Energy
Transitions
Commission

Emerging insights on the role of nuclear and geothermal in clean power systems

ETC Commissioners Meeting

30 October 2025

Agenda

- **Work programme introduction**
- Nuclear: Emerging Insights
- Geothermal: Initial Insights
- Next steps

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**.

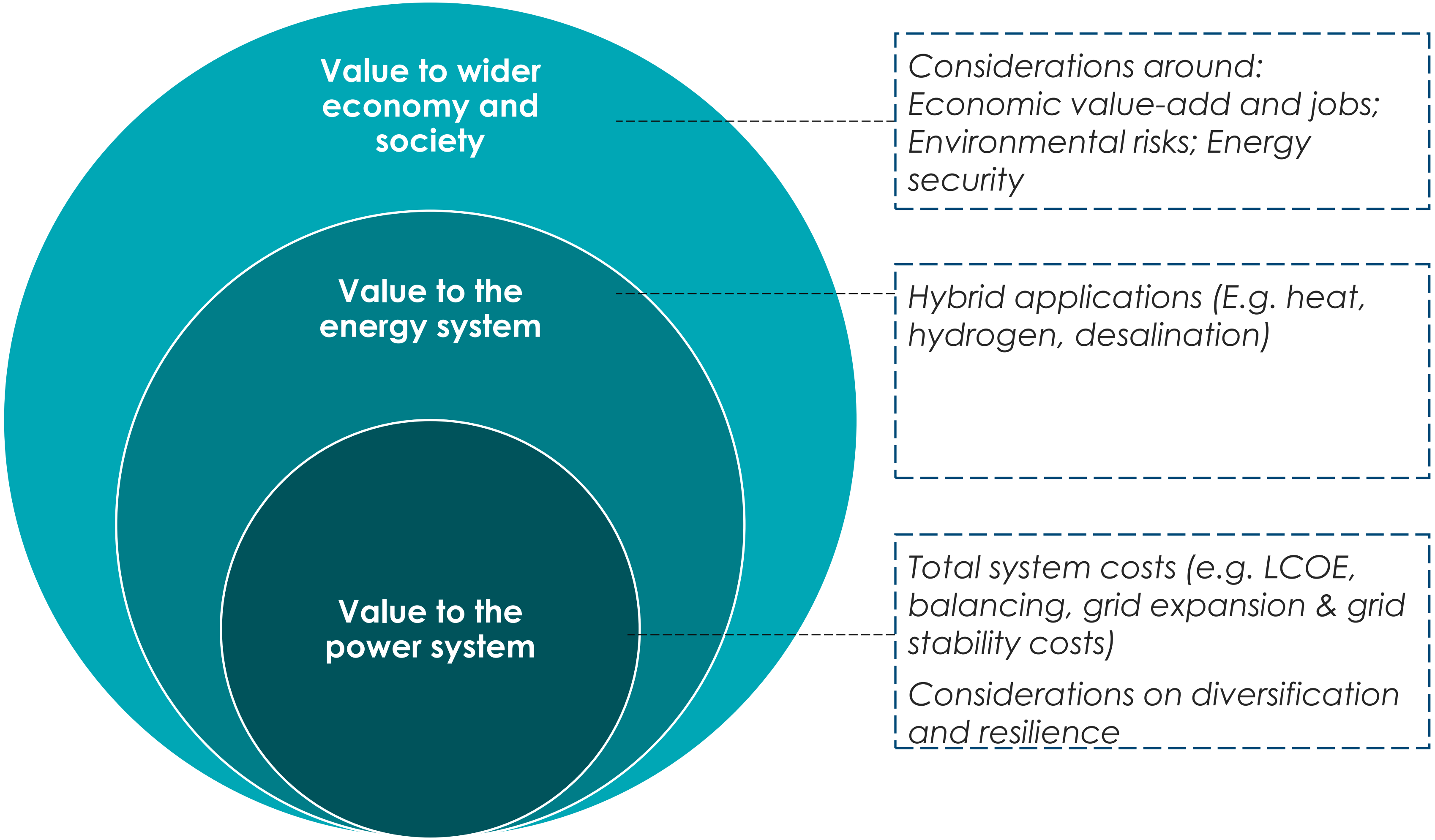
ETC WORKSTREAM WILL EXPLORE

- **What is the role of nuclear and 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** (2nd October 2025)
- ☐ **Workshop 2 - The role of Geothermal** (early December 2025)
- ☐ **Workshop 3 -** Key enablers to scale Nuclear and Geothermal

Value of Nuclear and Geothermal 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 and geothermal can complement a high renewable system

Agenda

- Work programme introduction
- **Nuclear: Emerging Insights**
- Geothermal: Initial Insights
- Next steps

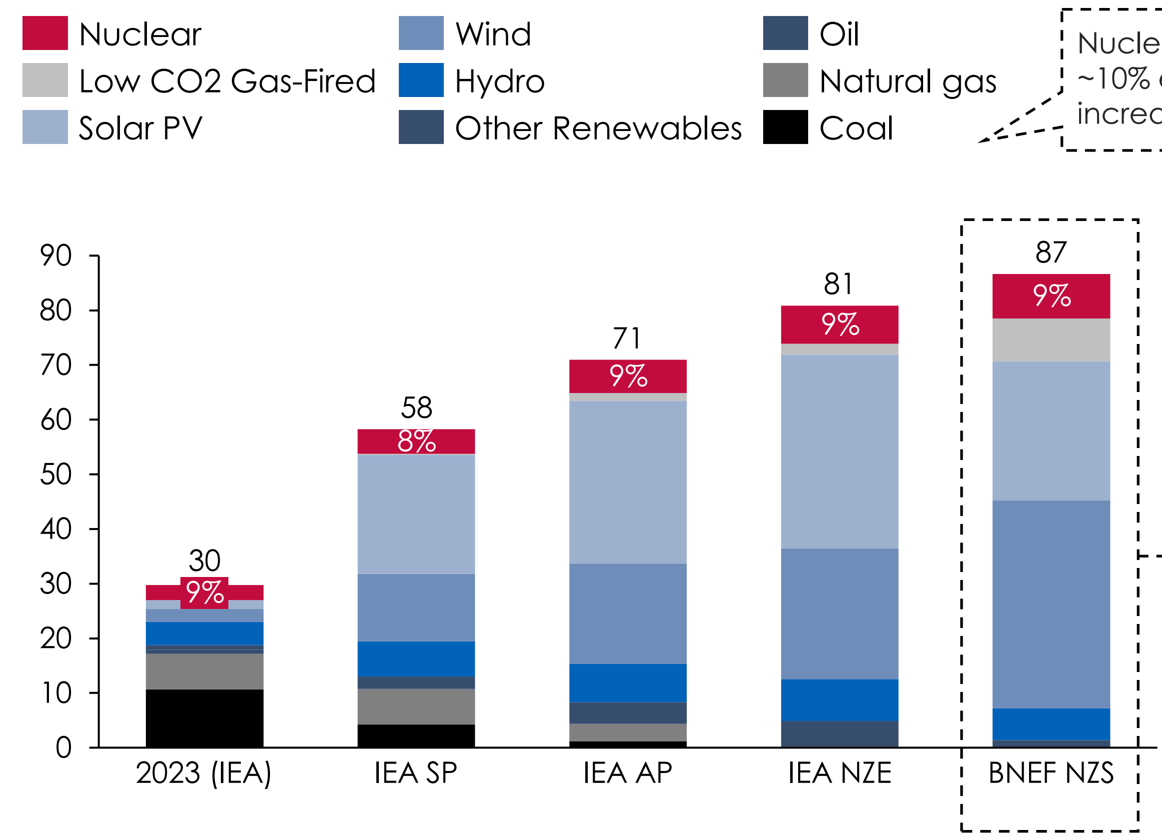
Emerging conclusions

1. **External projections of the global power system often include 10% of nuclear share of generation,** however **the current build rate will not be enough to meet that share**
2. **Nuclear LCOE and project timelines varies considerably across countries,** with the **Capex and cost of capital** having an outsized impact on total costs.
3. **Standardisation between nuclear design and regulations is the key to reducing Capex, finance costs and construction timelines,** deployment in next decade will be dominated by designs using mature technology, large unit sizes, and standardised designs (including SMRs).
4. **A 10-20% nuclear share of generation can result in total system costs equivalent to 100% renewables systems.** While nuclear generation is more expensive than clean alternatives, it can save some additional balancing, curtailment, grid stability and T&D costs.
5. The economic benefit and risks around nuclear have been highly featured in public debate this year, however **evidence points towards economic benefits being country and project cost dependent, while most risks already have proven solutions.**

1. 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)

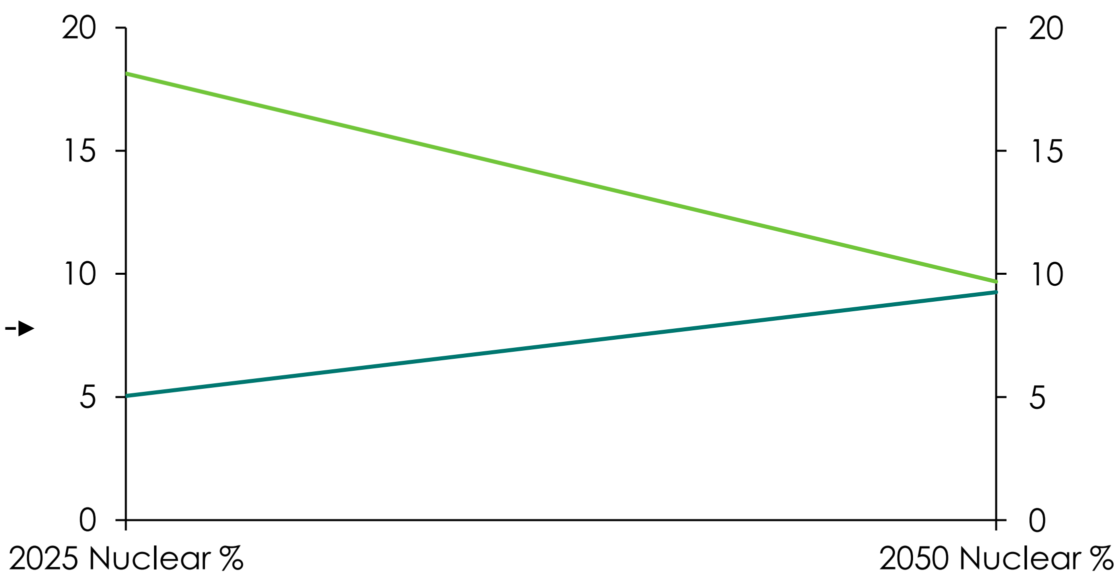
‘000 TWh



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).

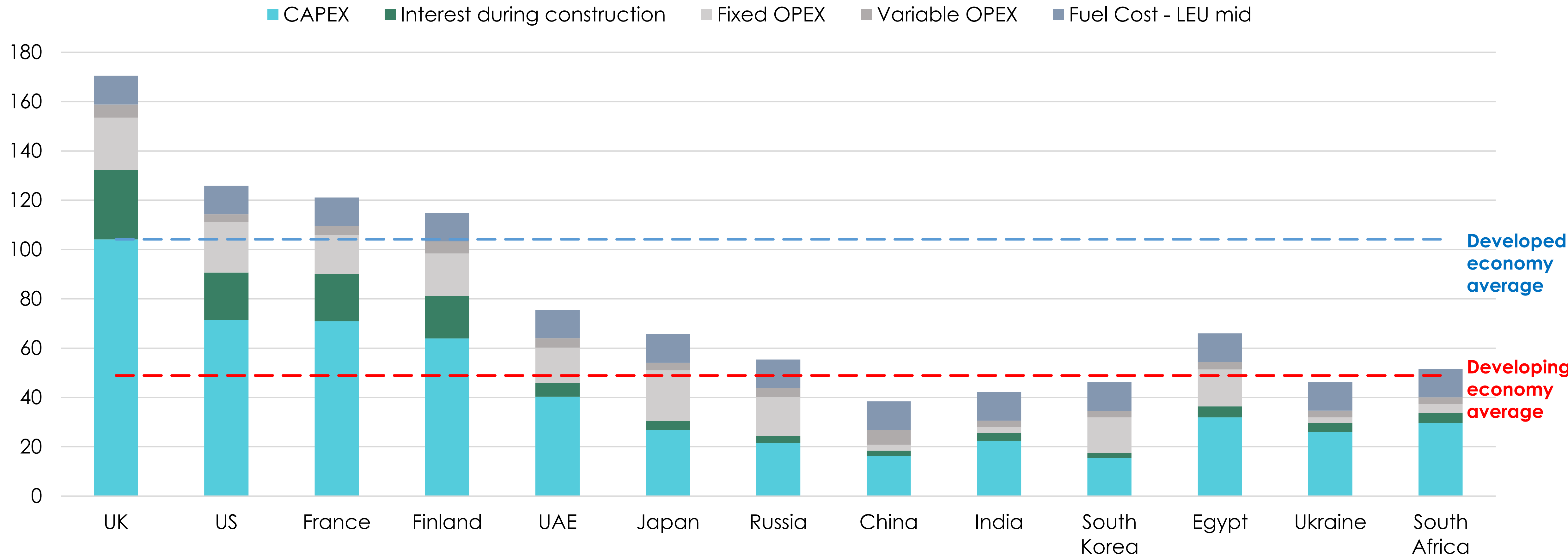
Notes: Nuclear generation includes conventional and SMR. Low CO2 Gas-Fired includes hydrogen and fossil fuels with CCS. SP = Stated Policies, AP = Announced Pledges, NZE = Net Zero Emissions, ETS = Economic Transition Scenario, NZS = Net Zero Scenario.

Sources: BNEF (2025), *New Energy Outlook 2025*, IEA (2024), *World Energy Outlook 2024*

2. Estimated LCOEs show a clear divergence between US / Europe and RoW, mainly driven by CAPEX and interest during construction

Current LCOE estimates by country, Gen III

$/MWh, real 2024



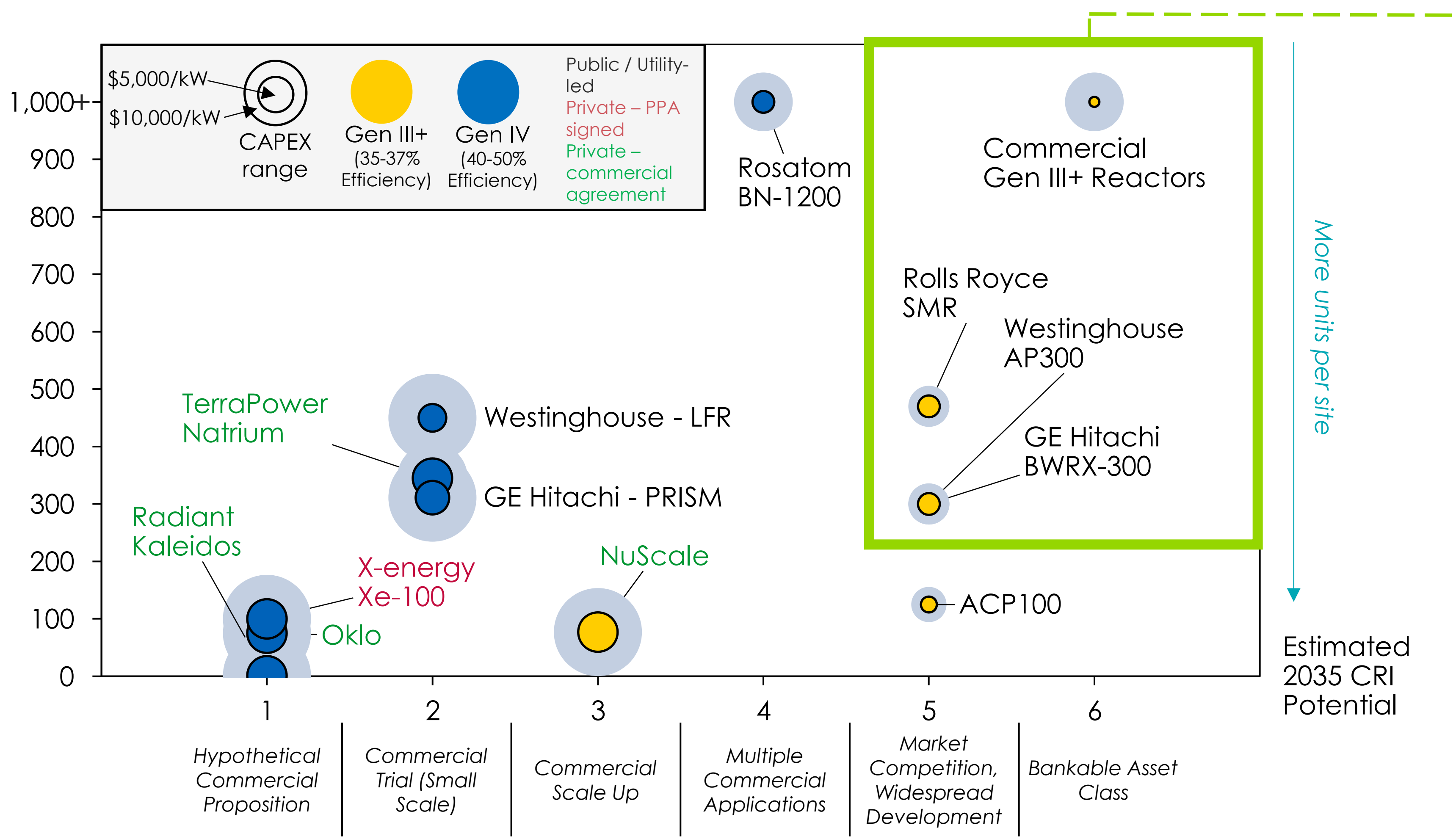
Upfront costs drive LCOE, but operating costs have a higher relative influence outside of Europe / North America

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*

3. Deployment in the next decade will be dominated by designs using mature technology, large unit sizes, and standardised designs

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**
2. **Large unit sizes** (e.g., 300+ MW)
3. **Standardisation and modularisation**

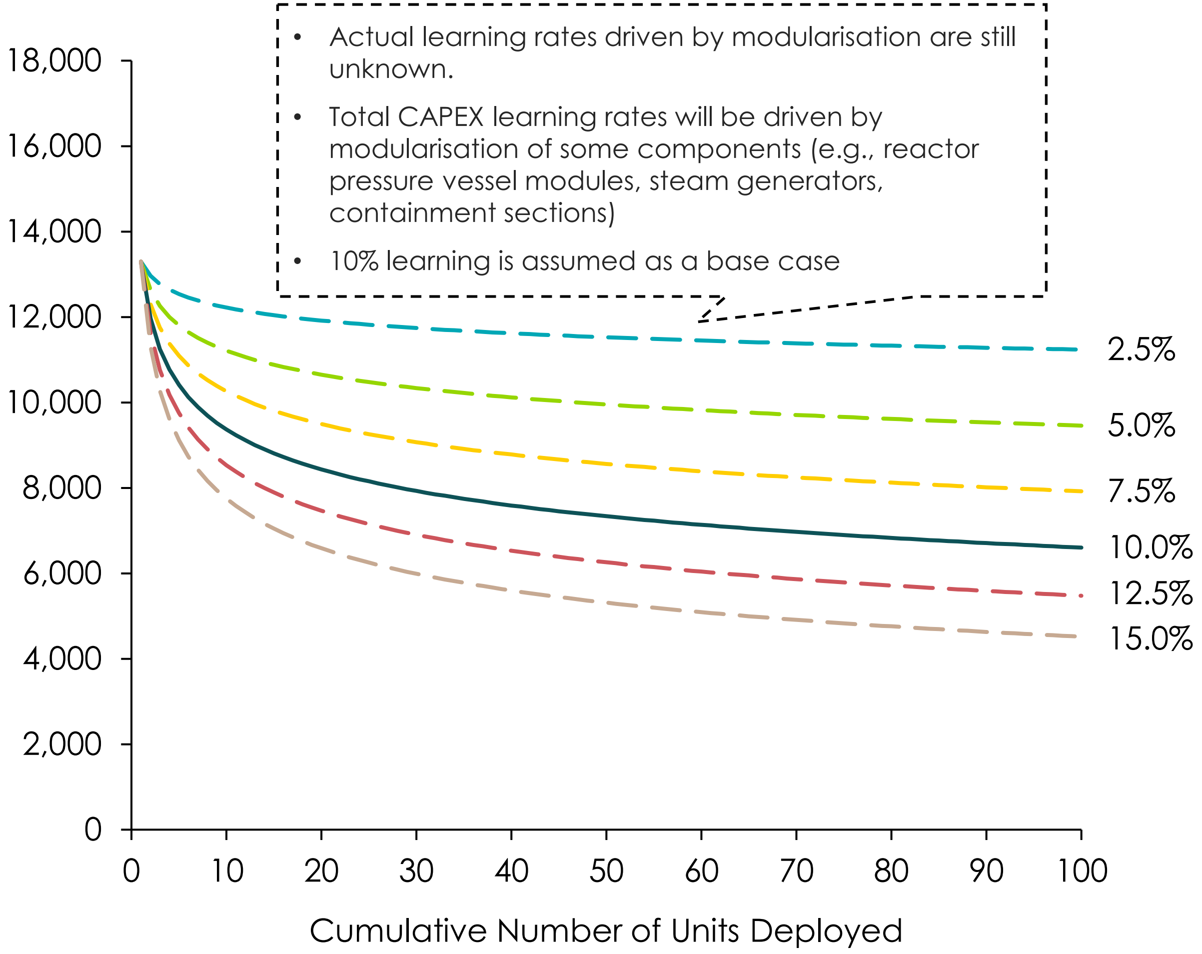
The impact / scalability of Gen IV innovations remain largely unproved in practice

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 = n^{th} of a kind. Source: Systemiq analysis for the ETC (2025); ARENA (2014), *Commercial Readiness Index for Renewable Energy Sectors*

3. CAPEX reductions for all designs will depend on standardisation and economies of scale, but have not been observed so far

Theoretical impacts of modularisation on learning rates and CAPEX

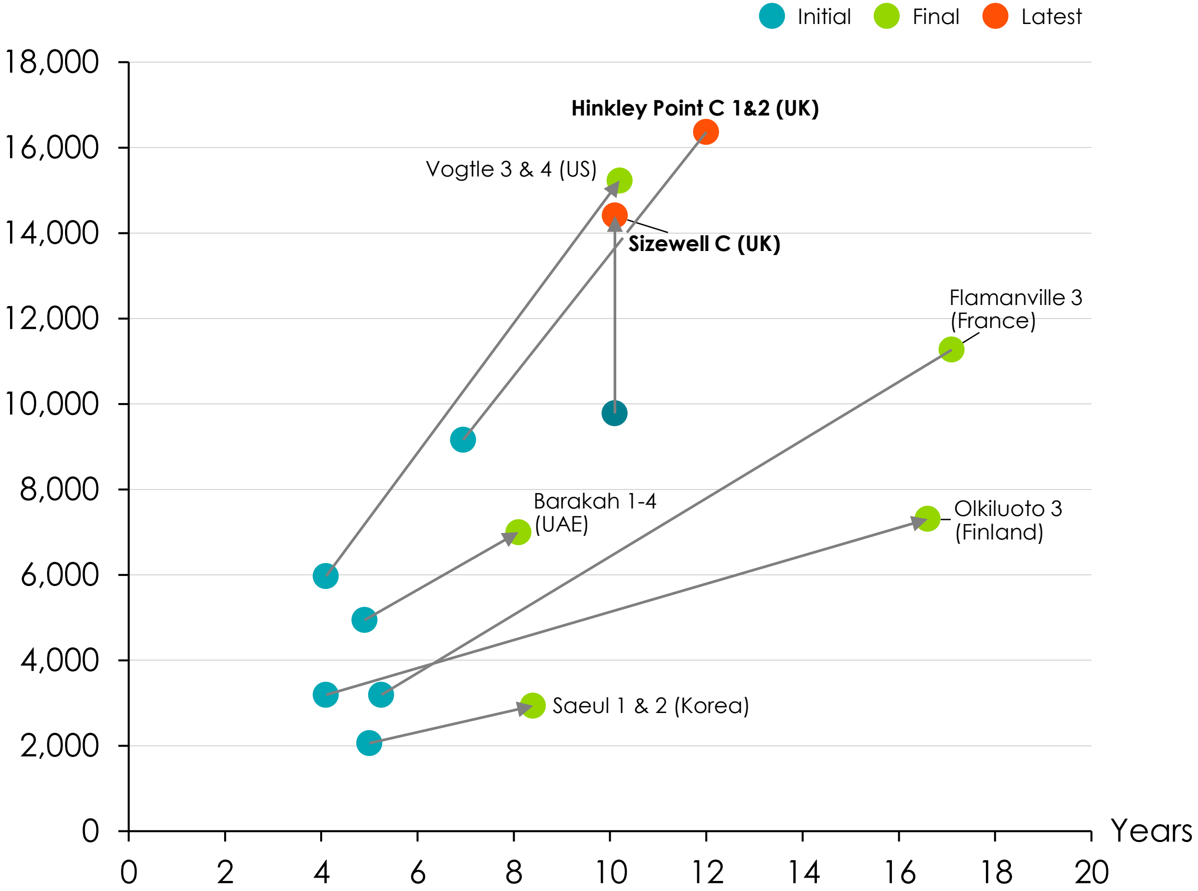
$/kW, real 2024



- 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

Initial and latest CAPEX estimates and construction times (Gen III+ reactors)

$/kW, real 2024



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?*

4. Understanding power "system value" requires accounting for full system costs

Definitions

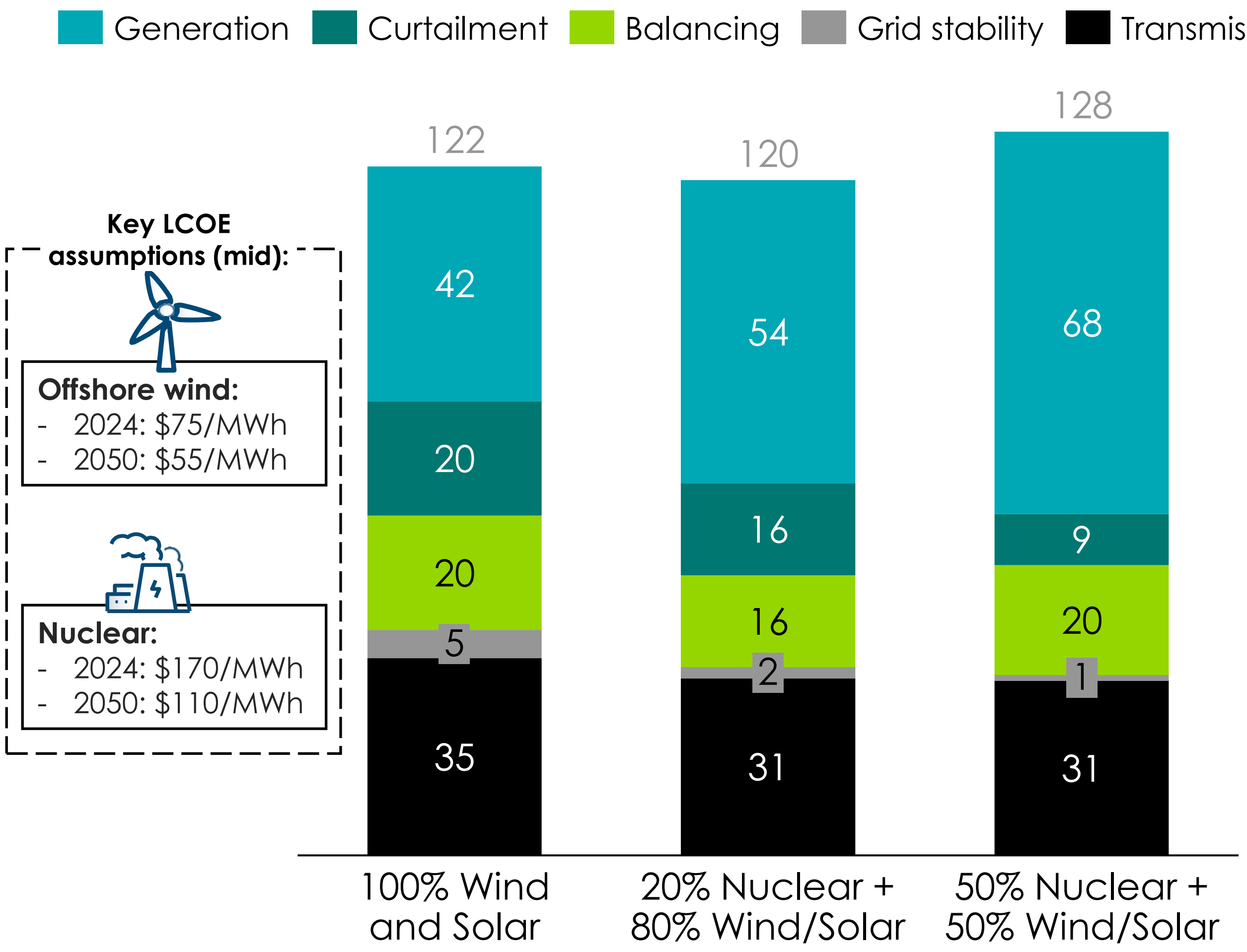
System Cost Component	Definition
Generation costs (LCOE)	Generation asset costs (CAPEX & OPEX), including of wind, solar, nuclear, geothermal, hydro, gas
Curtailment costs	Costs associated with curtailing generation assets
Balancing costs	Costs of assets to provide balancing/flexibility/storage (CAPEX & 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

4. 20% nuclear power in the UK is equivalent cost to a 100% renewables system; higher nuclear shares are likely to cost more

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

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



Key LCOE assumptions (mid):

Offshore wind:
- 2024: $75/MWh
- 2050: $55/MWh

Nuclear:
- 2024: $170/MWh
- 2050: $110/MWh

The nuclear scenarios have:

- **Higher generation costs:** Nuclear has significantly higher LCOE compared to offshore wind
- **Lower balancing costs**: require less balancing with 20% nuclear but similar with 50%
- **Lower grid stability costs:** nuclear can provide a wider set of grid stability services than variable renewables
- **Lower T&D costs**: more nuclear reduces offshore wind capacity which reduces T&D buildout by ~10%

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*

4. 10% nuclear power in India is equivalent cost to a 100% renewables system, a higher nuclear shares are likely to cost more

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

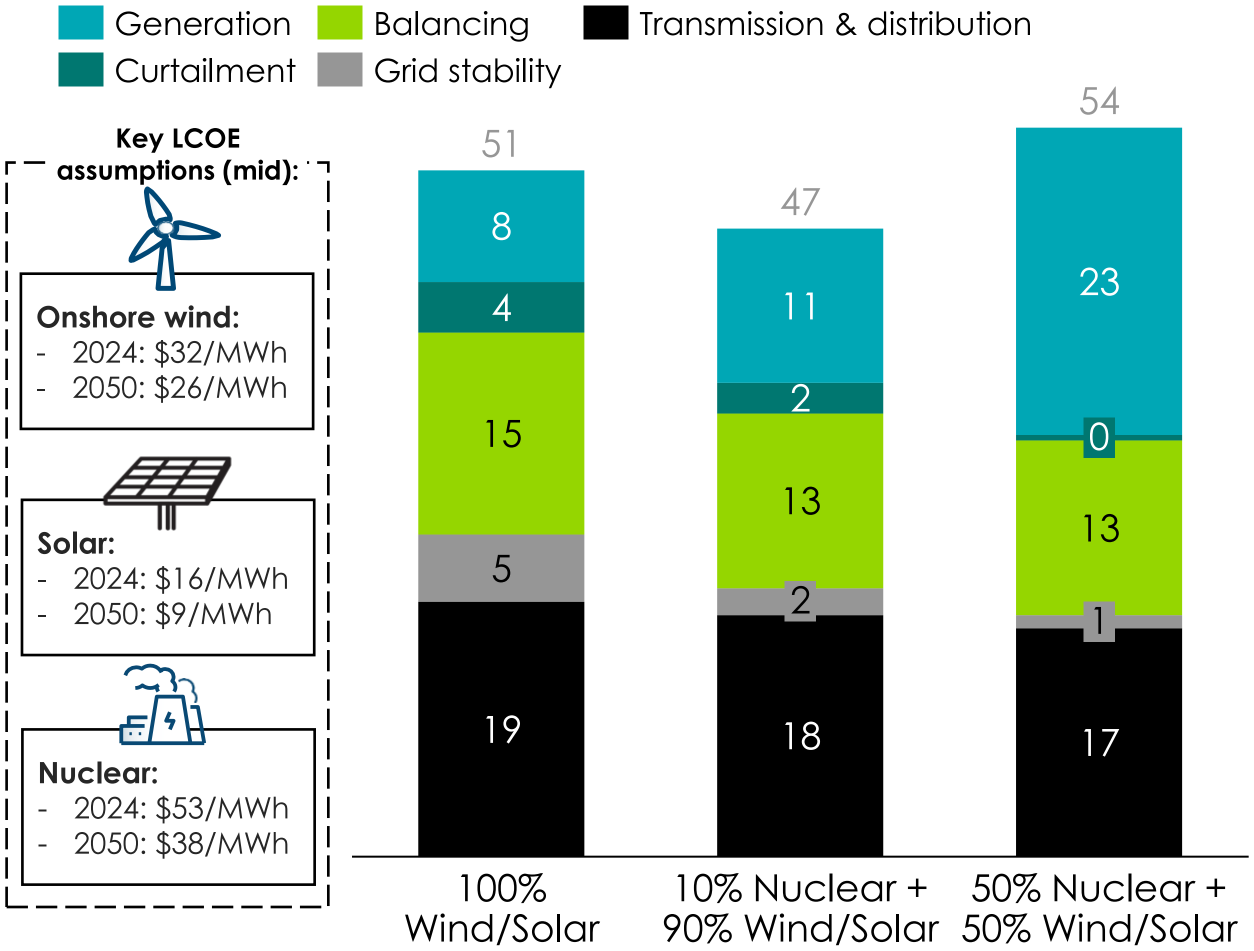
$/MWh of final electricity demand (real 2024$)

Key LCOE assumptions (mid):

Onshore wind:
- 2024: $32/MWh
- 2050: $26/MWh

Solar:
- 2024: $16/MWh
- 2050: $9/MWh

Nuclear:
- 2024: $53/MWh
- 2050: $38/MWh



The nuclear scenarios have:

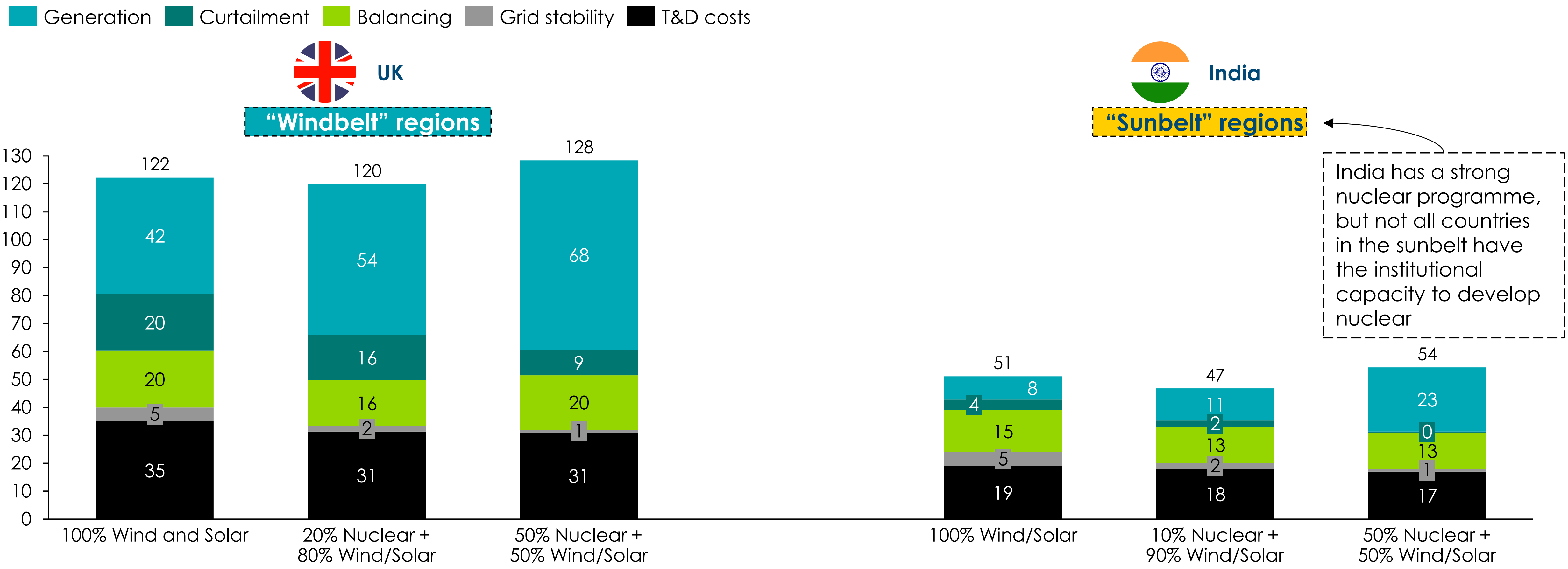
- **Higher generation costs:** Nuclear has higher LCOE compared to wind and solar in India
- **Lower balancing costs**: require less balancing and meet a lower peak capacity deficit
- **Lower grid stability costs:** nuclear can provide a wider set of grid stability services than variable renewables
- **Lower T&D costs**: more nuclear reduces offshore wind and solar capacity which reduces T&D buildout by 5-10%

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*

4. Clean power systems, with or without nuclear, could be significantly lower cost in the global "Sunbelt" than the "Windbelt"

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

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



India has a strong nuclear programme, but not all countries in the sunbelt have the institutional capacity to develop nuclear

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*

5. Five key considerations impacting nuclear deployment

i

Economic value-add and job creation

Localising manufacturing crucial to increasing value add and job creation

ii

Political will

Sustained political will crucial and highest in countries with legacy programmes

iii

Energy resilience and security

Fuel supply chain risk due to high concentration in small number of countries

iv

Safety and waste disposal

Current waste disposal manageable and safe; long-term disposal facing challenges

v

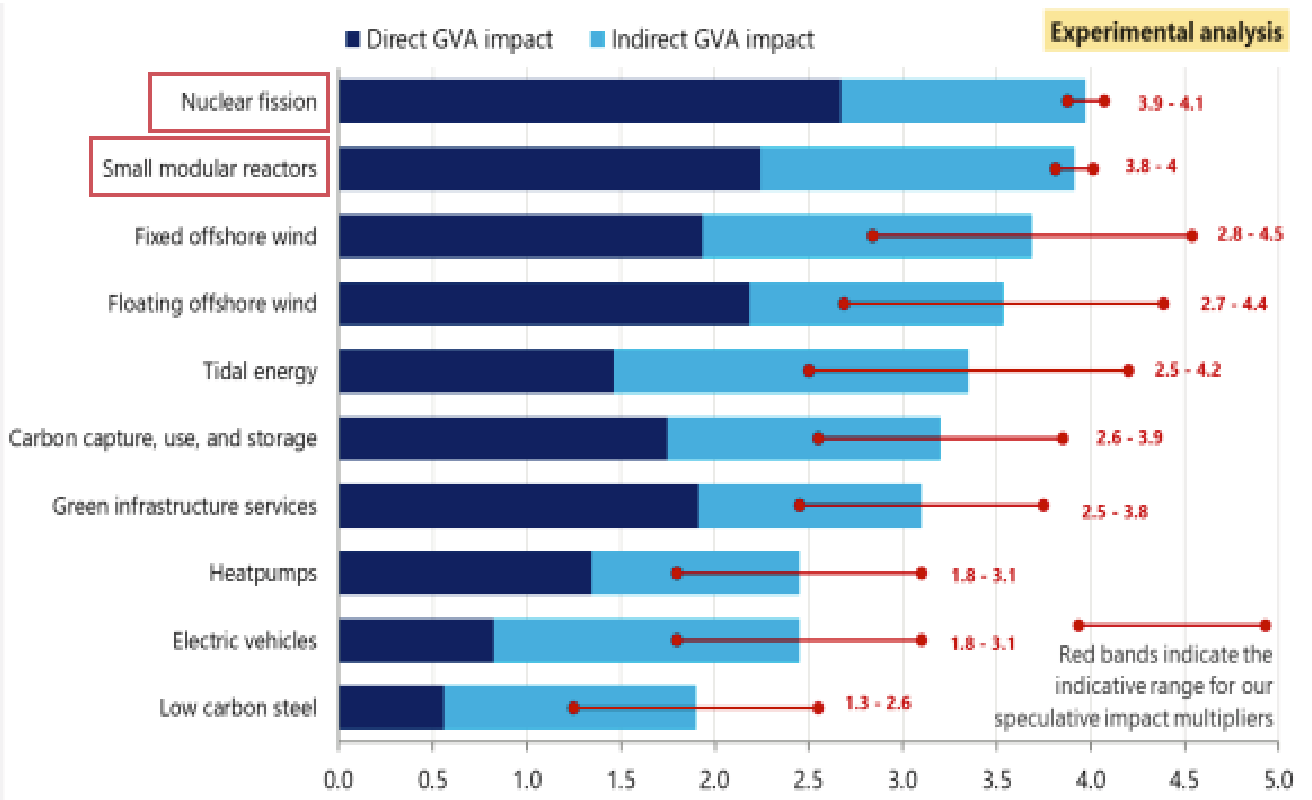
Resource intensity

High water consumption the key resource risk

While some studies frame nuclear as a high Gross Value Added (GVA) technology, this is driven by the high costs and not high efficiency

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

£ billion, 2023 prices



Disadvantages of GVA metric

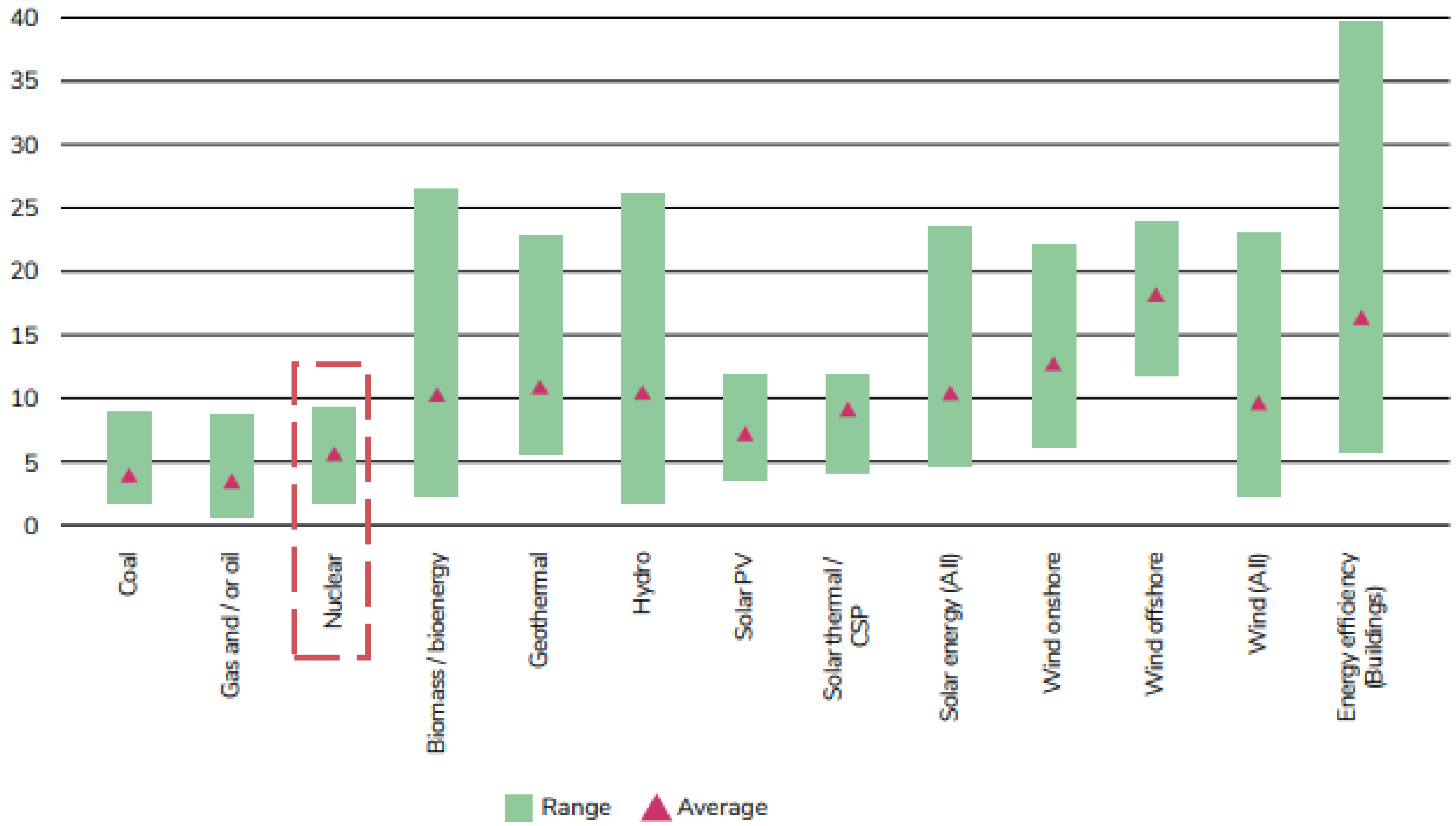
- High GVA reflects high capital spend, not economic efficiency or competitiveness
- Driven mainly by costly construction activity, local supply chains and long operational life rather than sustained value creation
- Ignores system value, affordability, and innovation spillovers

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*.

Nuclear delivers low job creation relative to investment spend compared to other clean technologies

Gross jobs created per £ million invested in clean technologies

jobs/ £ million invested



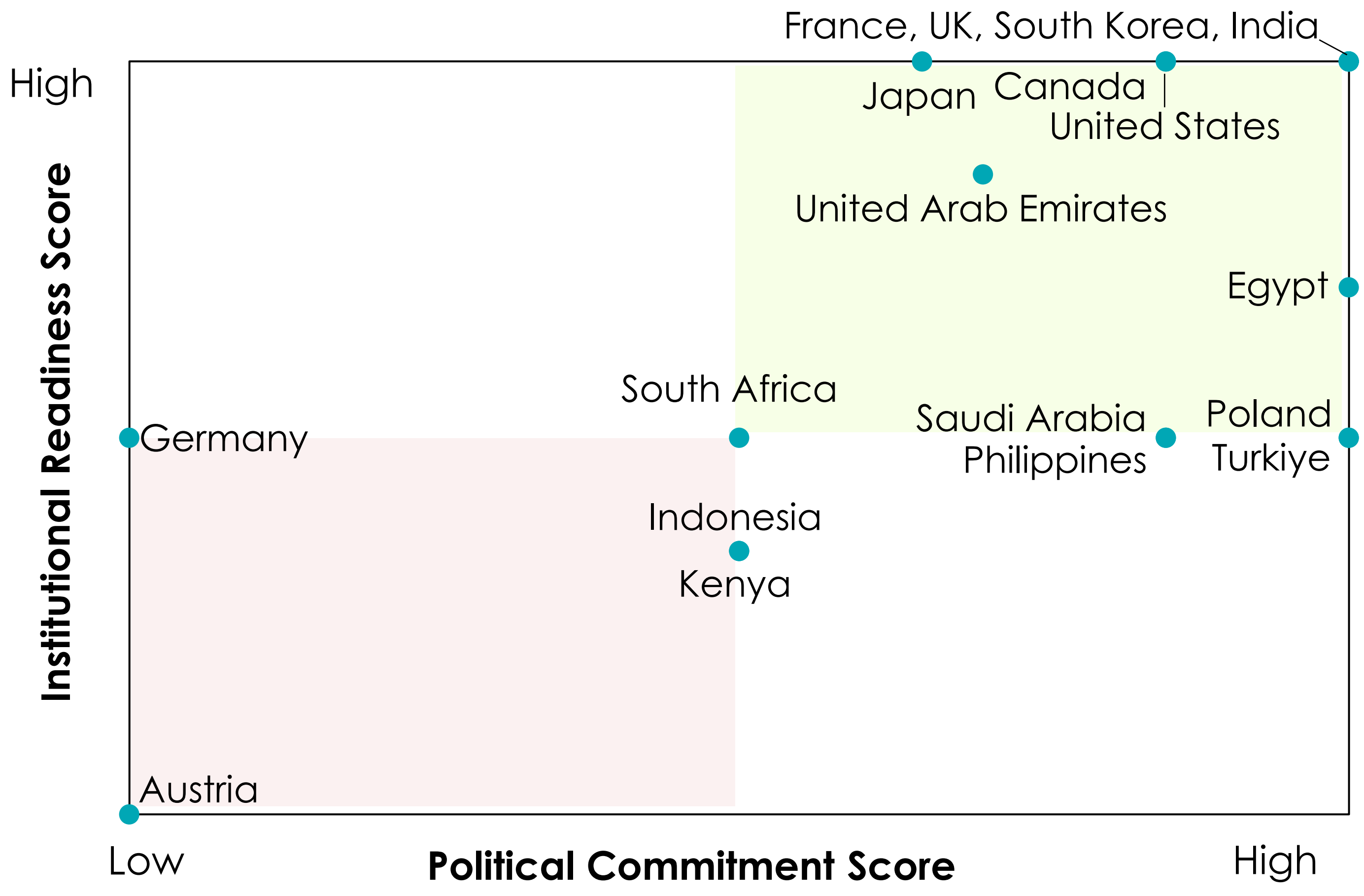
Key insights

- 2022 report on job creation across key technologies conducted a **systematic review of 145 studies on low carbon global job creation**
- Study found **nuclear projects spending mostly goes to capital equipment** rather than wages, making nuclear **inefficient at job creation per pound invested**
- **The amount of jobs per unit invested for nuclear will vary by country** dependent on nuclear expertise and domestic supply chain

Source: Hanna et al (2022) Green job creation, quality and skills: A review of the evidence on low carbon energy ii

Political will and institutional readiness determine the role of nuclear, as shown by simple political will matrix

Illustrative political will matrix



Illustrative examples of how varying levels of political commitment and readiness shape nuclear outcomes

France
- Strong mandate and mature institutions; national champion
- Active projects and domestic supply chain

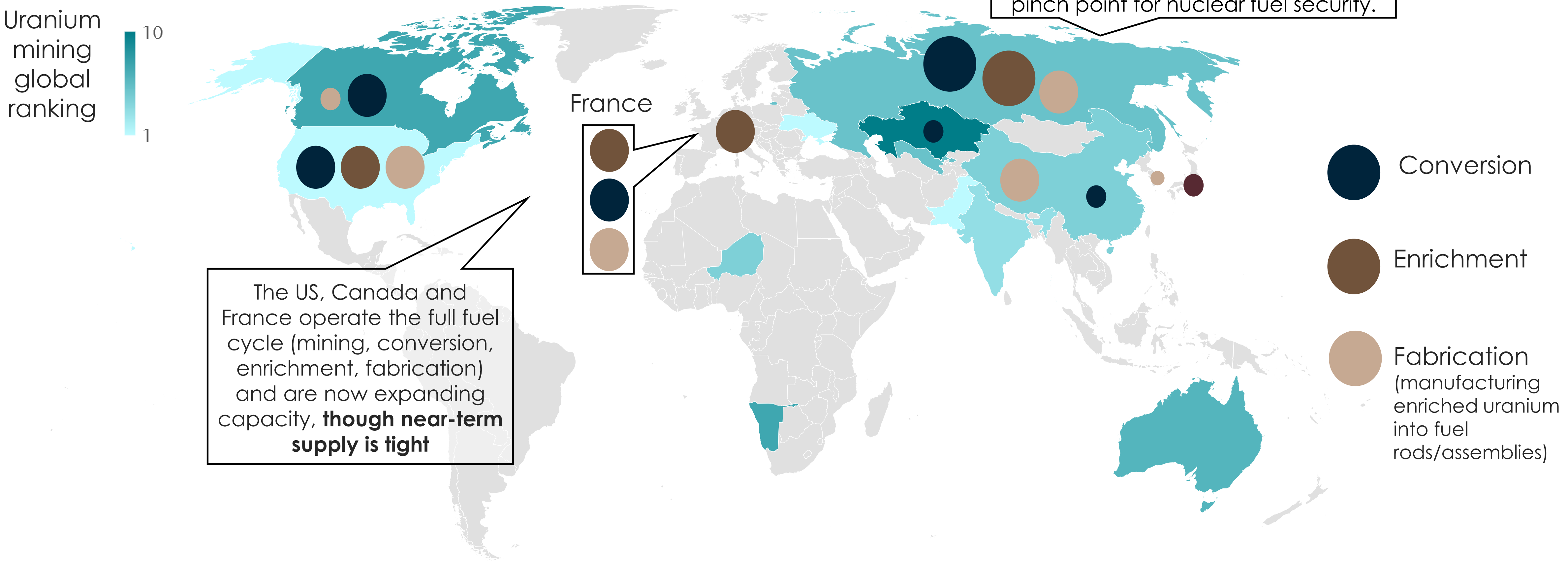
UK
- Robust institutions but mixed commitment
- Delays constrain delivery

Kenya
- Political intent but weak readiness as regulator, human capital and technical expertise nascent
- Value remains speculative until capacity builds

Note: Scores built from three observable signals per country, Political signal, Regulatory readiness, Project pipeline. Each scored 0 to 2, converted to 0 to 5 for the axes, then placed on the matrix. Source: IAEA PRIS and IAEA peer review notes, national energy strategies and budget papers, national nuclear regulators, parliamentary or cabinet announcements, World Nuclear Association country profiles, credible project announcements and procurement notices.

iii Fuel supply chain remains highly concentrated across few suppliers, with enrichment dominated by Russia

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



In 2020 Russia controlled ~45% of **global enrichment** and **~20%** 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**

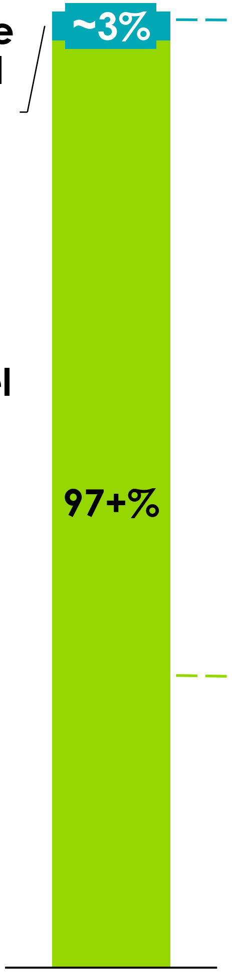
Note: Countries are ranked by share of global uranium mine output (World Nuclear Association 2025). Each share is converted to a score out of 10 by setting Kazakhstan, the largest producer, as 10 and assigning lower scores in decreasing bands of production share. Size of the circles - Large ≈ major global 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; Haneklaus et al (2025),* Dependencies of the European Union and the world on Russian nuclear fuel cycle services, and how to reduce them iv

Low- and intermediate-level waste are fully managed today; high-level waste remains safely stored while long-term solutions progress

Breakdown of nuclear waste by type and management approach

High-level (HLW) waste
e.g. spent nuclear fuel and vitrified residues from reprocessing

Low-intermediate-level (LLW or ILW)
e.g. contaminated components, filters, clothing and building materials



- HLW today is safely managed in pools and dry casks; the agreed **end point is deep geological disposal.**
- Most HLW within countries is **civil, with smaller amounts from military** – though military typically more radioactive per unit

- LLW and ILW safely managed in surface or near-surface facilities

Long term disposal of HLW: safe but politically contested

- Interim storage works well, but deep geological disposal is pursued to ensure passive containment for millenia
- Projects in France, Finland, Sweden and Canada are advancing; others **face delays** due to:
  - Public opposition and siting consent challenges
  - High upfront costs and long development timelines
  - Political hesitation despite technical readiness

Source: World Nuclear Association (2025) Radioactive Waste – Myths and Realities; IAEA (2023), Status and Trends in Spent Fuel and Radioactive Waste Management, which notes defence activities as a significant but uneven contributor; OECD-NEA (2021), Radioactive Waste Management and Decommissioning Review; Nuclear Decommissioning Authority (2014), Fact sheet: waste from defence activities

Resource intensity for nuclear most severe around high water use; overall it is aligned with other clean technologies

Resource intensity risk matrix for key clean technologies

		Resources		
		Water Consumption (Billion m3)	**Land Use (m2 per MWh)**	**Raw Materials Accessibility Risk**
Technologies	**Solar**	4*	3-40	Moderate-High
	Onshore wind	NA	0.4**	Moderate
	Nuclear	4-14	0.3	Moderate-Low
	Gas	8	1	NA
	Electrolysers	11	-	Moderate
	DACC and point-source CCS	19-29	1	Moderate
	Coal	10	15	NA

Key insights relating to nuclear

Water – high risk due to the need for water for cooling ⚠

Materials – moderate risk due to uranium supply chains, but lower risk for main transition materials ✓

Land-use – **low** risk compared to other technologies ✓

Note: * = required for cleaning. ** Onshore wind project site area would be 8-99. Source: ETC (2023) Material and Resource Requirements for the Energy Transition; IEA (2021), The Role of Critical Minerals in the Energy Transition; Hannah Ritchie for Our World in Data (2022), How does the land use of different electricity sources compare?

Agenda

- Work programme introduction
- Nuclear: Emerging Insights
- **Geothermal: Initial Insights**
- Next steps

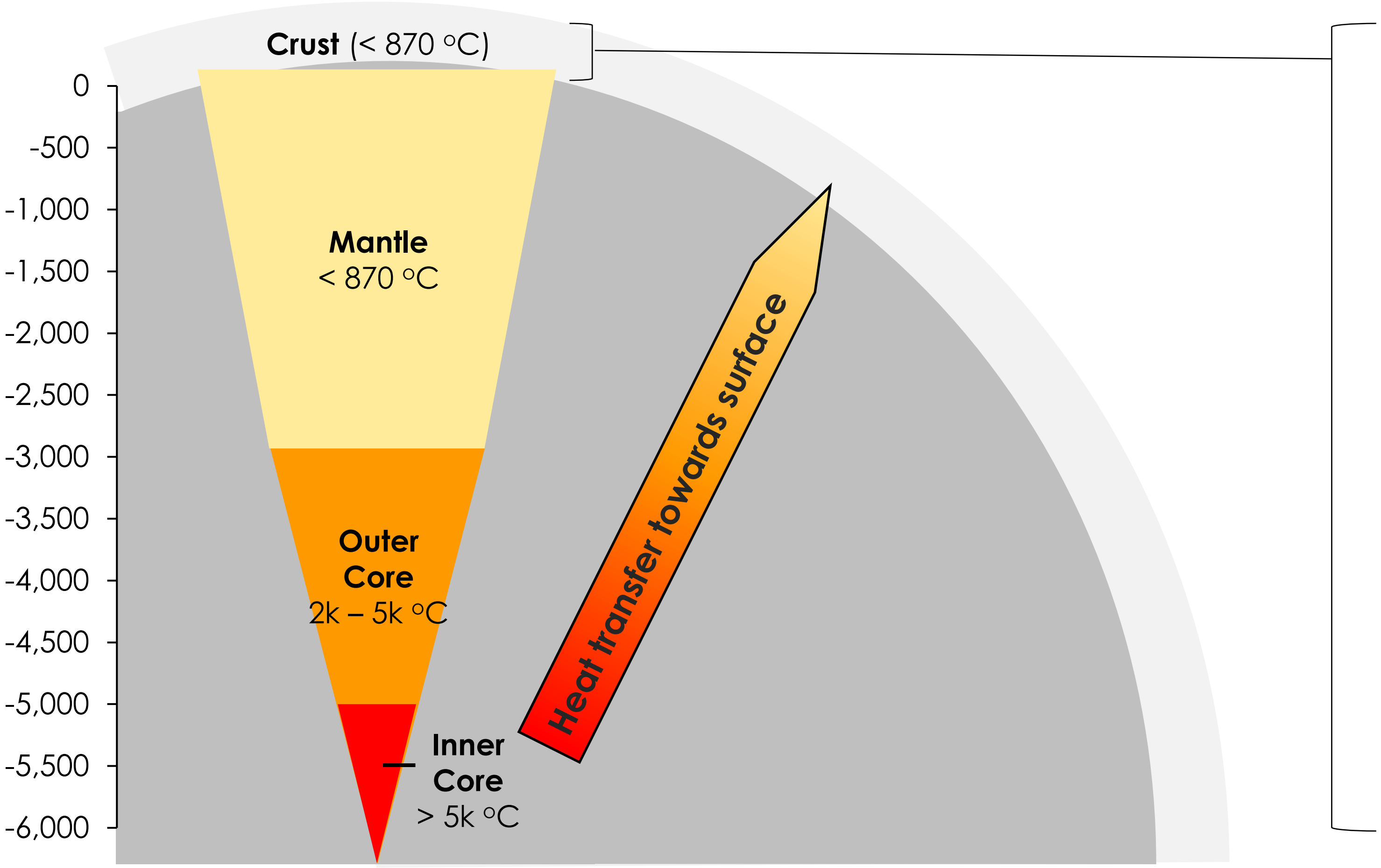
Guiding questions for the geothermal workstream

1. **Role of geothermal in future energy systems**
2. Next-generation geothermal energy could increase deployment significantly
3. How should geothermal be deployed effectively?

Geothermal energy refers to thermal energy transferred from beneath the Earth's solid surface

Geothermal resource depth, temperature ranges and composition by layer (indicative)

Depth (km), temperature annotated in °C



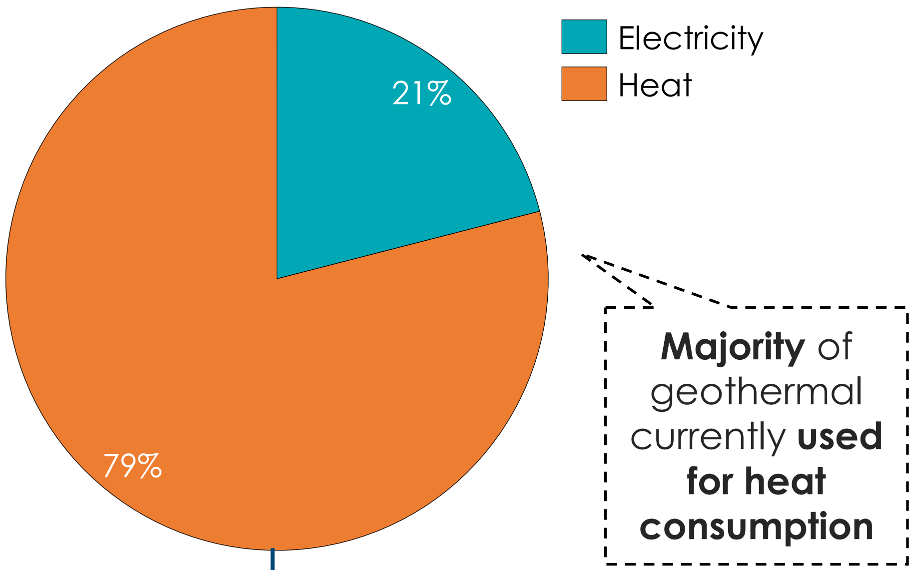
- Geothermal energy primarily stems from the **heat stored in the Earth's core**, transferring heat to natural resources.
- Subsurface temperatures rise rapidly, roughly 25-30 °C/km drilled
- Types of energy resource depend on the depth and temperature range:
  1. **Shallow geothermal** (<500 m)
  2. **Direct use or hydrothermal** (1-3 km)
  3. **Next-generation geothermal** (3-8 km)
- The Earth's crust is 30 km deep on average, so all geothermal extraction takes place in this layer

Sources: KEARNEY ETI (2025), Geothermal energy, turning up the heat; NASA (2025), Facts About *Earth*

Geothermal energy accounts for a small share of current final energy consumption, and is primarily used for heat

Total final geothermal energy consumption by application, world

%

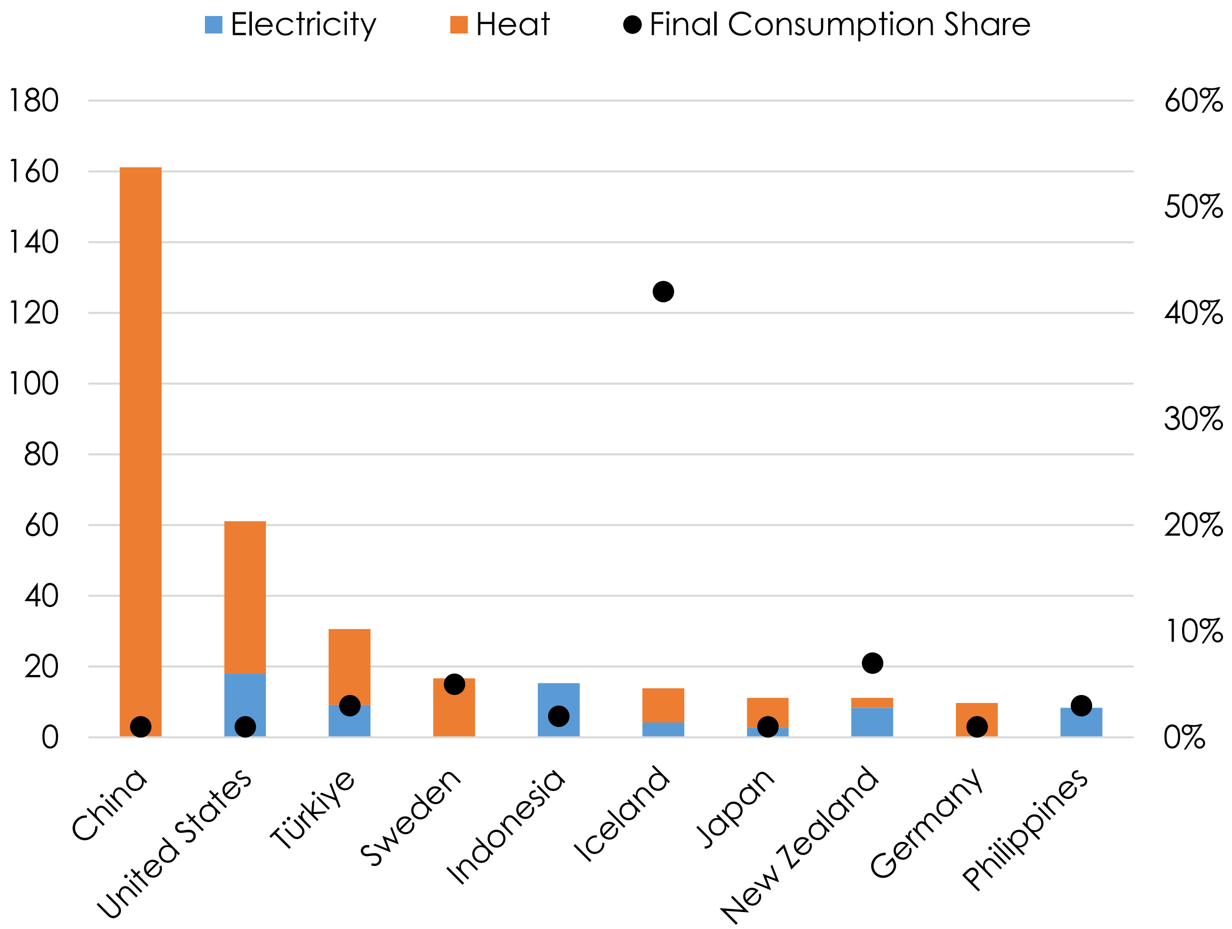


Majority of geothermal currently **used for heat consumption**

Geothermal heat provides useful energy in the form of space and district heating, industrial process heat, and agricultural heat

Top 10 consuming countries of geothermal energy

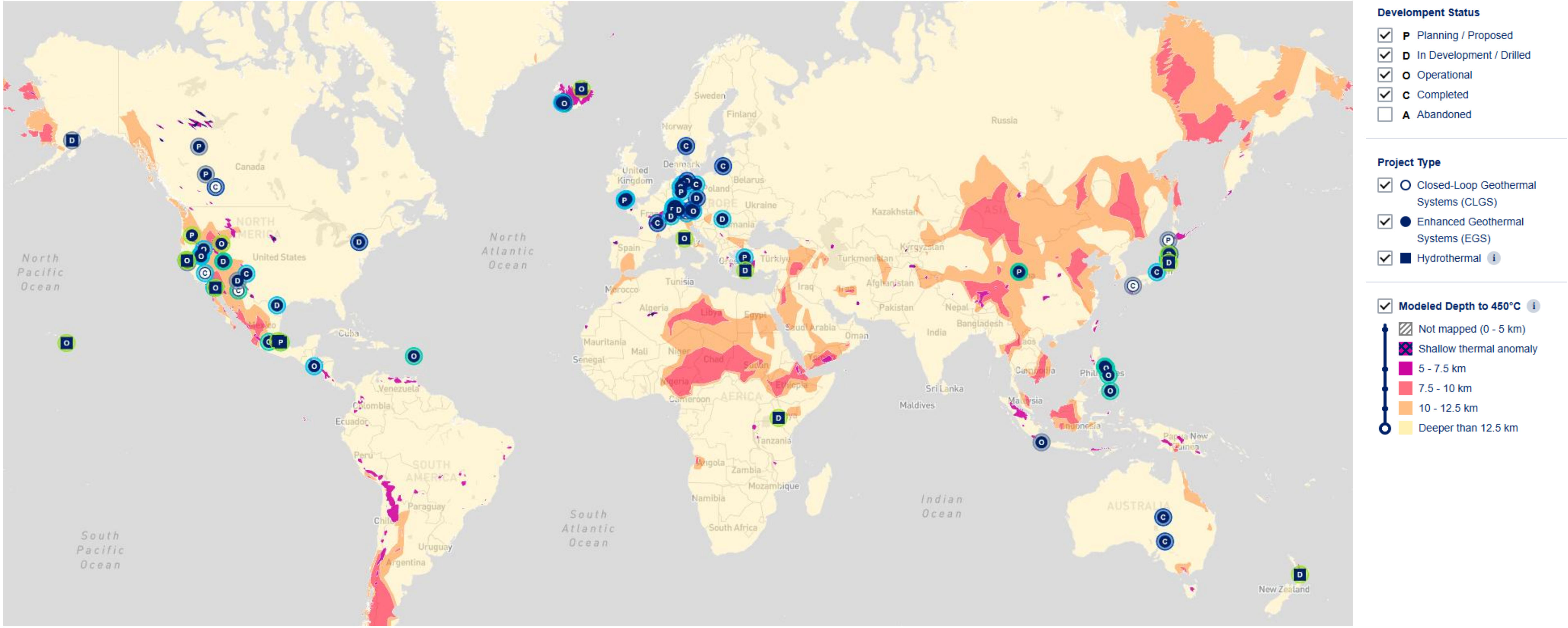
GWh (LHS), % (RHS)



Source: IEA (2024) *The Future of Geothermal Energy*

Projects using next-generation geothermal technologies are nearing completion with development concentrated in North America, Europe, and APAC

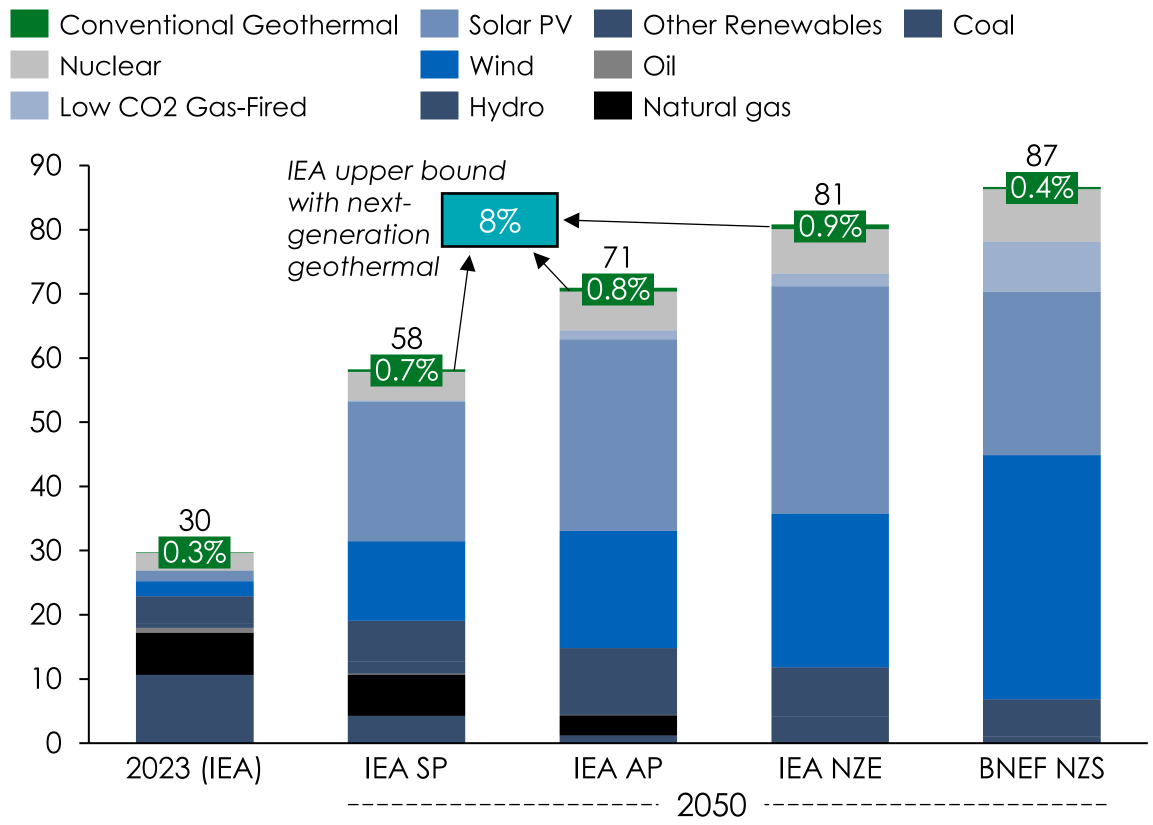
Global geothermal project deployment map



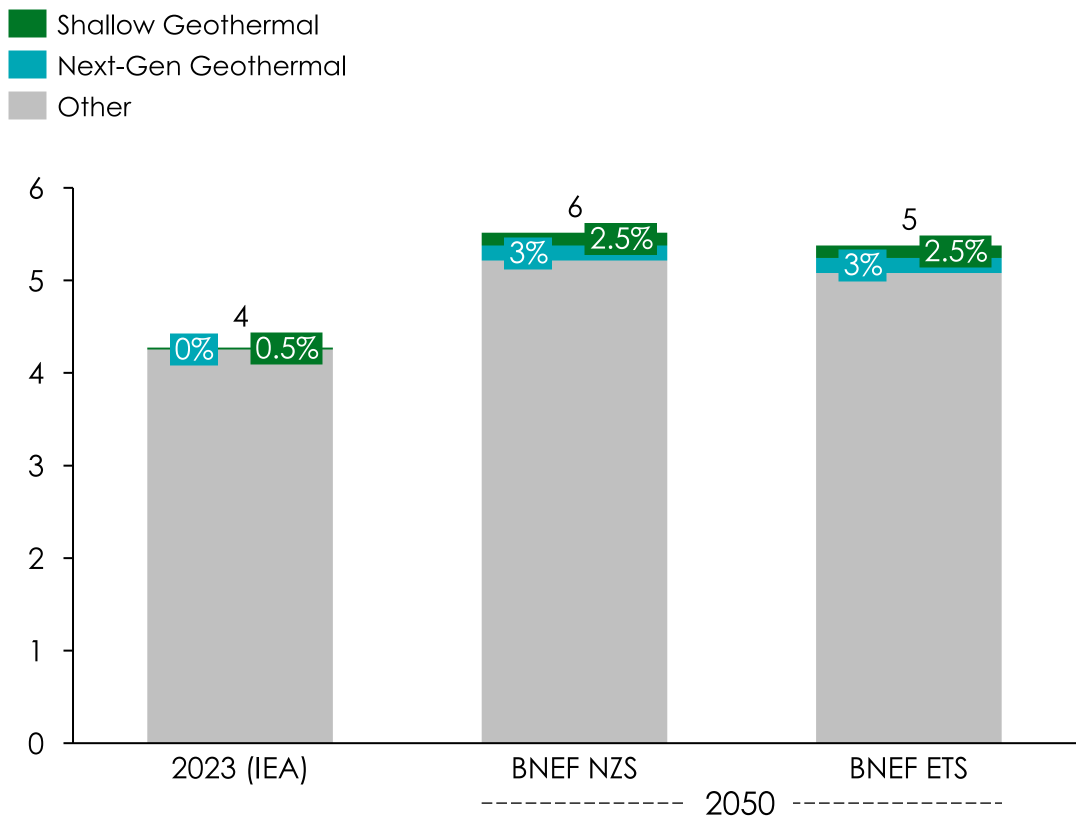
Sources: Clean Air Task Force (2025), The Next Generation of Geothermal Energy. Available at: https://www.catf.us/shr-map/

Future scenarios show conventional geothermal meets 1% of power and 4% of heat, with next-gen tech possibly raising both to ~10%.

Global geothermal share of electricity by scenario (2023 and 2050)
'000 TWh



Global geothermal share of heat by scenario (2023 and 2050)
'000 TWh



Geothermal share of global electricity generation remains <1% across existing scenarios – next-generation technologies change this

Geothermal share of global heat has potential growth opportunities which are expanding into cooling

Notes: SP = Stated Policies, AP = Announced Pledges, NZE = Net Zero Emissions, ETS = Economic Transition Scenario, NZS = Net Zero Scenario. Heat shares were estimated based on IEA data and applied to BNEF's total heat demand.
Sources: BNEF (2025), *New Energy Outlook 2025;* IEA (2024), *World Energy Outlook 2024;* IEA (2024) *The Future of Geothermal Energy*

Interest in geothermal power generation is driven by technology company investment and government incentives

Industry / Big Tech

- **Google:**
    - In 2021, **agreement with NV Energy to purchase 115 MW by 2030** from next-gen geothermal project developed by Fervo
    - In 2025, **10 MW geothermal PPA** with Baseload Capital in Taiwan, commencing in 2029
- **Microsoft:** In 2024, **partnered with G42**, UAE-based AI company, to build a 1 GW geothermal-powered data centre **in Kenya by 2027**.
- **XGS Energy and Meta have partnered on a 150 MW** next-generation geothermal project in New Mexico, targeting operations in 2030

Governments

- The **U.S. Department of Energy found that geothermal energy could provide up to 120 GW (16% of generation)** across the US.
- The California Public Utilities Commission mandated procurement of 1 GW of clean firm power by 2026, resulting in **262 MW of new geothermal PPAs**.
- **Kenya** has significant geothermal resources and aims to reach **5 GW by 2030** (up from ~1 GW today).
- The **Indonesian** government aims to reach 7.8 GW by 2030 and **9.3 GW by 2035** (up from 2.6 GW today)

Source: Google (2023), *A first-of-its-kind geothermal project is now operational*; Financial Times (2025), *How geothermal energy could provide 'always on' supply*; Data Center Dynamics (2025), *Google signs 10 MW geothermal PPA with Baseload Capital in Taiwan;* Business Wire (2025), *XGS Energy and Meta to partner on 150 MW advanced geothermal project;* Think Geoenergy (2025), *How Kenya's energy policy is driving geothermal development*; Proceedings World Geothermal Congress 2023 (2023), *Country Update: Geothermal as The Backbone of Energy Security in Indonesia's Energy Transition*

Guiding questions for the geothermal workstream

1. Role of geothermal in future energy systems
2. **Next-generation geothermal energy could increase deployment significantly**
3. How should geothermal be deployed effectively?

Geothermal heat and power generation technologies range from high-maturity shallow geothermal to low-maturity ultra-deep superhot rock

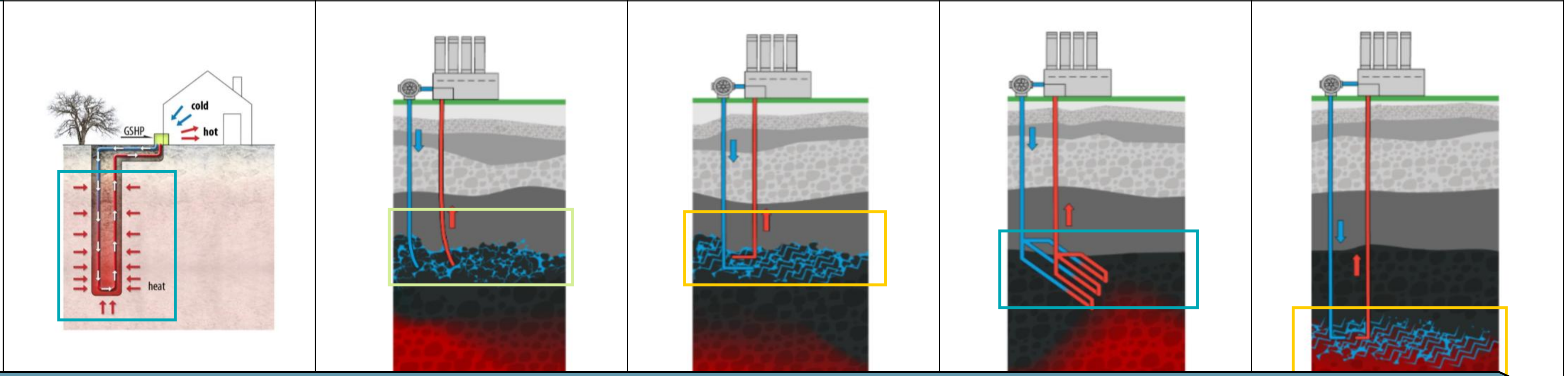
Hybrid next-generation sites are also under development

	Conventional		Next-Generation		
	Shallow	Direct-use or Hydrothermal	Enhanced geothermal systems (EGS)	Closed-loop geothermal systems (CLGS)	Superhot rock
Resource depth (km)	< 0.5	< 3.5	2 – 7	< 7	3 – 20
Application	Heat	Heat or power	Heat or power	Heat or power	Heat or power
Resource temp. (°C)	4 – 25	10 – 170 (direct use); 100 – 370 (hydrothermal)	80 – 300	70 – 400	375 – 500
Output per well (MWe)	0.001 – 0.01	3 – 25 (up to 50)	3 – 5	2 – 9	Varies, but >30
Market Leaders	DAIKIN VIESSMANN NIBE STIEBEL ELTRON BOSCH KensaGroup DIG ENERGY	ORMAT PERTAMINA GEOTHERMAL ENERGY CALPINE KenGen enel Green Power Reykjavík Energy	FERVO ENERGY 400C Energy Eavor GEOTHERMIX	Eavor GreenFire Energy XGS ENERGY green therma EXCEED GEO ENERGY	ALTAROCK U.S. DEPARTMENT of ENERGY QUAISE IDDP Fluid Flow Heat

Natural reservoir

Reservoir not required

Engineered reservoir



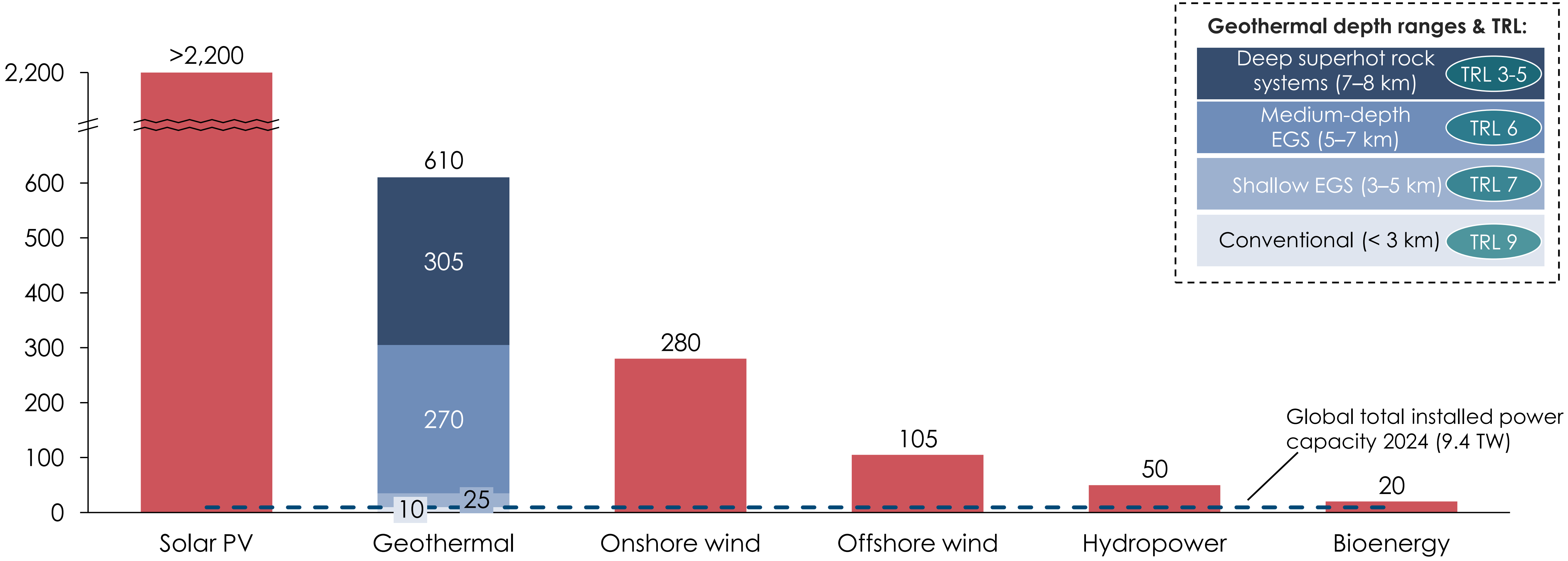
TRL (Technology readiness level)	9	9	7	6	3-5

Notes: 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
Source: BNEF (2025), *US Next-Generation Geothermal Makes Unsung Progress;* US DoE (2024) *Pathways to Commercial Liftoff: Next-Generation Geothermal Power Updated*

Power: Next-Generation geothermal technologies could unlock significant global electricity generation potential

Technical potential of selected renewable energy technologies for electricity generation (IEA estimate)

TW

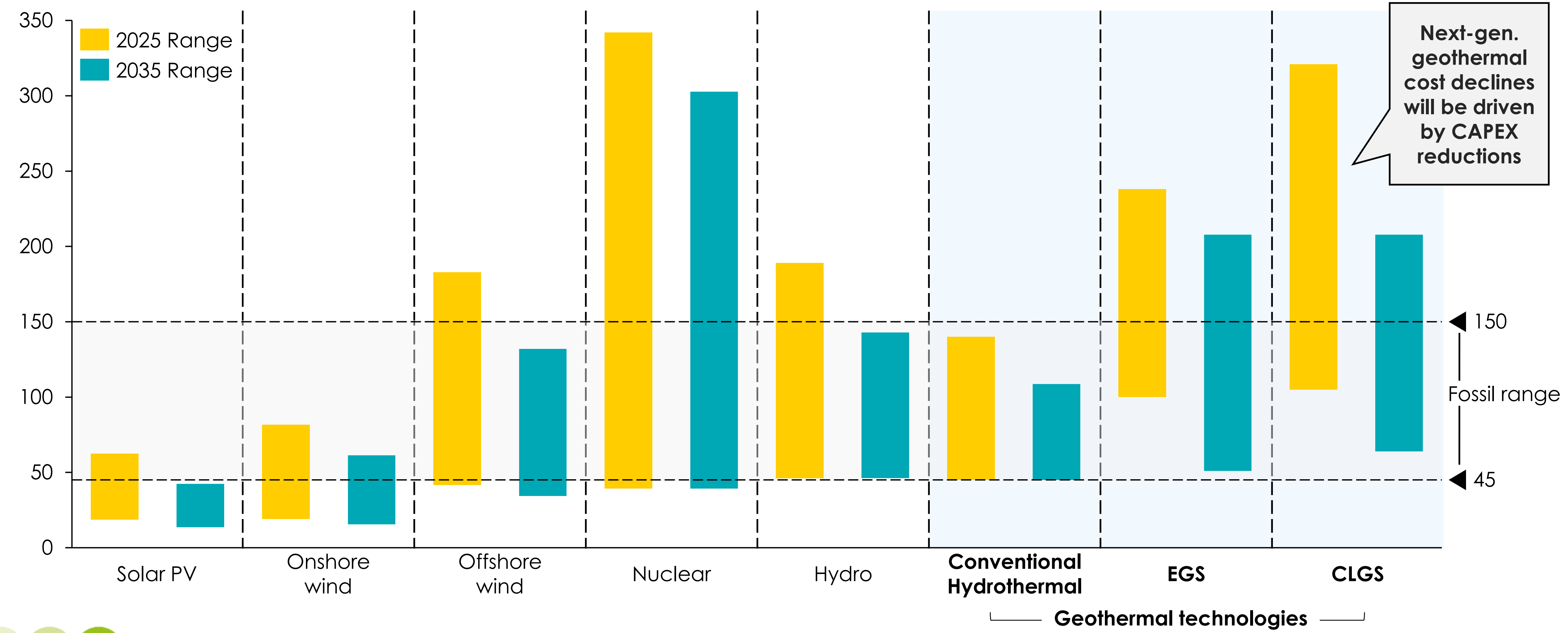


Source: IEA (2024) *The Future of Geothermal Energy*: Geothermal: *Project InnerSpace™ calculations for EGSs based on GeoMap™ data with a threshold of USD 300/MWh, in collaboration with IEA. Offshore wind: IEA (2019), Offshore Wind Outlook 2019. Hydropower: IEA TCP 2010.Bioenergy: IEA calculation based on the assumption that all sustainable bioenergy potential of 100 EJ is used for power generation. Onshore wind: Based on DTU-2027 study. Solar PV: Technical potential from various studies in de La Beaumelle N.A. et al. (2023), The Global Technical, Economic, and Feasible Potential of Renewable Electricity.*

Power: Next-generation geothermal is likely to be more expensive than solar and onshore wind, but competitive with fossil and other clean alternatives in the next decade

Levelised cost of energy ranges in 2025 and 2035 for selected clean energy technologies

$/MWh (real 2024)



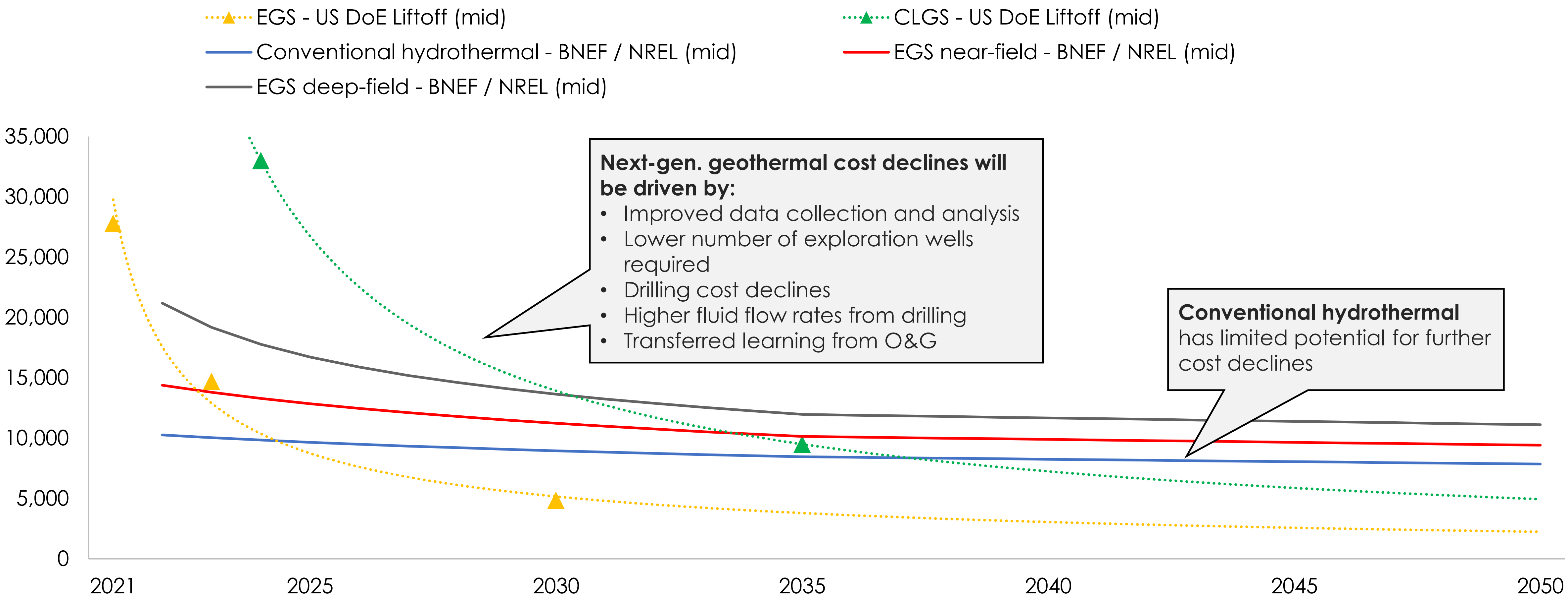
Next-gen. geothermal cost declines will be driven by CAPEX reductions

Source: BNEF (2025), LCOE Data Viewer; BNEF (2025), *US Next-Generation Geothermal Makes Unsung Progress*

Power: CAPEX for next-generation geothermal technologies are expected to significantly decline from today's levels

Next-generation geothermal (EGS and CLGS) CAPEX declines over time

$/kW, real 2024



Next-gen. geothermal cost declines will be driven by:

- Improved data collection and analysis
- Lower number of exploration wells required
- Drilling cost declines
- Higher fluid flow rates from drilling
- Transferred learning from O&G

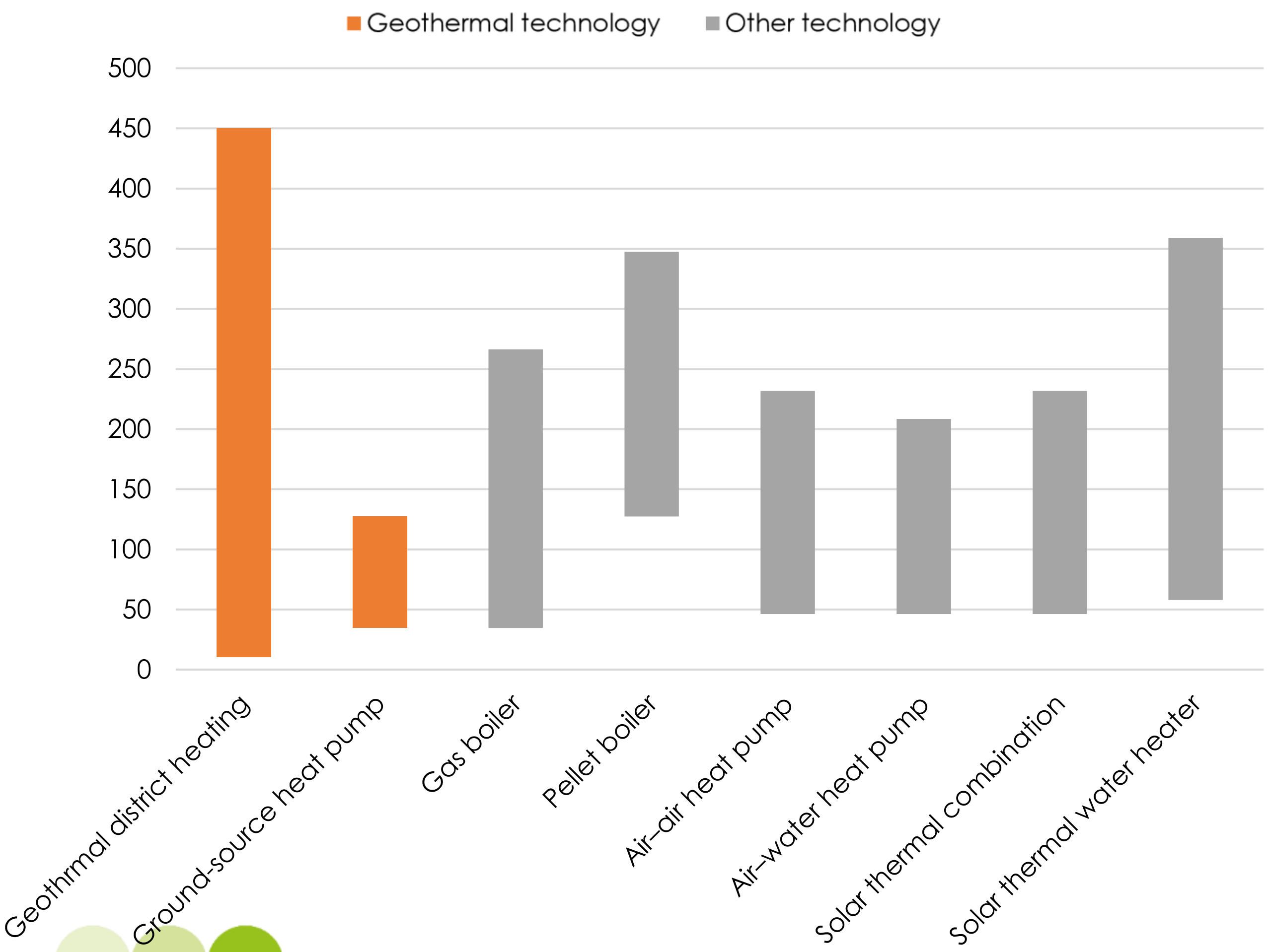
Conventional hydrothermal has limited potential for further cost declines

Source: US DoE (2024) *Pathways to Commercial Liftoff: Next-Generation Geothermal Power Updated;* BNEF (2025), *US Next-Generation Geothermal Makes Unsung Progress;* Michael Barnard (2025), *Beyond the Hype: Geothermal in Context — separating viable heat solutions from speculative drilling dreams*

Heat: Geothermal levelised costs of heat (LCOH) are competitive with alternatives; wide range of geothermal district heating costs by country

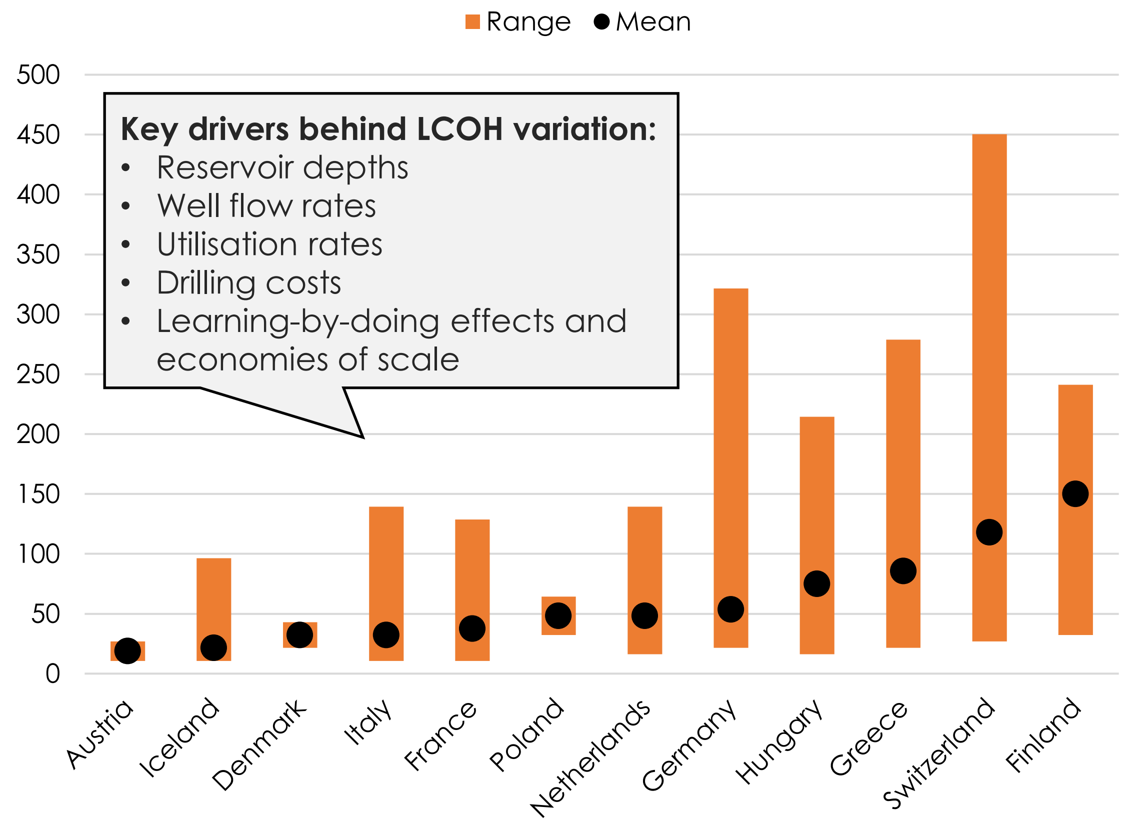
European LCOH range by technology, representative of early-2020s costs

$/MWh$_{heat}$ (real 2024)



Geothermal district heating LCOH range by European country

$/MWh$_{heat}$ (real 2024)



Key drivers behind LCOH variation:

- Reservoir depths
- Well flow rates
- Utilisation rates
- Drilling costs
- Learning-by-doing effects and economies of scale

Source: KEARNEY ETI (2025), Geothermal energy, turning up the heat

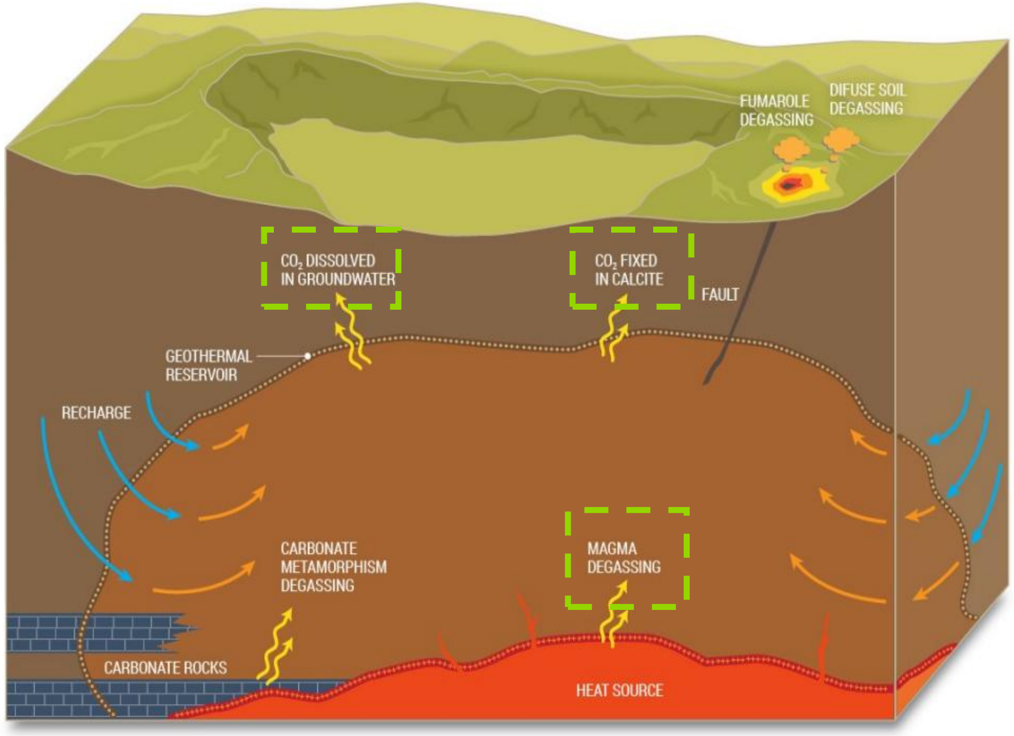
Wider considerations of geothermal energy

Key considerations

System Value	• **Limited capability** for geothermal power generation systems to **run flexibly** • **Underground thermal storage** could provide longer-duration storage / balancing • **Geothermal district heating and industrial heat** provide a huge opportunity to **reduce power-to-heat needs and load peaks**
Emissions	• **Operational CO_2 can occur from reservoir gases**, yet lifecycle intensities are 45 gCO_2e/kWh on average, well below fossil power (~400-1,000 gCO_2e/kWh); vary widely by plant type and local geology
Resource Use	• Geothermal is **water and material intensive** during construction, though reinjection can minimise net freshwater demand • **Steel and concrete use is high per MW**, but technology relies on no critical minerals
Public Acceptance	• Main concern is **induced seismicity**, especially for EGS • While long-term land and visual impacts are low, **drilling and construction phases can cause temporary disruption** requiring active community management
Financing	• Exploration and drilling risks drive **high pre-drill cost of capital and bankability gaps** • Integrating geothermal energy production with critical mineral extraction (e.g. lithium) is a method to enhance the viability of projects

Source: IEA (2024) *The Future of Geothermal Energy*; NREL (2012) *Geothermal Power and Interconnection: The Economics of Getting to Market*; NREL (2025) *Geothermal Grid Integration and Modeling*; Brasnett et al. (2023) *Mapping Techno-Economic Feasibility of Geothermal Energy*; World Bank / ESMAP (2012) *Geothermal Handbook: Planning and Financing Power Generation*; IRENA (2023) *Geothermal Energy: Technology Brief*;

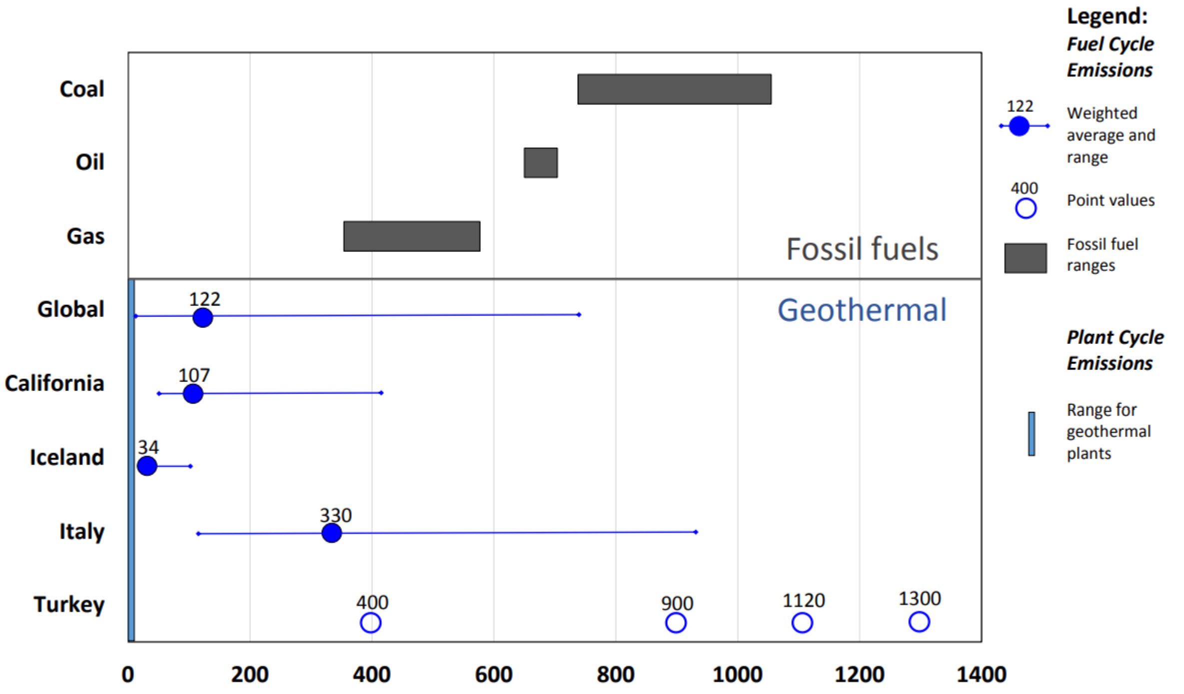
Geothermal can have direct GHG emissions from the reservoir during operation, but lifecycle emissions remain low versus fossil power



- Emissions mainly CO_2, from gases in geothermal fluids.
- Levels depend on geology and plant type.
- Occur mostly during operation, particularly in dry steam, flash plants. Some emissions during construction, but minimal.

Weighted average and range of emission factors from geothermal plants

CO2 emission factor (g/kWh)



Emissions: generally low and well below fossil power; depends on field geology and geothermal technology, with enhanced systems having lower emissions

Lifecycle emissions: total LCA (~45 gCO_2e/kWh) lower than gas or coal; can lower LCA by using closed loop systems, which enables LCA to equal nuclear and wind (~11 gCO_2e/kWh)

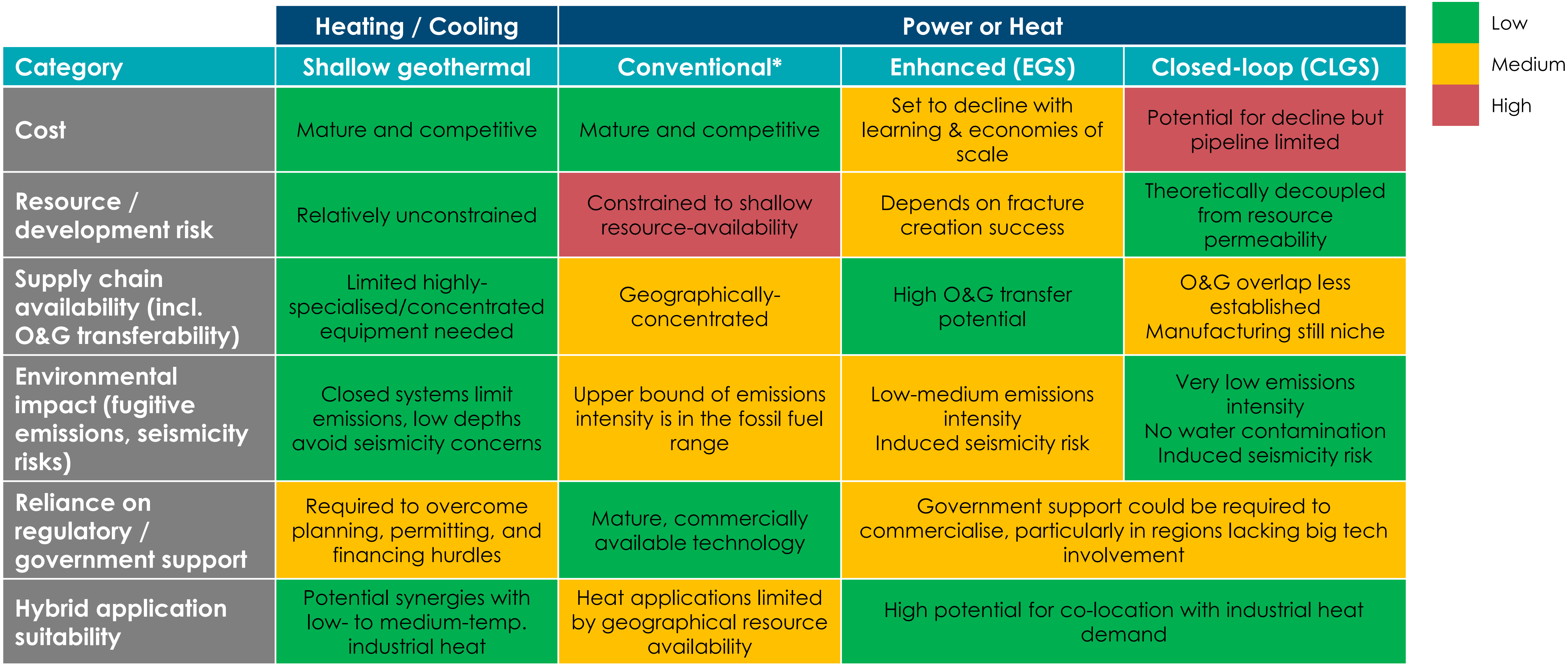
Note: RHS graph – The range of plant cycle emissions is shown with a light blue box. Emission ranges for power plants using fossil fuels shown in grey bars. Source: World Bank (2017), Greenhouse Gas Emissions from Geothermal Power Production; NREL – Sullivan et al. (2013), "Life Cycle Assessment of Geothermal Systems in the United States.

Guiding questions for the geothermal workstream

1. Role of geothermal in future energy systems
2. Next-generation geothermal energy could increase deployment significantly
3. **How should geothermal be deployed effectively?**

What’s holding geothermal back? Key barriers span upfront costs, development risk, supply chain, and environmental impacts

Risk rating by category and geothermal technology type



	Heating / Cooling	Power or Heat		
Category	**Shallow geothermal**	**Conventional***	**Enhanced (EGS)**	**Closed-loop (CLGS)**
Cost	Mature and competitive	Mature and competitive	Set to decline with learning & economies of scale	Potential for decline but pipeline limited
Resource / development risk	Relatively unconstrained	Constrained to shallow resource-availability	Depends on fracture creation success	Theoretically decoupled from resource permeability
Supply chain availability (incl. O&G transferability)	Limited highly-specialised/concentrated equipment needed	Geographically-concentrated	High O&G transfer potential	O&G overlap less established Manufacturing still niche
Environmental impact (fugitive emissions, seismicity risks)	Closed systems limit emissions, low depths avoid seismicity concerns	Upper bound of emissions intensity is in the fossil fuel range	Low-medium emissions intensity Induced seismicity risk	Very low emissions intensity No water contamination Induced seismicity risk
Reliance on regulatory / government support	Required to overcome planning, permitting, and financing hurdles	Mature, commercially available technology	Government support could be required to commercialise, particularly in regions lacking big tech involvement	
Hybrid application suitability	Potential synergies with low- to medium-temp. industrial heat	Heat applications limited by geographical resource availability	High potential for co-location with industrial heat demand	

🟩 Low
🟨 Medium
🟥 High

Notes: Conventional hydrothermal or direct-use. Source: Systemiq analysis for the ETC (2025); Michael Barnard (2025), *Beyond the Hype: Geothermal in Context — separating viable heat solutions from speculative drilling dreams*

Agenda

- Work programme introduction
- Nuclear: Emerging Insights
- Geothermal: Initial Insights
- **Next steps**

Next steps for the nuclear and geothermal workstream

	Workshop	Date	Focus
1	**Workshop Two: The role of Geothermal**	December 3rd 2025	Geothermal techno-economics, system value, wider risks and benefits.
2	**Workshop Three: Key enablers to scale Nuclear and Geothermal**	Early 2026	Guidelines and enablers required to scale nuclear and geothermal.