprom, Orano, TVEL Fuel Company	🇨🇦 🇰🇿 🇫🇷 🇷🇺
6. Operations & maintenance ☑	Day-to-day plant ops, inspections, refuelling	Exelon Generation, Ontario Power Generation, CGN	🇺🇸 🇨🇦 🇨🇳
7. Waste & de-commissioning ☑	Spent fuel handling, waste processing, dismantling, site remediation	Veolia Nuclear Solutions, EnergySolutions, NUKEM Technologies	🇫🇷 🇺🇸 🇩🇪

Source: IAEA (2018) Managing Nuclear Knowledge: Supply Chain and Human Resources Challenges; OECD NEA (2019) The Supply of Medical Radioisotopes and Nuclear Fuel Cycle Services; World Nuclear Association (2023) *World Nuclear Supply Chain: Outlook 2040*

2. Nuclear may deliver high UK job impact per £ invested driven by labour-intensive construction and long-lived service phases…

Indicative ranges for the employment impact of £1 billion government investment

£ billion, 2023 prices



Questions for discussion:

- Do these figures resonate with your experience?

Why does nuclear score highly?

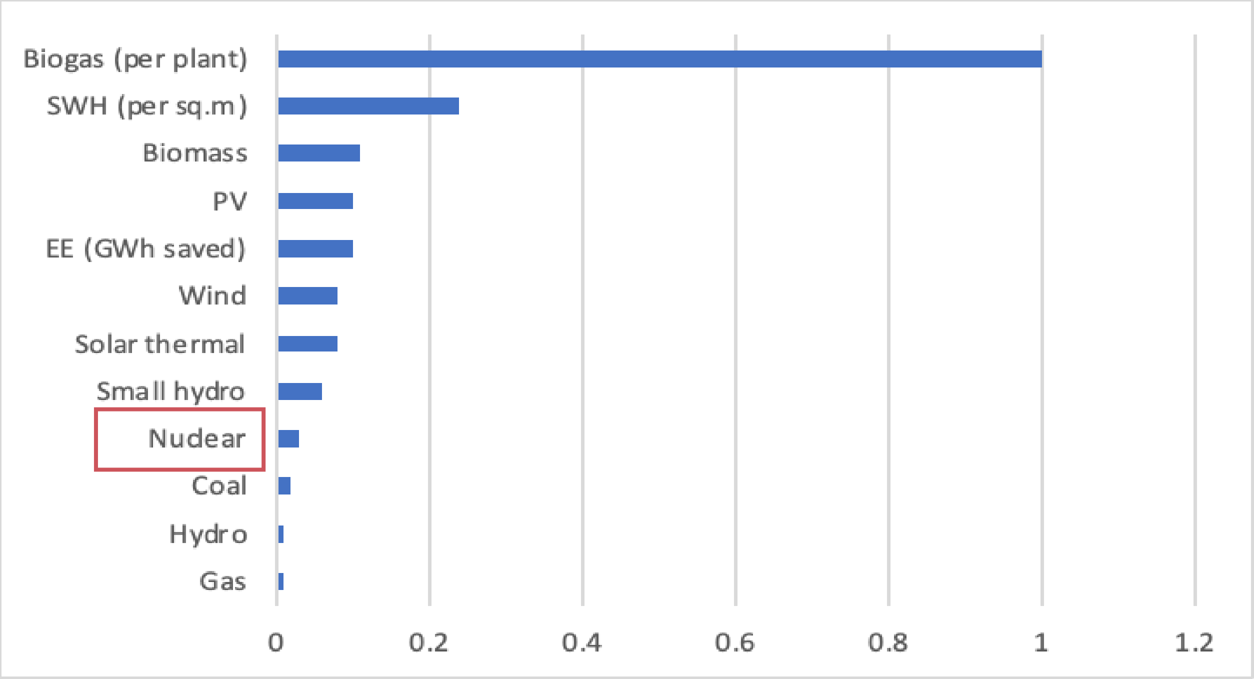
- **Labour-intensive construction and long-lived service phases** (O&M, decommissioning) are mapped to domestic, high-employment sectors
- Renewables score lower **as capital goods and equipment are often imported**, with fewer localised jobs captured in UK input–output tables
- Nuclear's decommissioning tail provides an additional employment stream not present for most renewables.
- **SMRs** are included in the modelling and also show high UK job multipliers, driven by **construction** and **long-term service phases**

Source: Tony Blair Institute for Global Change & Oxford Economics (2024), *The UK's Competitive Advantage in Green Innovations: Capturing Growth from the Global Green Transition*.

2. …however, cross-country evidence showcases that nuclear's impact varies with economic structure and methodology

Level of employment per Rs. Million invested, India

Jobs per 1,000,000 rupees spent



Source: B. Sudhakara Reddy (2014), India's Energy System Transition – Survival Of The Greenest

Why does nuclear score low?

- In India, a large share of nuclear spend maps to **equipment/engineering sectors with low jobs-per-₹ in India's I-O tables**; the **on-site civil works share is smaller** than for decentralised renewables, so fewer domestic jobs are recorded per ₹ invested
- **Imported reactor components/services are treated as non-domestic and don't create Indian jobs** in the model, lowering nuclear's measured employment intensity.

Key assumptions

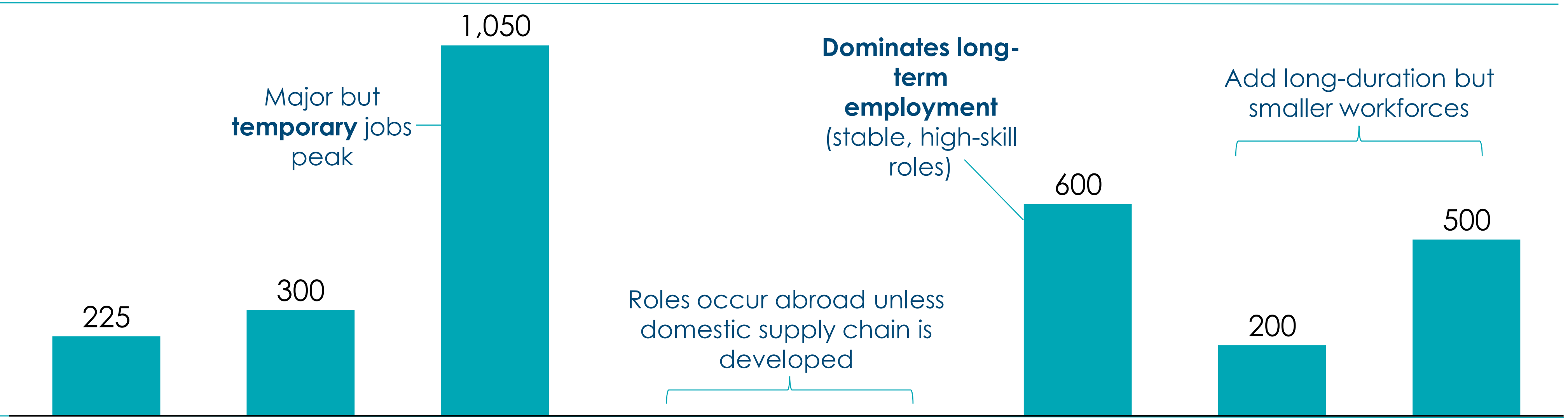
- Direct, indirect and induced effects calculated using India's national input–output tables.
- Imported inputs are excluded from value-added and job counts.
- Results are from the Green Economy (GE) scenario, which limits nuclear build and emphasises renewables; when averaged over the horizon, nuclear yields fewer lifetime job-years

2. In terms of project phases, civil construction and installation offer the largest amount of jobs in absolute terms

Global average – 1 GW Light Water Reactor; 10-year build, 50-year operation

Nuclear plant development phases

	Project development and design	Site preparation	Civil construction	Manufacturing	Fuel cycle	Operations & maintenance	Waste management	De-commisioning
Jobs per year per GW	225	300	1,050			600	200	500
Scale of pay per role	●	◔	◑	◕	●	●	◕	◑
Duration (years)	4	2	10	10	50	50	40	10



Major but **temporary** jobs peak

Roles occur abroad unless domestic supply chain is developed

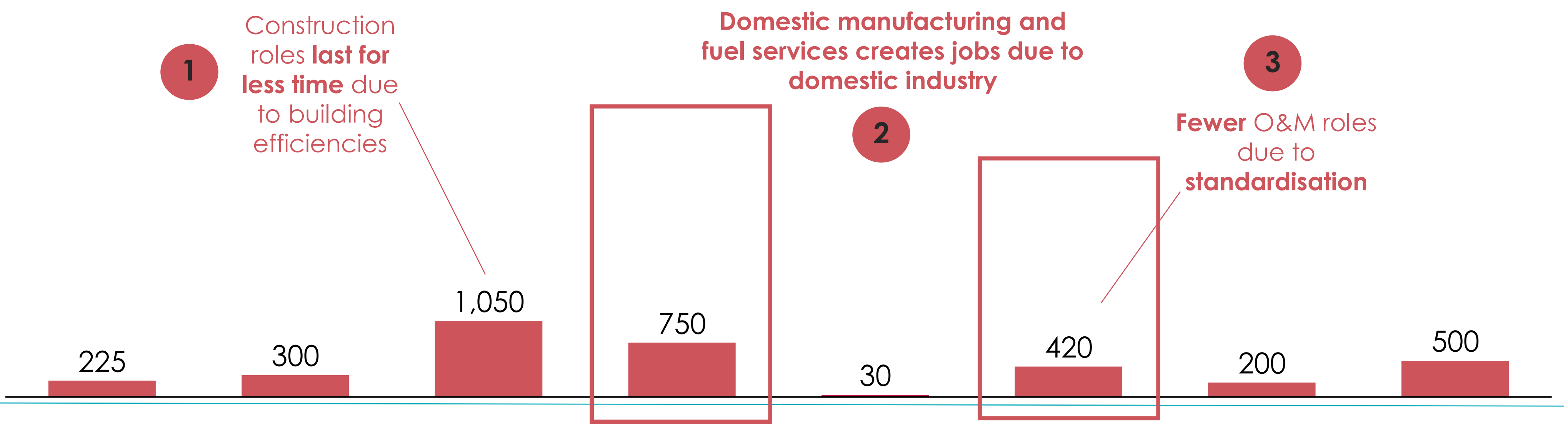
Dominates long-term employment (stable, high-skill roles)

Add long-duration but smaller workforces

Source: Systemiq analysis for the ETC (2025); OECD-NEA & IAEA (2018), *Measuring Employment Generated by the Nuclear Power Sector*

2. Experienced countries' standardisation and efficient build practices result in fewer roles in construction and operations, with shorter durations

South Korea – 1 GW Light Water Reactor; 10-year build, 50-year operation



① Construction roles **last for less time** due to building efficiencies

② **Domestic manufacturing and fuel services creates jobs due to domestic industry**

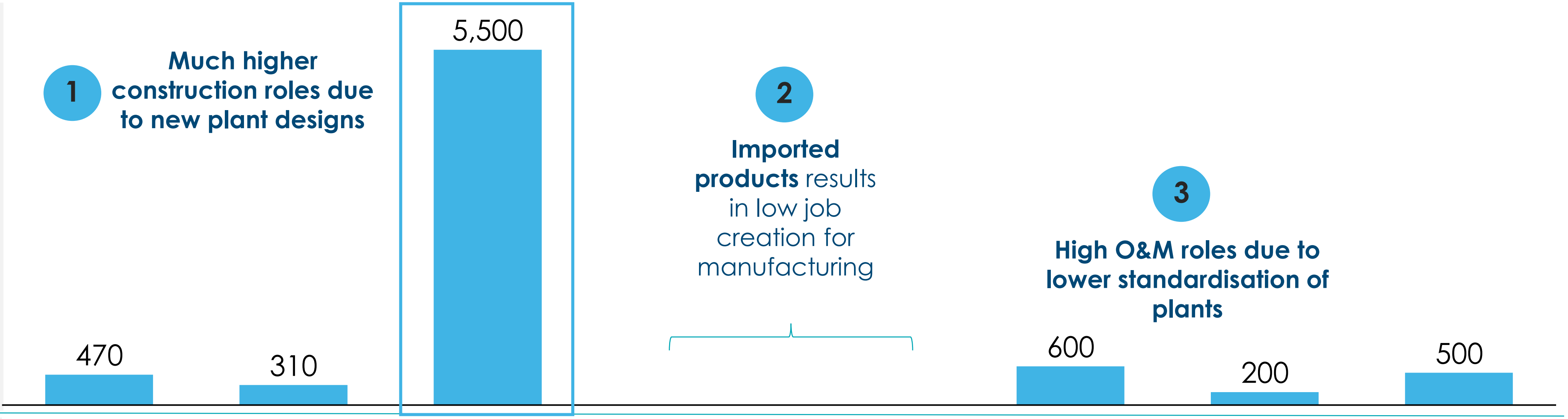
③ **Fewer** O&M roles due to **standardisation**

	Nuclear plant development phases							
	Project development and design	**Site preparation**	**Civil construction**	**Manufacturing**	**Fuel cycle**	**Operations & maintenance**	**Waste management**	**De-commisioning**
Jobs per year per GW	225	300	1,050	750	30	420	200	500
Scale of pay per role	●	◔	◑	◕	●	●	◕	◑
Duration (years)	**4**	**2**	**4-5**	**10**	**50**	**50**	**40**	**10**

Source: Systemiq analysis for the ETC (2025); OECD-NEA & IAEA (2018), *Measuring Employment Generated by the Nuclear Power Sector*

2. In terms of project phases, civil construction and installation offer the largest amount of jobs in absolute terms for a new entry country

UK – 1 GW Light Water Reactor, Hinkley Point C; 10-year build, 50-year operation



① **Much higher construction roles due to new plant designs**

② **Imported products** results in low job creation for manufacturing

③ **High O&M roles due to lower standardisation of plants**

	Nuclear plant development phases							
	Project development and design	Site preparation	Civil construction	Manufacturing	Fuel cycle	Operations & maintenance	Waste management	De-commisioning
Jobs per year per GW	470	310	5,500			600	200	500
Scale of pay per role	●	◔	◑	◕	●	●	◕	◑
Duration (years)	4	2	10	10	50	50	40	10

Source: Systemiq analysis for the ETC (2025); OECD-NEA & IAEA (2018), *Measuring Employment Generated by the Nuclear Power Sector;* EDF (2025), *3,000 new jobs in Somerset as Hinkley Point C hits peak construction*

2. Most nuclear roles are broadly transferrable to other industries, meaning if one phase completes, roles can be found elsewhere

While nuclear job creation is seen as a value-add for countries, transferability of skills to other industries or technologies is crucial when a particular project phase ends i.e. plant construction has completed.

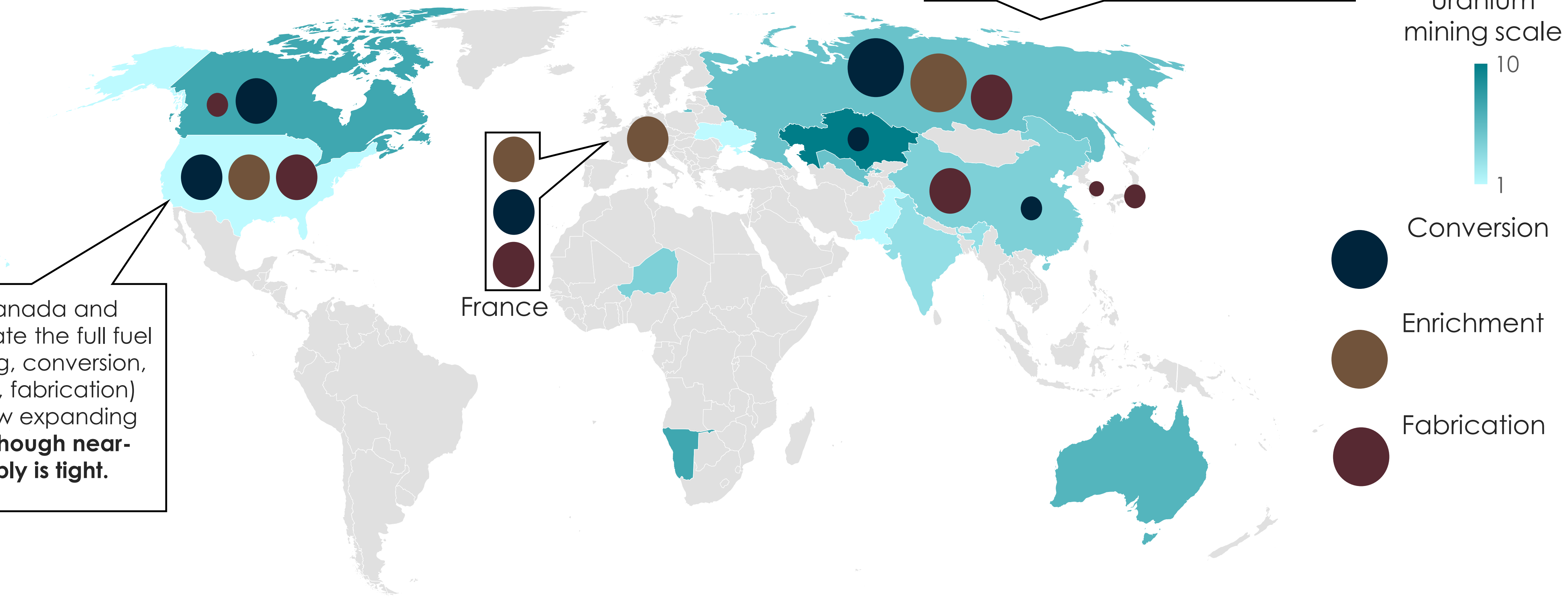
This will differ by country, but the table below uses sources to encapsulate transferability and sustainability of different roles.

Phase	Transferabiliity potential	Destinations
1. Project development & design	High	Project management, engineering consultancy, major infrastructure project
2. Site preparation	High	Civil works, construction, transport and urban development
3. Civil construction & installation (10 years)	High	Large infrastructure (tunnelling, offshore wind foundations, rail, industrial construction)
4. Manufacturing & equipment supply	Medium - High	Advanced manufacturing, aerospace, oil & gas equipment, offshore energy supply chains
5. Fuel cycle services	Low	Highly nuclear-specific; limited crossover to chemicals or medical isotopes
6. Operations & maintenance (50 years)	Medium	Broader power generation O&M, industrial facilities, renewables
7. Waste management (40 years) & decommissioning (10 years)	Medium	Hazardous waste management, demolition, environmental remediation

Sources: Robert Gordon University (2021), *UK Offshore Energy Workforce Transferability Review*; Major Projects Association (2021), *Decommissioning: Learning Lessons for Major Projects*; Astute People (2024), *Transferable Skills in the Nuclear Industry*.

3. Security and resilience – conventional reactor fuel supply chain is concentrated in a small pool of countries

Global uranium mining ranked by annual production (score out of 10)



Russia still controls ~40% of global enrichment and **~25%** of conversion, making this the main pinch point for nuclear fuel security.

The US, Canada and France operate the full fuel cycle (mining, conversion, enrichment, fabrication) and are now expanding capacity, **though near-term supply is tight.**

Note: Countries are ranked by share of global uranium mine output (World Nuclear Association 2025). Each share is converted to a score out of 10 by setting Kazakhstan, the largest producer, as 10 and assigning lower scores in decreasing bands of production share. Size of the circles - Large ≈ major global player, Medium ≈ significant but secondary, Small ≈ minor share. Source: World Nuclear Association (2025) *World Uranium Mining Production; Supply of Uranium, Conversion, Enrichment and Fuel Fabrication*.

3. Fuel conversion and enrichment are the stages that present the highest supply chain risk

Fuel-cycle stage	Main countries with significant capacity (low-risk producers)	Notes
Uranium mining	Kazakhstan, Canada, Namibia, Australia, Niger	**Moderately concentrated** – top 3 countries supply over 60 % of global uranium, with Kazakhstan ~40 %.
Conversion ($U_3O_8 \rightarrow UF_6$)	China, France, Russia, Canada, United States	**Highly concentrated** – Canada and France lead non-Russian supply, but Russia still ~25 % of global capacity.
Enrichment (UF_6 → enriched UF_6)	Russia, China, France, United States, Netherlands	**Very concentrated** – Russia holds about 40 % of capacity; Urenco and Orano are main Western alternatives.
Fuel fabrication (fuel assemblies)	United States, Russia, France, China, South Korea	**Moderately concentrated** – many nations have some fabrication, but Russia remains important for certain reactor types (e.g. VVER).

Note: *Risk level reflects supplier concentration and geopolitical exposure, not cost. Source: Kearney (2022) Supply chain resilience management in the nuclear industry: addressing concentrated risks

3. ETC identifies three strategic vulnerabilities in nuclear fuel supply chains

1

Overdependence

Dependence on a few suppliers creates risk. Russia provides ~40% of global enrichment, making diversification a strategic priority.

2

Construction timelines

New enrichment or fabrication capacity takes close to a decade to build, so hedging requires early investment.

3

New supply chains

Advanced reactors and SMRs require fuels with no commercial supply chain today, adding future uncertainty.

Without early action to diversify supply and build strategic reserves, **developers and governments face sustained security and cost exposure**

3. Climate resilience is a critical risk factor for nuclear fleets: lessons from France and the UAE

Thermal stress risk

In 2022 **EDF curtailed up to 5GW of nuclear** due to river water cooling limits during European heatwaves

Inland French reactors **dependent on rivers** were exposed to warming and drought

Climate-adaptive design features

The Barakah plant uses **coastal seawater cooling, avoiding freshwater stress.**

Designed for desert heat extremes, reactors have **higher temperature-tolerant cooling systems,** though high Gulf seawater temperatures **still reduce efficiency** and pose long-term climate resilience challenges.

System insight

Nuclear can withstand climate stress **if located and engineered appropriately**, but site choice and cooling technology are decisive

Reliance on freshwater cooling creates systemic risks under climate change; while coastal or hybrid systems can enhance resilience, they are not totally immune from climate challenges

Question: are you aware of costs relating to 'climate proofing' reactors?

Source: WNN (2022), Barakh nuclear plant reaches full power – lessons for desert cooling; World Nuclear Association (2023) Cooling power plants; IAEA (2019), Adapting nuclear power plants to climate change

4. Public perceptions of nuclear centre around fear of accidents and radioactive waste disposal

Accident risks and safety concerns

- **Historical accidents** (Chernobyl, Fukushima) drive lasting safety fears
- Zaporizhzhia nuclear plant **in conflict zone reinforces** global risk perception
- **Higher concern in non-nuclear countries**; lower in experienced nuclear nations (France, Sweden)

Prospect of Nuclear Accident 'Dangerously Close' at Zaporizhzhia Power Plant in Ukraine, International Atomic Energy Agency Chief Warns Security Council

Waste disposal

- Main concerns focus on **long-term waste storage** and **leakage risks**
- Local opposition common for **new disposal sites** (e.g. UK geological disposal facility plans)

'It'll be a shortlist of one!' Villagers in England fear nuclear dump proposal

Sources: International Atomic Energy Agency (2022) *Public Attitudes Towards Nuclear Power: Trends and Influences;* World Nuclear Association (2023) *Public Opinion on Nuclear Energy;* Eurobarometer (2021) *Europeans' Attitudes Towards Climate Change;* Ipsos (2022) *Global Attitudes on Climate Change and Nuclear Energy;* Pidgeon, N. et al. (2014) *Public Perceptions of Nuclear Power, Climate Change and Energy Security: UK Findings*.

4. Public concerns over accidents - past nuclear major incidents have raised concerns over wider safety

These high-profile accidents **significantly eroded public trust in nuclear power**, leading to stronger regulation, delays in new builds, and in some cases, nuclear phase-out policies.

Incident	Year	Cause	Impact on perception / policy	Steps taken after incident
Three Mile Island	1979	Equipment failure and operator error	**First major US nuclear accident**; halted new reactor orders for decades	Strengthened training and safety systems
Chernobyl	1986	Reactor design flaws + safety violations	**Symbol of nuclear risk**; accelerated anti-nuclear movements in Europe	IAEA safety conventions, better containment designs
Fukushima	2011	Tsunami disabled cooling systems	**Renewed global safety reviews**; Germany and others accelerated nuclear phase-out	Flood/seismic protections, severe accident guidelines

Source: NRC (1980) Report of the President's Commission on the Accident at Three Mile Island; IAEA (1992) The International Chernobyl Project: Assessment of Radiological Consequences and Evaluation of Protective Measures; World Nuclear Association ((2023) Chernobyl Accident 1986

4. Plant solutions - technology design key for new build reactors; operational practices more crucial for existing plants

Technology design	• **Conventional reactor upgrades** with passive safety, redundant cooling and robust containment • **Advanced reactors** with inherent safety, low-pressure coolants and underground siting • **SMR's** modular design increases safety	**China** – AP1000 reactors with passive safety at Sanmen.
Operational practices	• **Enhanced operator training** for extreme-event scenarios • **Real-time monitoring** and predictive maintenance to detect anomalies early	**United States** – FLEX programme with portable pumps and generators post-Fukushima.
Regulatory frameworks	• **Post-Fukushima requirements** for extended power-loss coping, flood and seismic resilience • **Periodic safety reviews** with stress tests for extreme events and cybersecurity standards • **Waste rules mandating** multi-barrier geological repositories with long-term monitoring	**Finland** – Onkalo deep geological repository licensed for spent fuel.

Most critical for **new-build** plants

Most critical for **existing** plants

Source: IAEA (2018) Nuclear Power and the Post-Fukushima Safety Framework; OECD NEA (2020) Advanced Nuclear Fuel Cycles and Radioactive Waste Management; World Nuclear Association (2023) Nuclear Power in China

4. Public concern: in reality nuclear waste is minimal and safely managed, making public engagement critical

France generates the following amounts of waste* per inhabitant per year:

13.8 t
of trade waste
(construction, industry, ag r iciculture, health care activities)

354 kg
of household waste

100 kg
of toxic industrial waste

2 kg
of radioactive waste
Of this waste:
60% is from the nuclelear industry, and 40% fron other setors

*Source ADEME (2016)

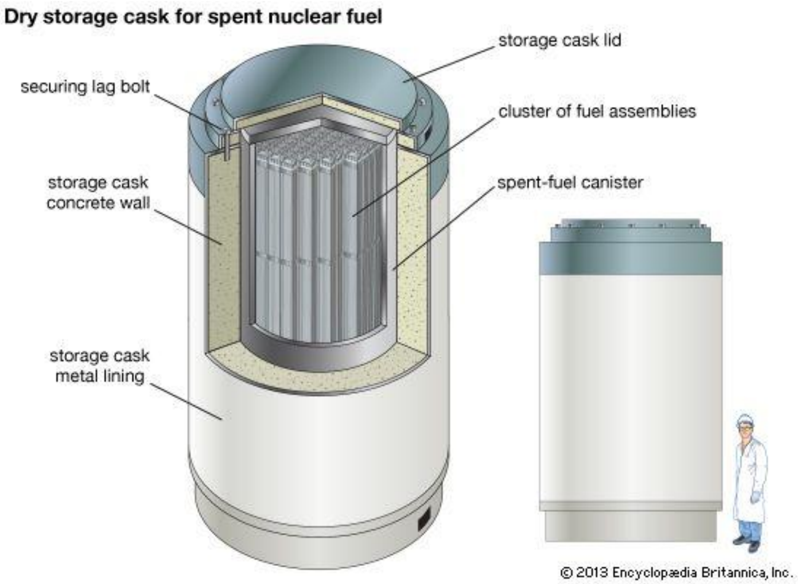
Public fear is often disproportionate: the scientific record shows nuclear waste is small in volume, highly regulated, and safely managed

Source: ADEME (2016) *Déchets: chiffres-clés. Édition 2016*; IAEA (2022) *Status and Trends in Spent Fuel and Radioactive Waste Management;* World Nuclear Association (2023) *Radioactive Waste Management*

4. Waste solutions exist and the majority of waste is low risk

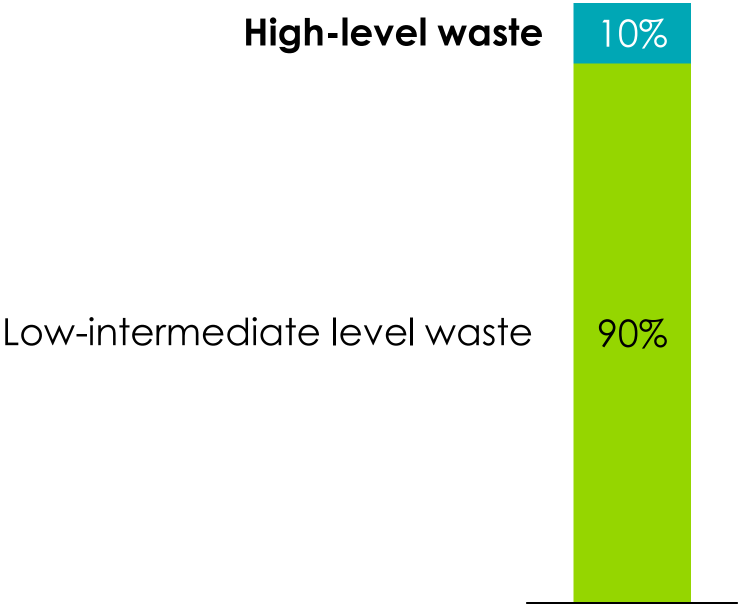
How nuclear waste is handled today?

- Spent fuel is first cooled in on-site water pools for several years to absorb heat and radiation.
- It is then moved to **dry cask storage** (steel and concrete containers) where it can safely sit for 50–100 years



What amount of nuclear waste is high-risk?

- **Over 90% of volumes are low- or intermediate-level waste** (protective clothing, tools, filters) which are routinely disposed of in engineered surface or near-surface facilities
- Only a small fraction (<10%) is high-level waste/spent fuel, which is contained but awaits permanent disposal



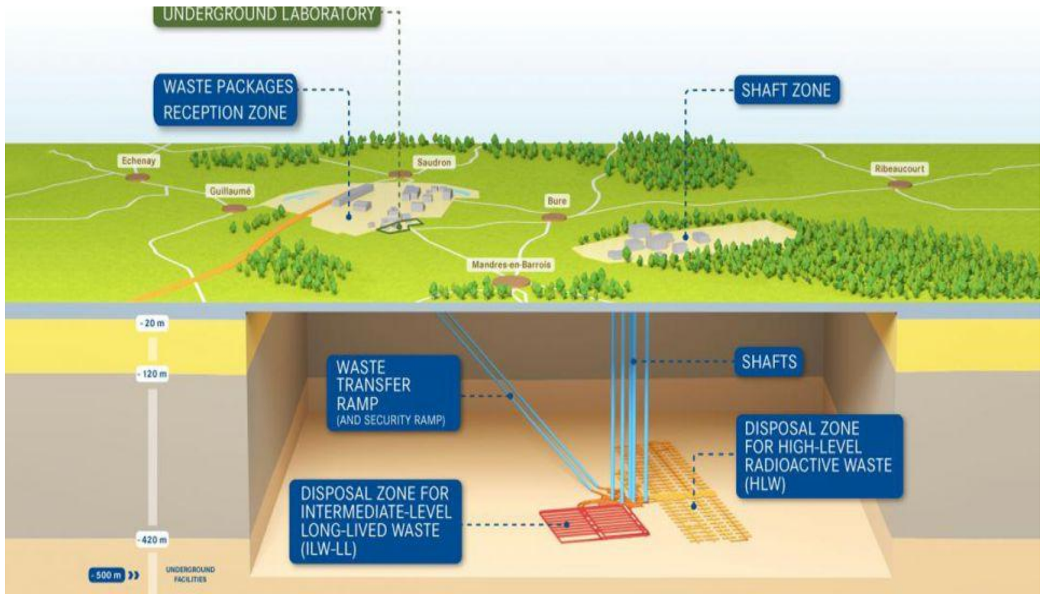
Source: Encyclopaedia Britannica (2013) *Dry storage cask for spent nuclear fuel;* World Nuclear Association (2023) *Radioactive Waste Management*.

4. While nuclear waste safe in storage, permanent, long-term disposal faces technical, cost and political hurdles

How is waste disposal changing?

- France (Cigéo) and other countries are advancing, but **most nations still rely on interim storage**.
- Finland (Onkalo, 2025) and Sweden (Forsmark, 2030s) will open the **first deep geological repositories** for **permanent disposal**.
- New R&D (partitioning, transmutation, recycling) **could reduce volumes of long-lived waste**, but these remain at pilot or demonstration stages.

France's planned Cigéo repository



Is waste therefore an ongoing risk?

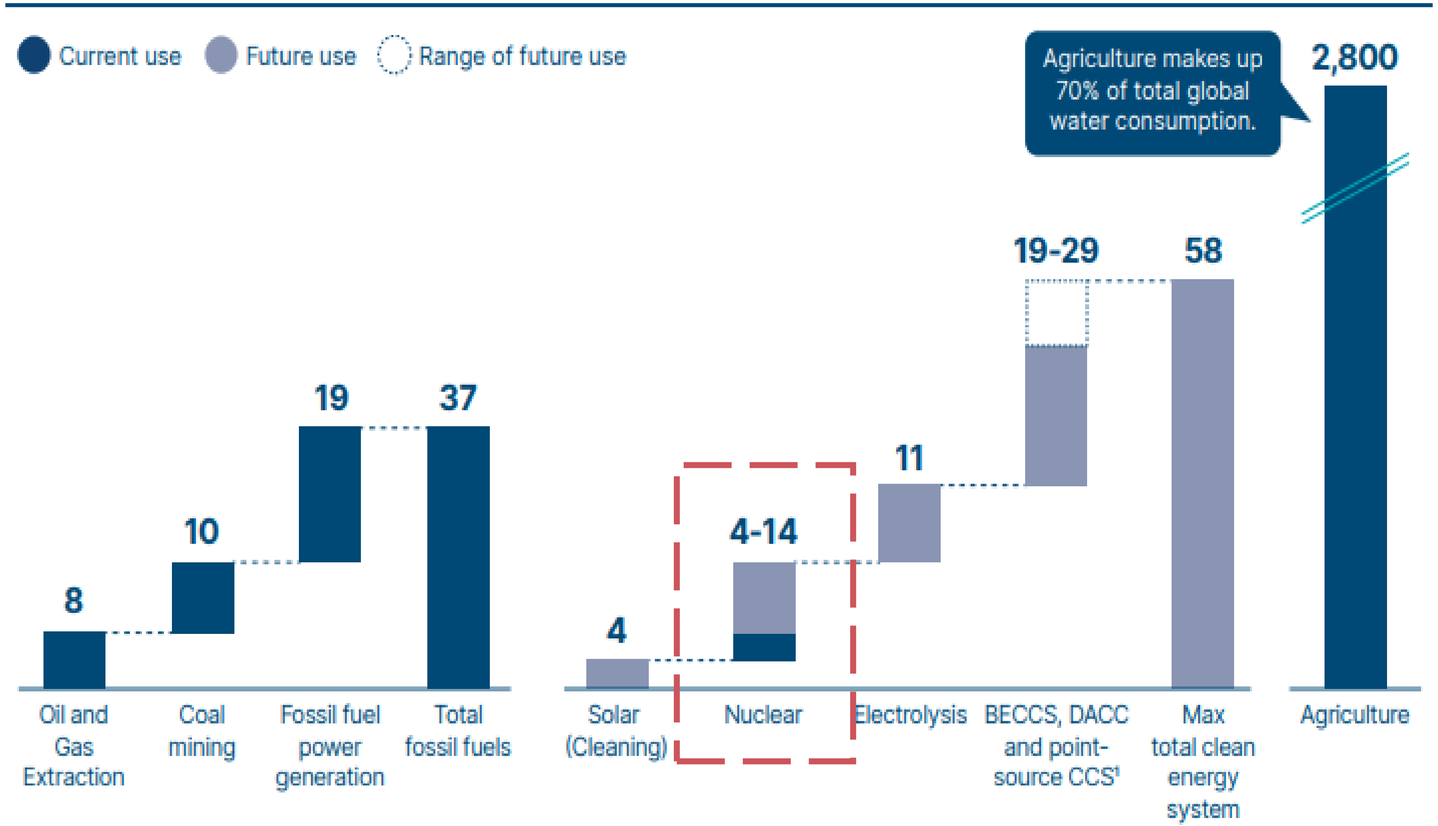
- **Technically, waste is managed safely today**; there is no ongoing public health risk from stored material
- The risk lies in long timelines, cost overruns, and political resistance to **siting repositories**
- Decommissioning adds further complexity, as dismantling old reactors produces large waste volumes and requires long-term funding commitments.

Source: Andra (Agence nationale pour la gestion des déchets radioactifs) (2022) *Cigéo project: Deep geological disposal for radioactive waste;* World Nuclear Association (2023) *Storage and Disposal of Radioactive Waste*.

5. Resources: nuclear requires a relatively higher share of water consumption relative to other clean electricity generation sources

Annual water consumption

Billion m3



Key Insights

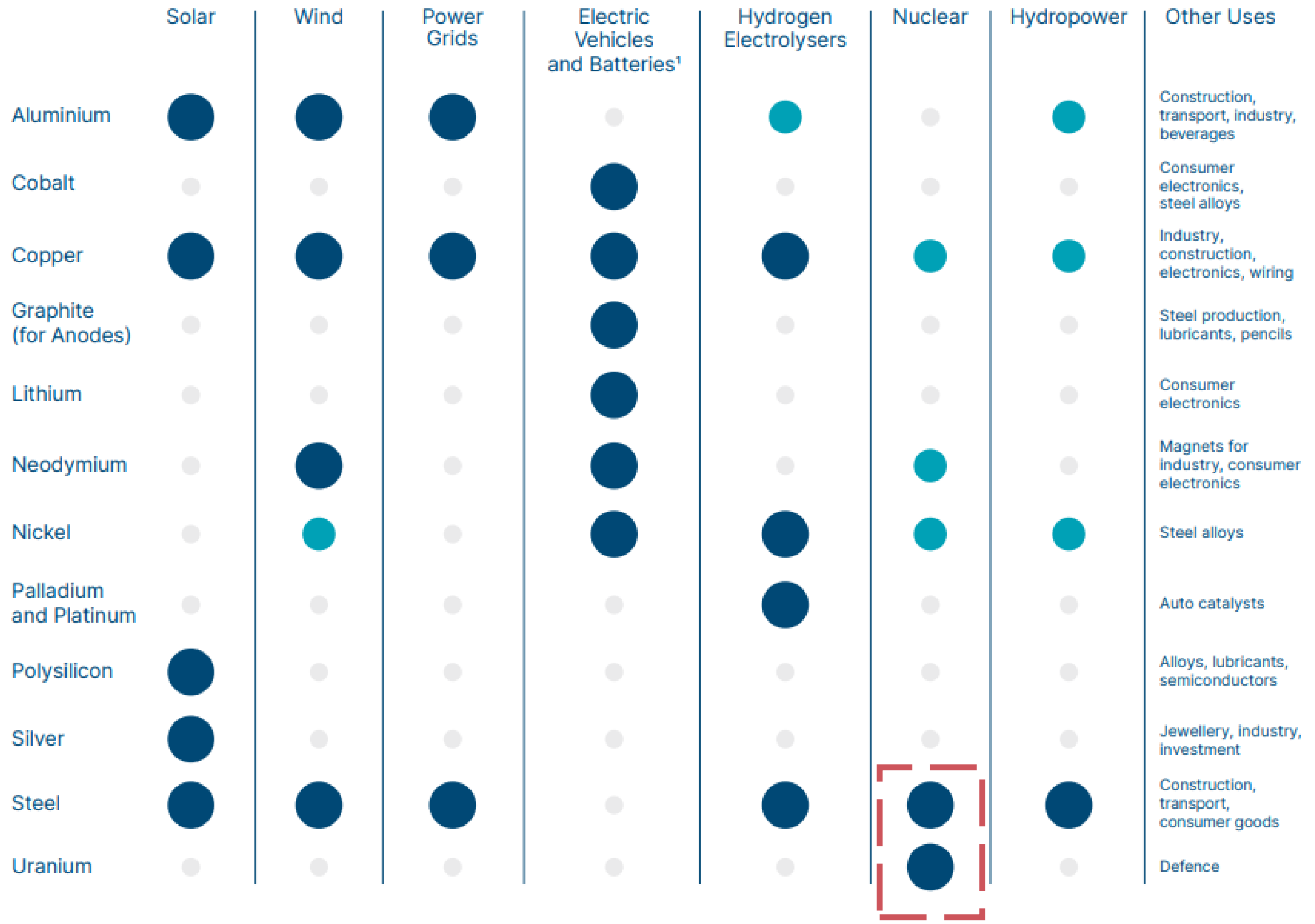
Nuclear power dominates water requirements for electricity generation and could reach up to **14 billion m3 each year**, similar to current fossil fuel power generation needs.

Nuclear has high water withdrawals (mainly for cooling) but low net consumption. Most would be expected to be sited near rivers or coastal waters.

Advanced designs aim to cut water use, **and projected demand is manageable,** though local water stress may limit siting

Sources: Systemiq analysis for the ETC; IEA (2021), *The Role of Critical Minerals in Clean Energy Transitions*; IEA (2016), *Water-Energy Nexus*; Meissner (2021), *The impact of metal mining on global water stress and regional carrying capacities*; Macknick et al. (2012), *Operational water consumption and withdrawal factors for electricity generating technologies*; Our World in Data (2017), *Water use and stress*; ETC (2021), *Making the hydrogen economy possible*; Smith et al. (2016), *Biophysical and economic limits to negative CO_2 emissions*; Rosa et al. (2021), *The water footprint of carbon capture and storage technologies*.

5. On raw materials, nuclear removes pressure from high-demand materials in the transition, the focus being on steel and uranium



	Solar	Wind	Power Grids	Electric Vehicles and Batteries[1]	Hydrogen Electrolysers	Nuclear	Hydropower	Other Uses
Aluminium	●	●	●	·	•	·	•	Construction, transport, industry, beverages
Cobalt	·	·	·	●	·	·	·	Consumer electronics, steel alloys
Copper	●	●	●	●	●	•	•	Industry, construction, electronics, wiring
Graphite (for Anodes)	·	·	·	●	·	·	·	Steel production, lubricants, pencils
Lithium	·	·	·	●	·	·	·	Consumer electronics
Neodymium	·	●	·	●	·	•	·	Magnets for industry, consumer electronics
Nickel	·	•	·	●	●	•	•	Steel alloys
Palladium and Platinum	·	·	·	·	●	·	·	Auto catalysts
Polysilicon	●	·	·	·	·	·	·	Alloys, lubricants, semiconductors
Silver	●	·	·	·	·	·	·	Jewellery, industry, investment
Steel	●	●	●	·	●	●	●	Construction, transport, consumer goods
Uranium	·	·	·	·	·	●	·	Defence

Importance of material to clean energy technology:

● High • Mid · Little/no requirement, or not applicable

Key Insights

Nuclear mainly requires steel and uranium, with **minimal reliance on critical minerals in high demand from other clean technologies.**

This **reduces competition for scarce materials** and eases supply chain pressures.

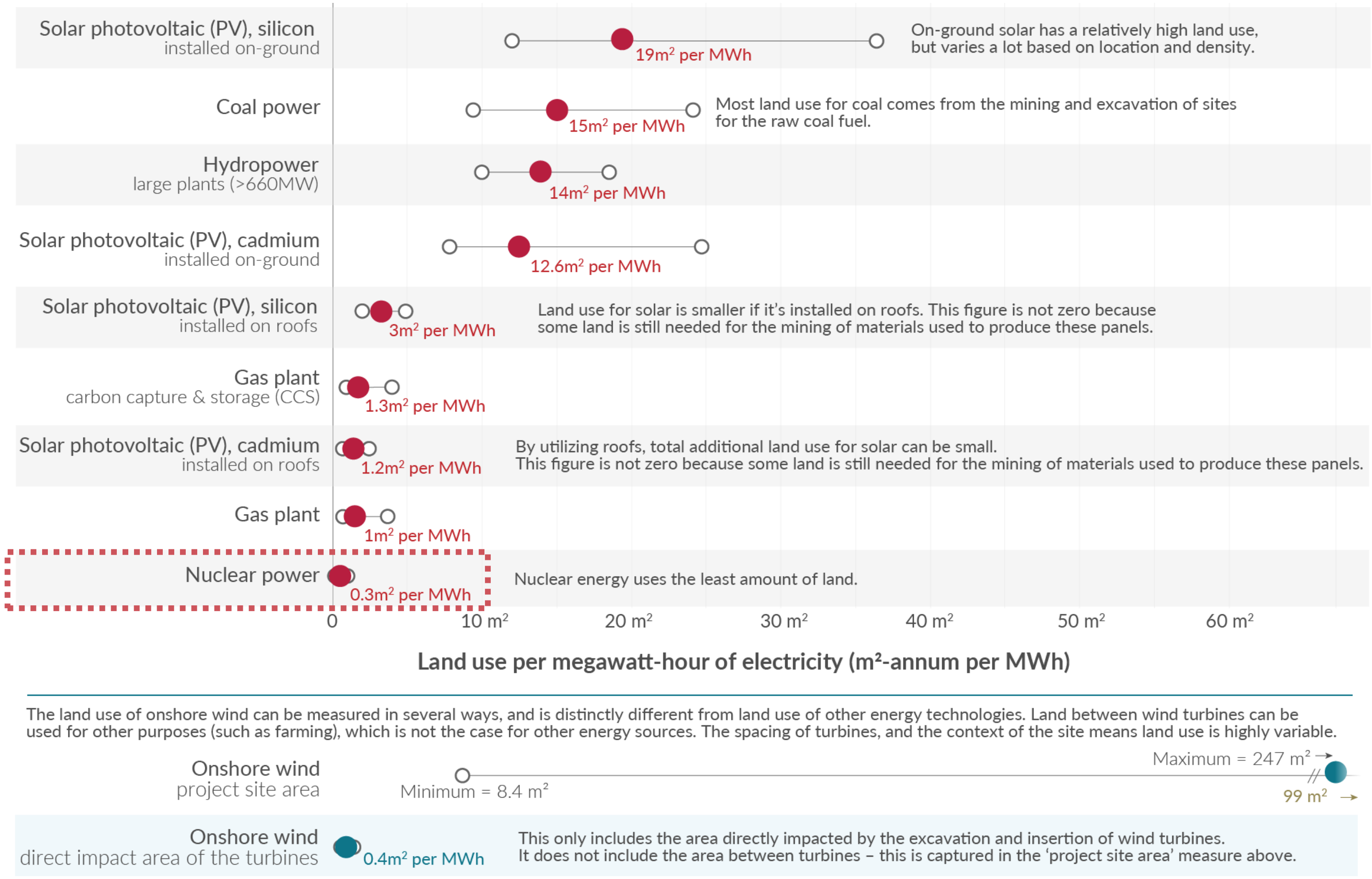
Steel demand is significant but manageable within expected global capacity.

Source: ETC (2023), *Materials for the Energy Transition*

5. Resources: the land footprint of nuclear is much smaller than that of wind and solar

Land use of energy sources per unit of electricity

m3 per MWh



Key Insights

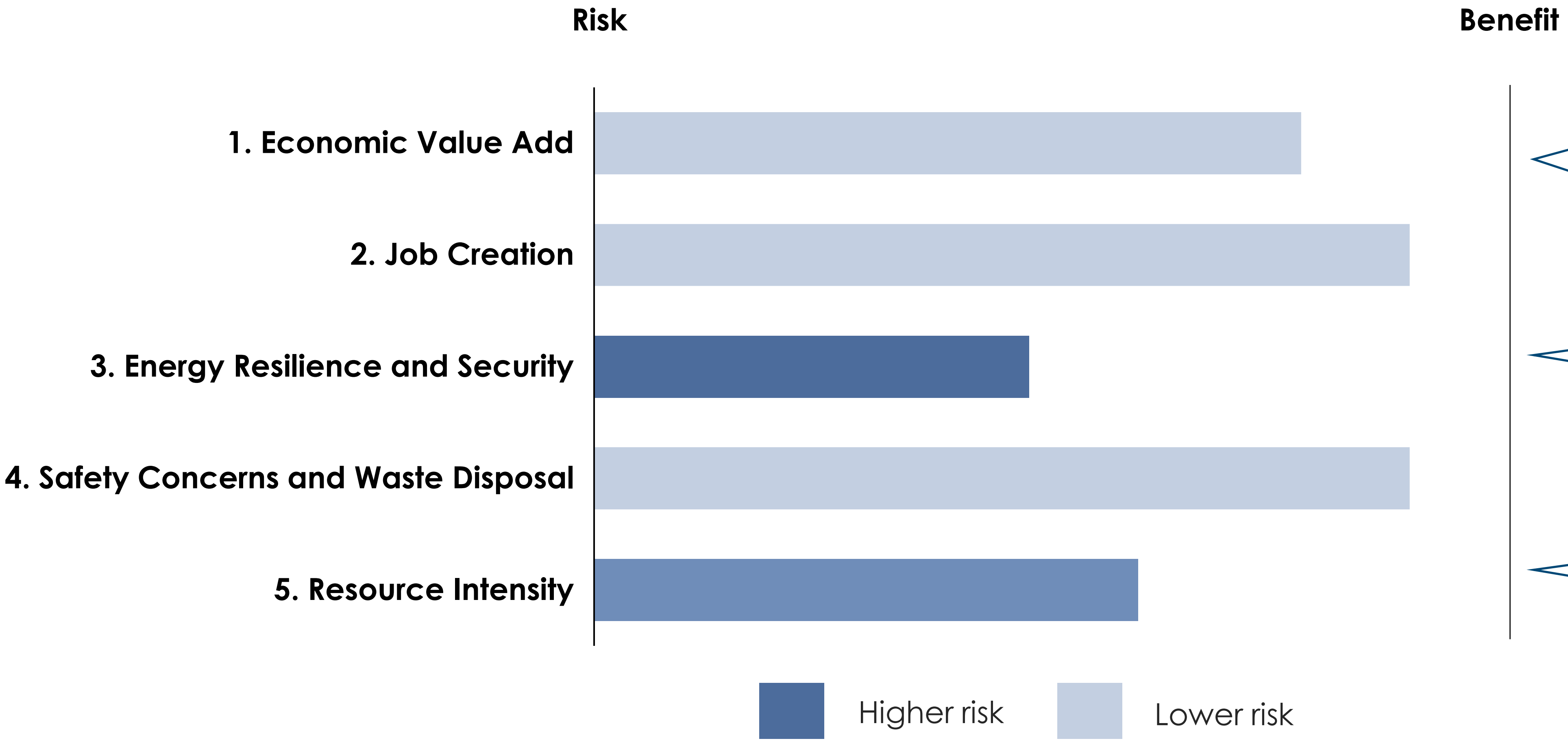
Nuclear has the smallest land footprint of major low-carbon technologies, at ~0.3 m²/MWh.

Onshore wind and utility-scale solar require 40–200 times more land per MWh

Low land use benefits dense regions and areas with competing land needs

Note: land use is based on life-cycle assessment; this means it does not only account for the land of the energy plant itself but also land used for the mining of materials used for its construction, fuel inputs, decommissioning, and the handling of waste. Source: Hannah Ritchie for Our World in Data (2022), How does the land use of different electricity sources compare?

Key takeaways on wider risks and benefits relating to nuclear power



Both highly dependent on market structure and domestic industries

Short-term risks from fuel supply chains

Water a risk

Agenda

- Context: the state of play of nuclear
- Techno-economics and understanding “system value”
- Wider risks and benefits
- **Emerging conclusions**

Role of nuclear and geothermal will vary in different geographies

1. Is there alternative clean resource availability?
2. Can it be effective from a system cost perspective?
3. Can it deliver other energy system benefits?
4. Can it deliver benefits & is there sufficient regulatory capacity?

Role of nuclear and geothermal across key geographies

Next steps for the nuclear and geothermal workstream

	Workshop	Date	Focus
1	**Workshop One: The role of Nuclear**	02 October 2025, 9:30am–12:30pm	The current state of play, the techno-economics of new projects, the system value nuclear can provide, and the wider risks and benefits of development.
2	**Workshop Two: The role of Geothermal**	November / December	Geothermal techno-economics, system value, wider risks and benefits.
3	**Workshop Three: Key enablers to scale Nuclear and Geothermal**	Early 2026	Guidelines and enablers required to scale nuclear and geothermal.