



Energy
Transitions
Commission

Carbon Molecules - Disruptions workshop

20/11/2024

Agenda

	Time (UKT)	Speaker
Welcome	11:00-11:05	Adair
Section 1: Introduction to the Carbon Molecules work	11:05-11:35	Andrea
Section 2: Changing trends for electrification and hydrogen		Andrea
Section 3: Deep dives		
• Electrification of high temperature Industrial Heat		Emilie
Discussion	11:35-11:50	
• Iron-ore and steel making – Electrowinning and Molten Oxide Electrolysis	11:50-12:15	Emilie
• Solid state batteries		Marlene
• Advanced Direct Air Capture		Marlene
Discussion	12:15-12:30	
• Sodium-based battery technologies	12:30-12:45	Marlene
• Hydrogen		Andrea
Conclusion and next steps		Andrea
Discussion	12:45-13:00	

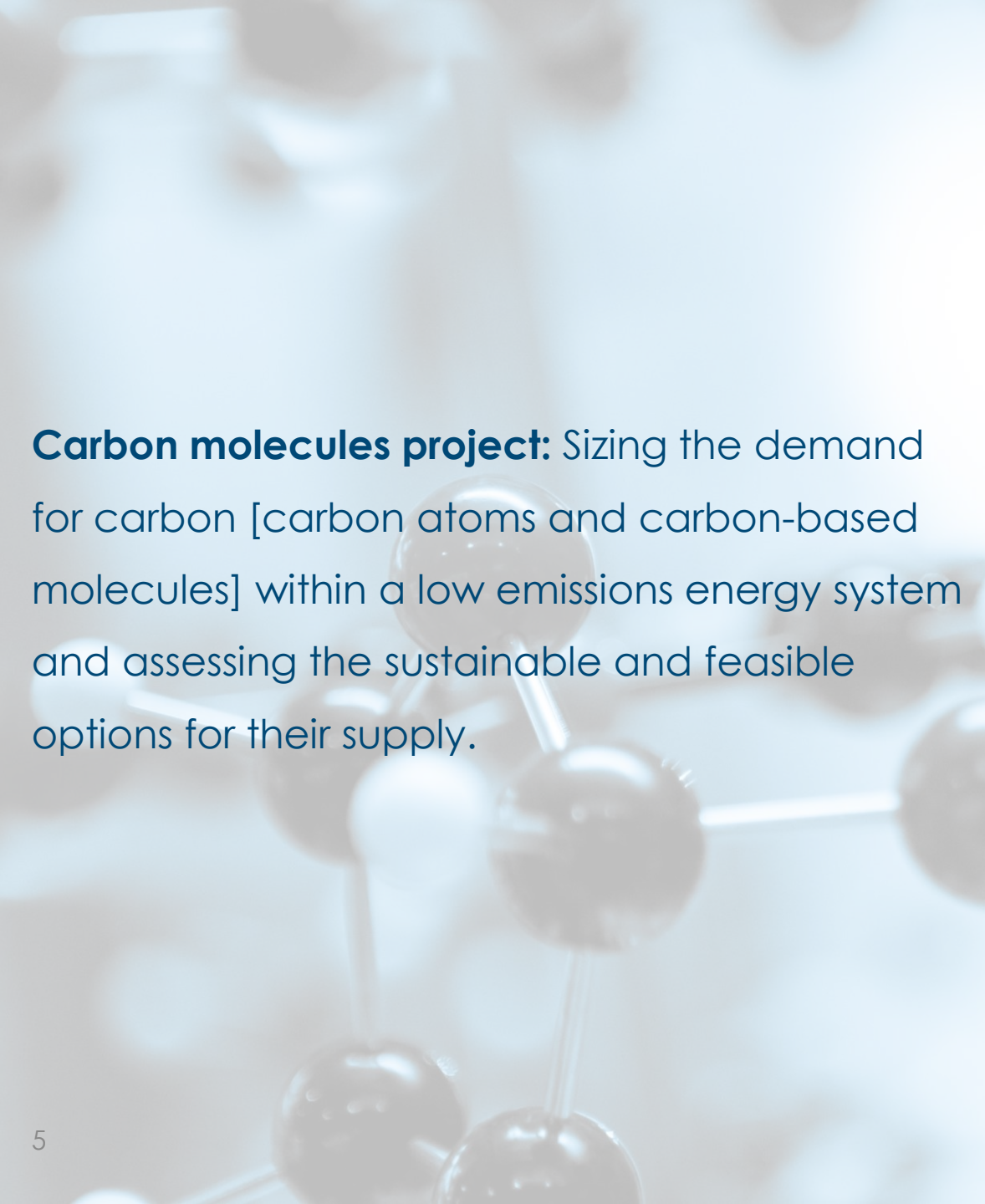


Agenda

Introduction to the Carbon Molecules Work

Changing trends for electrification and hydrogen
Disruption deep-dives





Carbon molecules project: Sizing the demand for carbon [carbon atoms and carbon-based molecules] within a low emissions energy system and assessing the sustainable and feasible options for their supply.

Aim:

Shape the narrative and conversation around low-carbon emission molecules in the lead-up to COP30

Organised in four sprints / questions

Our topic today

1. How large a role can and should direct electrification play in a zero emission economy?
2. The role of hydrogen and non-carbon H₂ derivatives
3. The potential to recycle and reuse carbon molecules
4. Sources of primary carbon: costs and sustainability

Carbon molecules in the zero-emission economy: work programme

Question

1. How large a role can and should direct electrification play in a zero-emission economy?

Deliverables

- An extreme scenario which identifies how much of the economy could in principle be electrified if zero carbon electricity were available at a very low cost and on the required scale.
- A revised version of our Possible but Stretching scenario which describes the optimal role of electricity in a world on target to limit global warming to 1.5oC.
- A constrained clean electricity scenario, which would serve as a counter to the 'extreme scenario' which would be based on more conservative clean power build out (e.g. B EF's clean energy project pipelines)
- A set of electrification innovation deepdives, covering technology, cost, barriers to deployment, impact on total electrification

2. The role of hydrogen and non-carbon H2 derivatives

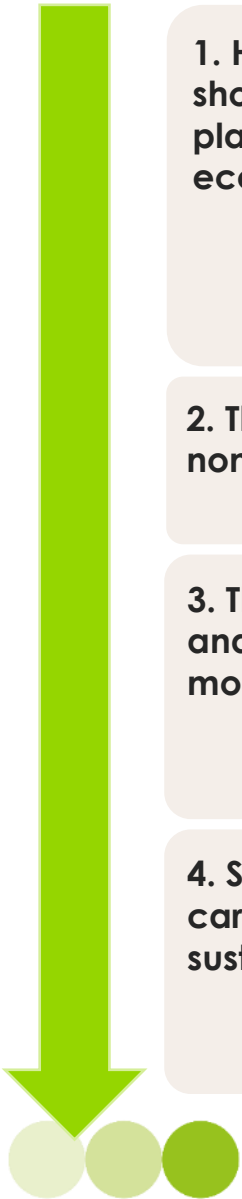
- Updated set of scenarios for the role of hydrogen, exploring in particular the balance between hydrogen and non-carbon H2 derivatives relative to carbon and hydrocarbon molecules in different sectors

3. The potential to recycle and reuse carbon molecules

- Extreme scenario to explore how close to total recycling of all carbon molecules it would be possible to get, and with what implications for the primary supply of new carbon still required to support a prosperous global economy
- A range of less extreme plausible scenarios for carbon source demands in a zero-emission economy

4. Sources of primary carbon: costs and sustainability

- Update (increasing or decreasing) of our past estimates of potentially sustainable bioresource supply
- Description of the latest technology development and cost trends in point source capture and direct air capture of CO₂ (DACCS)
- Brazil deepdive: assessment of the optimal decarbonisation path within Brazil's specific conditions



Sprint 1: evaluating the role of direct electrification, hydrogen and ammonia in a zero-emission economy

Integration in broader carbon molecule project

By sizing how much non-carbon technologies (electrification, hydrogen and ammonia) can deploy, we also assess the remaining need for carbon-based energy sources, which is the starting point of sprint 2 and 3.

	2024	2025			
	Q4	Q1	Q2	Q3	Q4
Workplan	<p>Sprint 1A How large can and should the role of direct electrification be in a zero-emission economy</p> <p>Sprint 1B The role of hydrogen and derivatives (i.e., ammonia) in a zero-emission economy?</p>	<p>Sprint 2 The potential to recycle and reuse carbon molecules</p>	<p>Sprint 3 Sources of primary carbon: costs and sustainability</p>	<p>Sprint 4 Report production and communication campaign running into COP30</p>	
Deliverables	<ul style="list-style-type: none"> A 5-pager published externally A series of short innovation briefs for publication 	<ul style="list-style-type: none"> Publication of the ETC report ahead of COP A series of short innovation briefs for publication 			
Key interactions	<ul style="list-style-type: none"> 1-2 workshops with ETC Commissioners 	<ul style="list-style-type: none"> Workshop Report reviews Report launch at COP 			



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Introduction to the Carbon Molecules Work

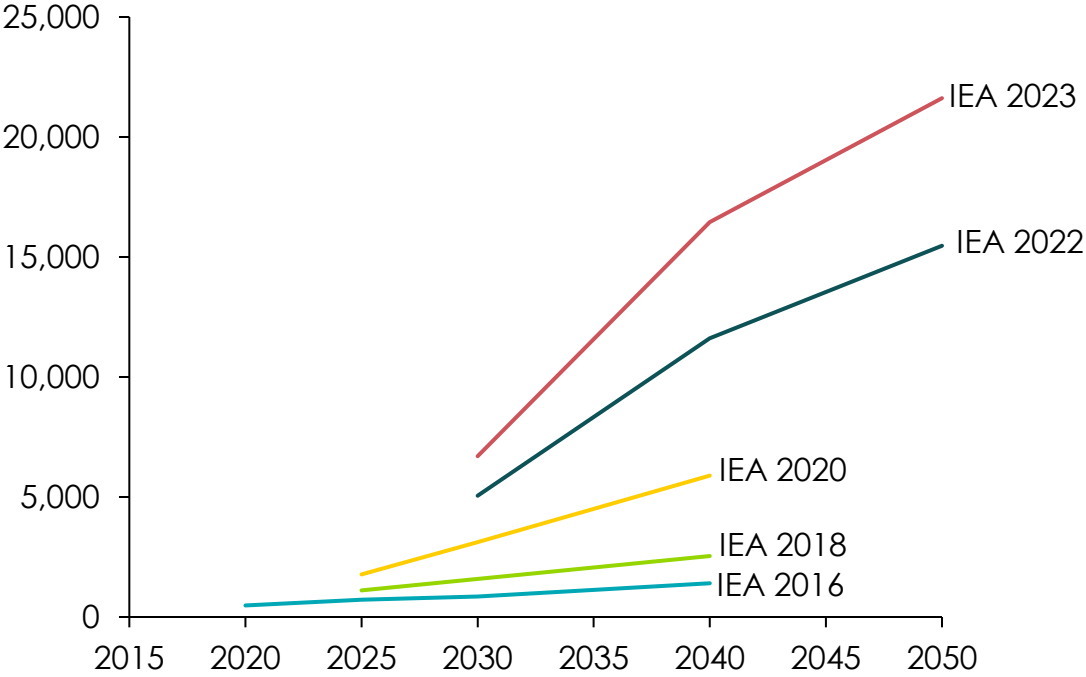
Changing trends for electrification and hydrogen

Disruption deep-dives

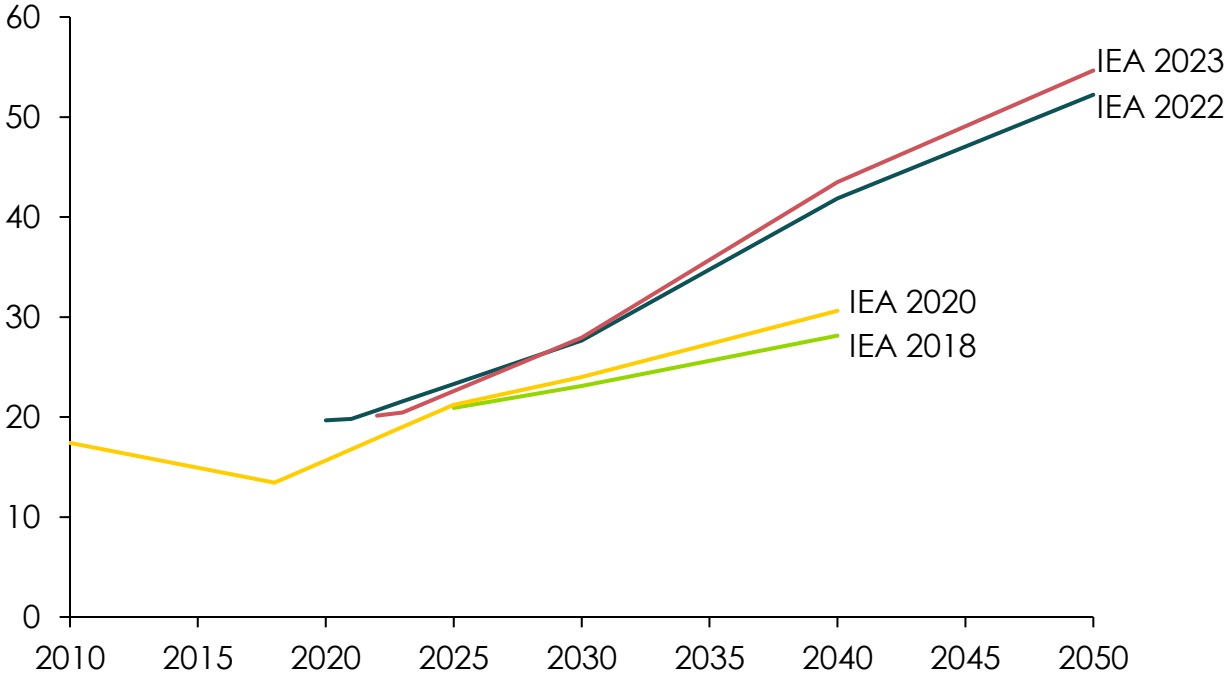


Our starting point: Informed observers and experts have consistently updated their electrification deployment forecasts upwards

Deployment of solar PV generation in IEA progressive scenarios, GW



Level of electrification in global final energy demand, %



IEA scenarios in World Energy Outlook reports

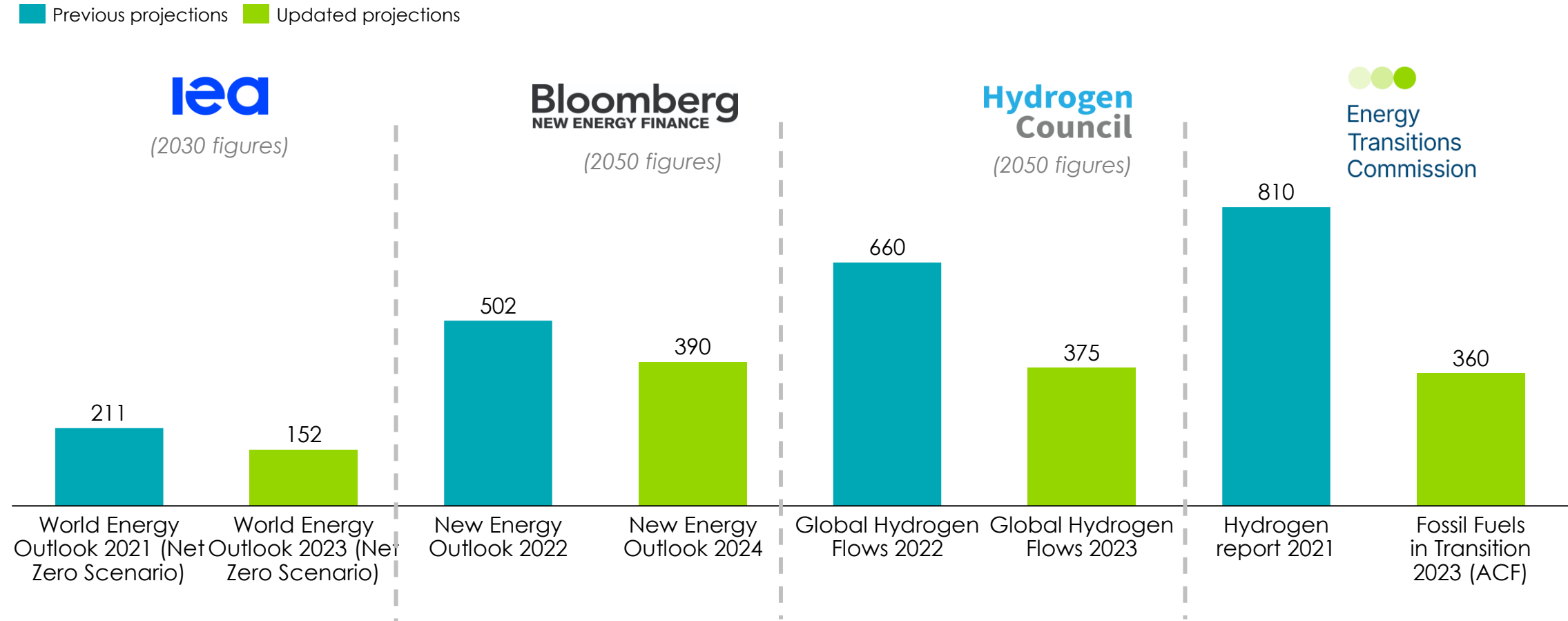
— IEA 2016 New Policies
 — IEA 2018 New Policies
 — IEA 2020 Sustainable Development
 — IEA 2022 Net Zero by 2050
 — IEA 2023 Net Zero by 2050



Sources: IEA (various) World Energy Outlook

In comparison, most recent forecasts on hydrogen are revising down its role in the decarbonisation journey

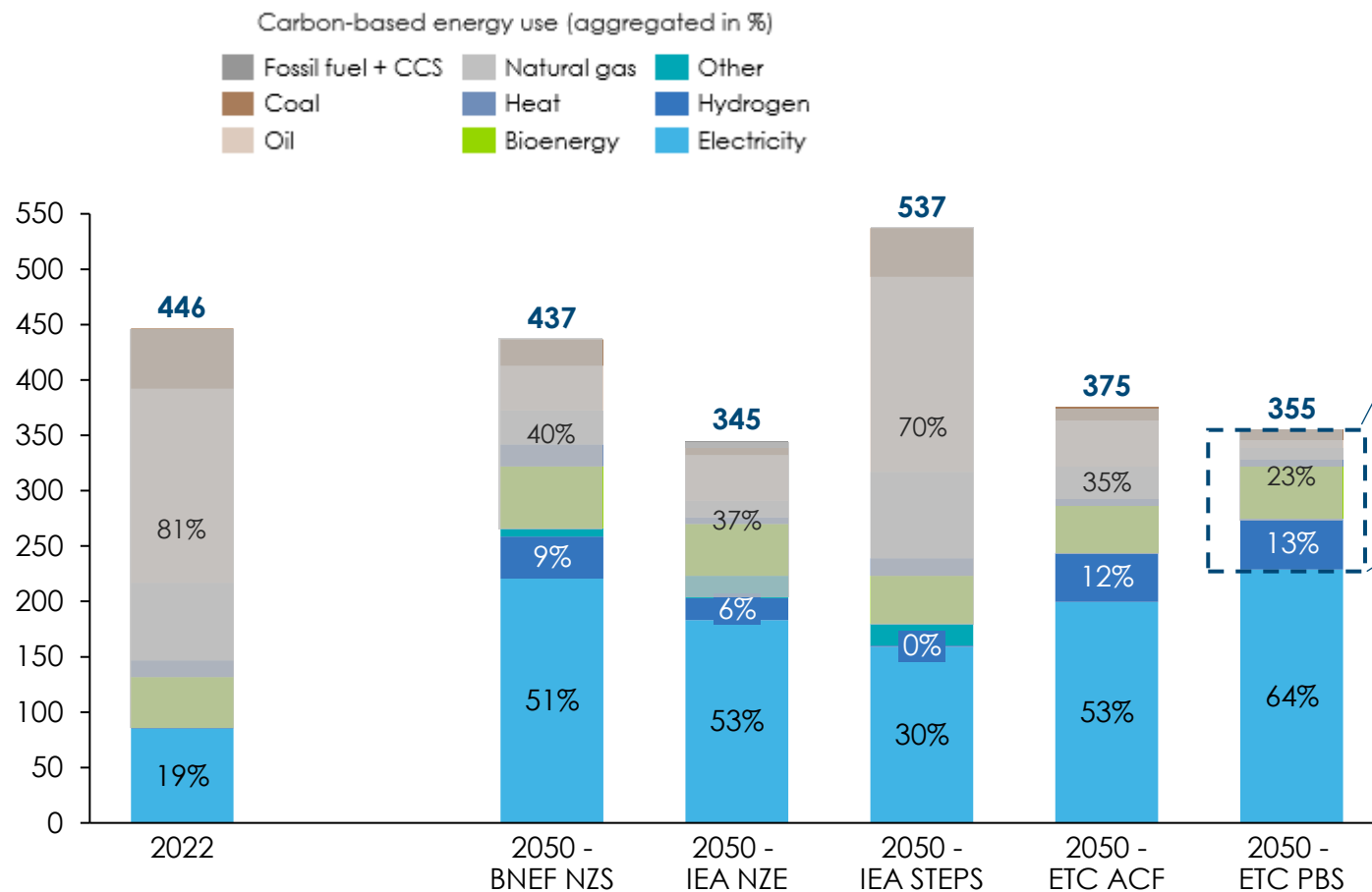
Global hydrogen demand has been revised downwards, Mt H2



Source: IEA (2023), World Energy Outlook 2023; IEA (2021), World Energy Outlook 2021; Hydrogen insights (2024), 'Getting to net zero will need nearly a quarter less clean hydrogen than we initially predicted'; BNEF; Hydrogen insights (2023), Half of all clean hydrogen produced globally could be transported long-distance by 2030, says Hydrogen Council. ETC (2021), Making the Hydrogen Economy Possible. ETC (2023), Fossil Fuels in Transition

The energy demand scenarios in the ETC Fossil Fuel report forecast a high level of electrification, though not radically divergent from peers.

Global Final Energy demand by energy source and scenario EJ (%), 2050



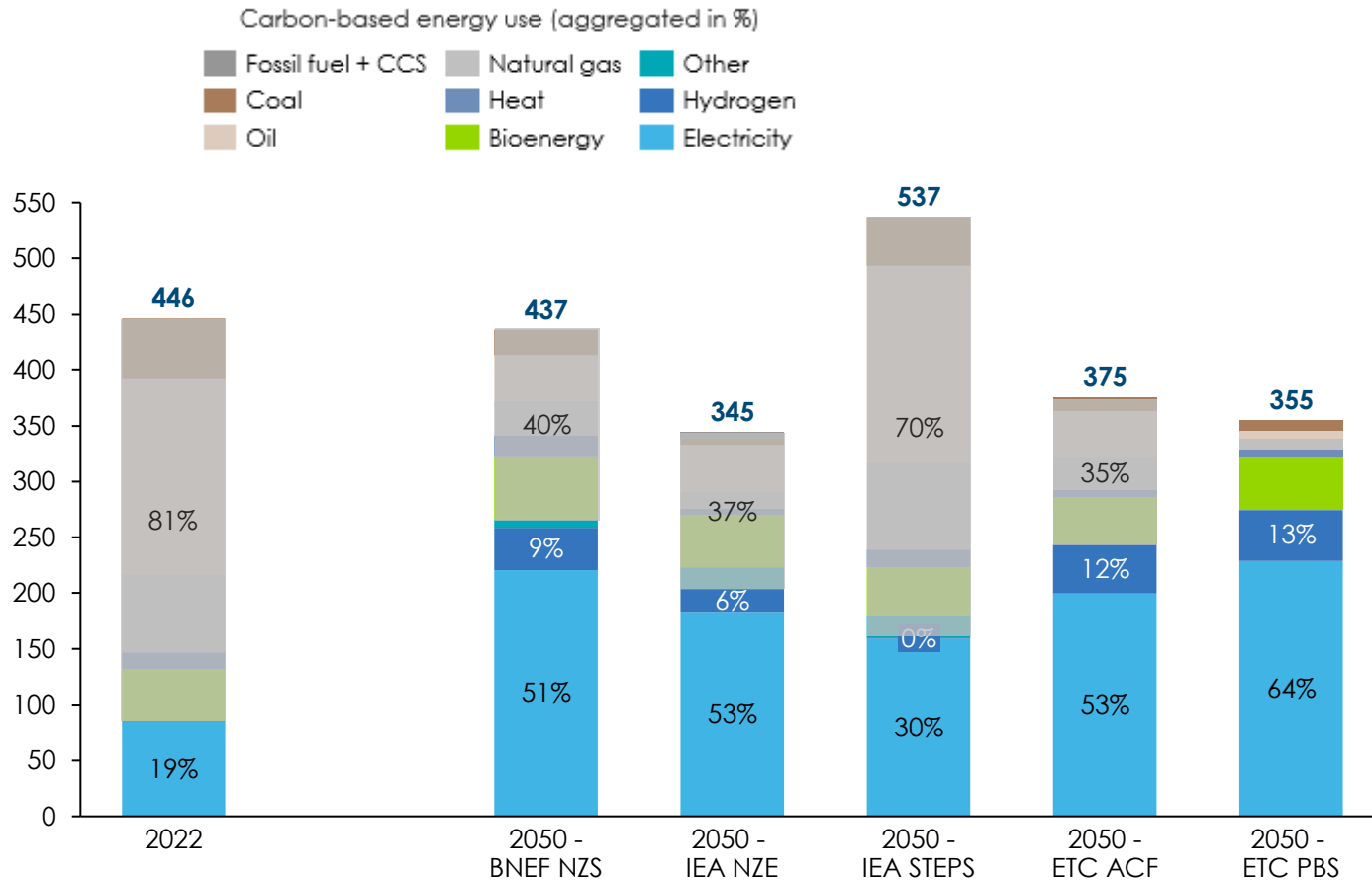
Role of Molecules:

- **30-45% of overall Final Energy Demand, of which:**
 - 10-15% is **hydrogen or derivatives**
 - 5-10% is **biomass-derived carbon-based molecules**
 - 10-25% is **fossil carbon-based molecules**

Note: BNEF ZNS = BloombergNEF Net Zero Scenario; NZE = Net Zero by 2050; STEPS = Stated Policies; ACF = Accelerated but Clearly Feasible; PBS = Possible but Stretching;
Sources: 2022 scenario: Taken from ETC; ACF and PBS scenario: Taken from ETC FFIT Report 2023; IEA NZE, Taken from World Energy Outlook 2023

The new ETC constrained and unconstrained scenarios will highlight the potential range of electrification by 2050

Global Final Energy demand by energy source and scenario EJ (%), 2050



Systemiq/ETC is producing a new updated set of scenarios:

- Updating our latest view (ETC ACF and PBS) to include the latest trends in terms of hydrogen cost and use, energy demand (other industry)
- Producing 2 new scenarios:
 - Unconstrained scenario, based on a list of disruptions (deployment of technologies allowing an electrification breakthrough)
 - Constrained scenario, based on a conservative view of the low emission power supply deployment and slow-paced electrification

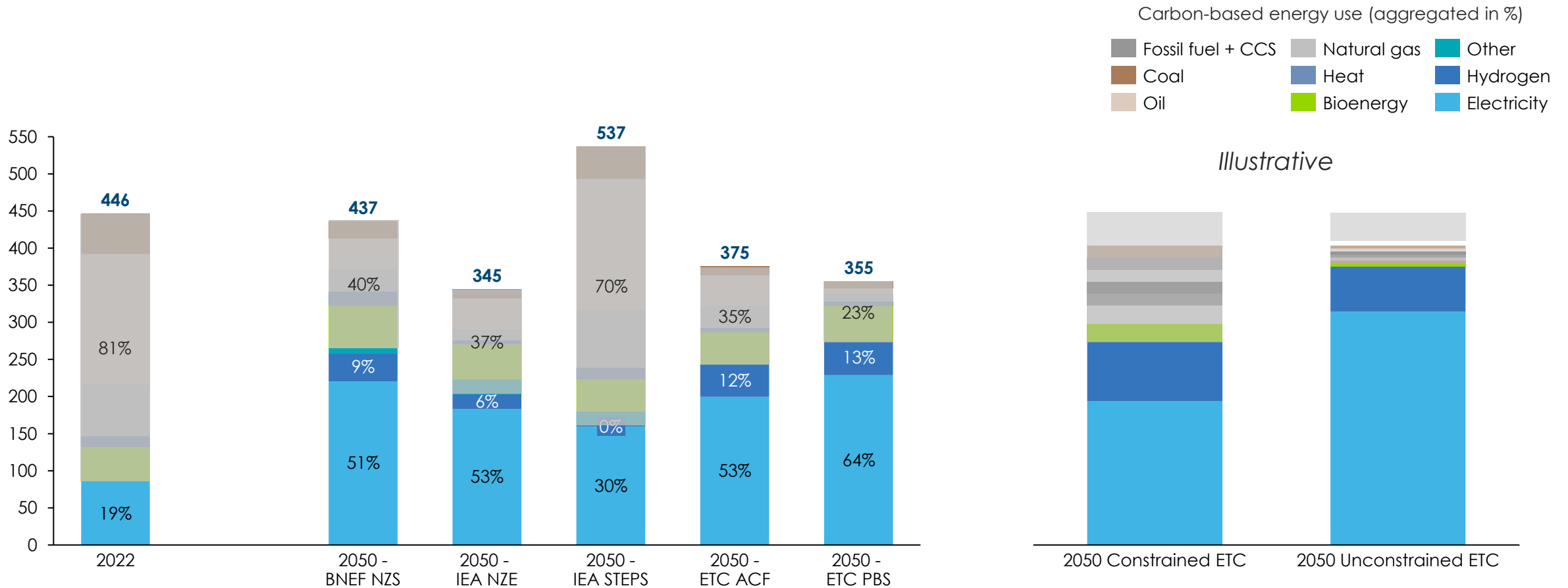
=> Objective for the next phases of this work: sizing the minimum and maximum demand for direct electrification and use of hydrogen/ammonia allows us to estimate the demand for carbon in a net zero economy (remaining energy uses)

Note: BNEF ZNS = BloombergNEF Net Zero Scenario; NZE = Net Zero by 2050; STEPS = Stated Policies; ACF = Accelerated but Clearly Feasible; PBS = Possible but Stretching;
Sources: 2022 scenario: Taken from ETC; ACF and PBS scenario: Taken from ETC FFIT Report 2023; IEA NZE, Taken from World Energy Outlook 2023

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Global Final Energy demand by energy source and scenario
EJ (%), 2050

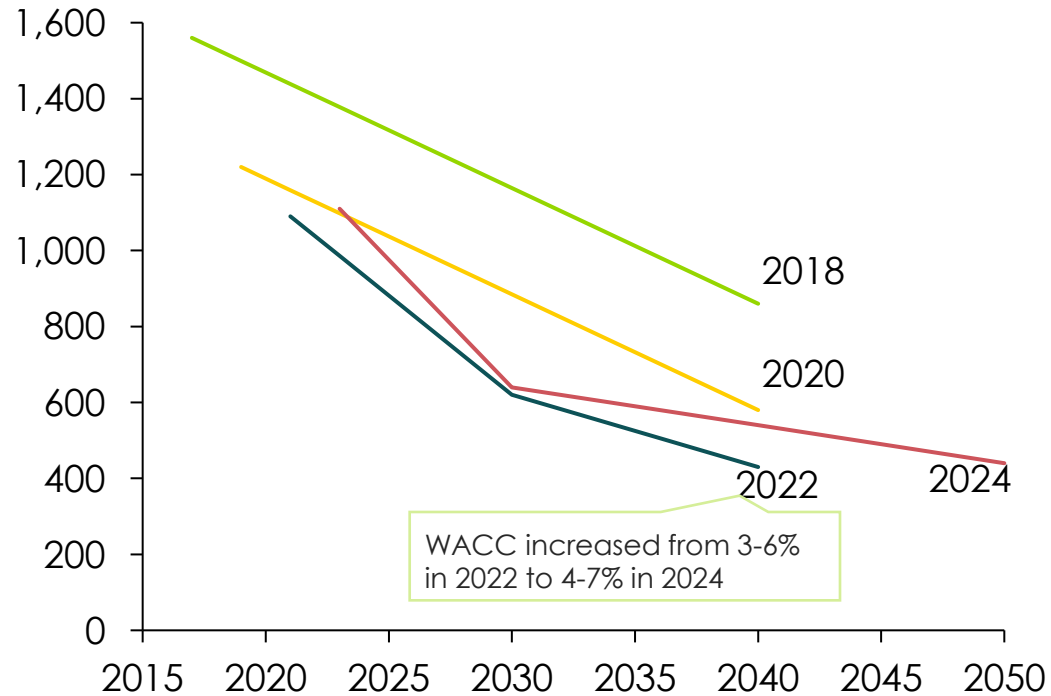
Global Final Energy demand in new ETC scenarios, EJ (%), 2050



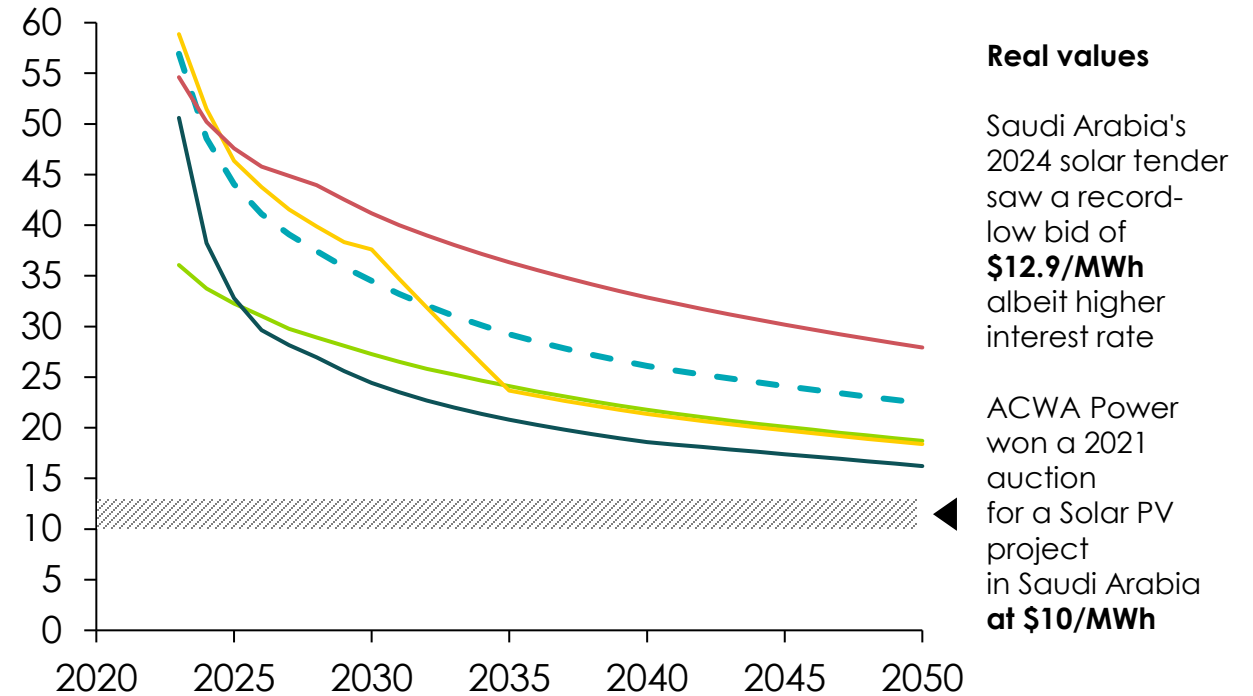
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Sources: 2022 scenario: Taken from ETC; ACF and PBS scenario: Taken from ETC FFIT Report 2023; IEA NZE, Taken from World Energy Outlook 2023

[Power] The decline in solar PV costs has been underestimated in the past and is project to reduce further

Cost of solar PV in IEA progressive scenarios, USD/kW, real capital cost from year of report



BNEF projected LCOE of Solar PV¹ globally & select countries USD/MW (2022 real)



IEA scenarios in World Energy Outlook reports

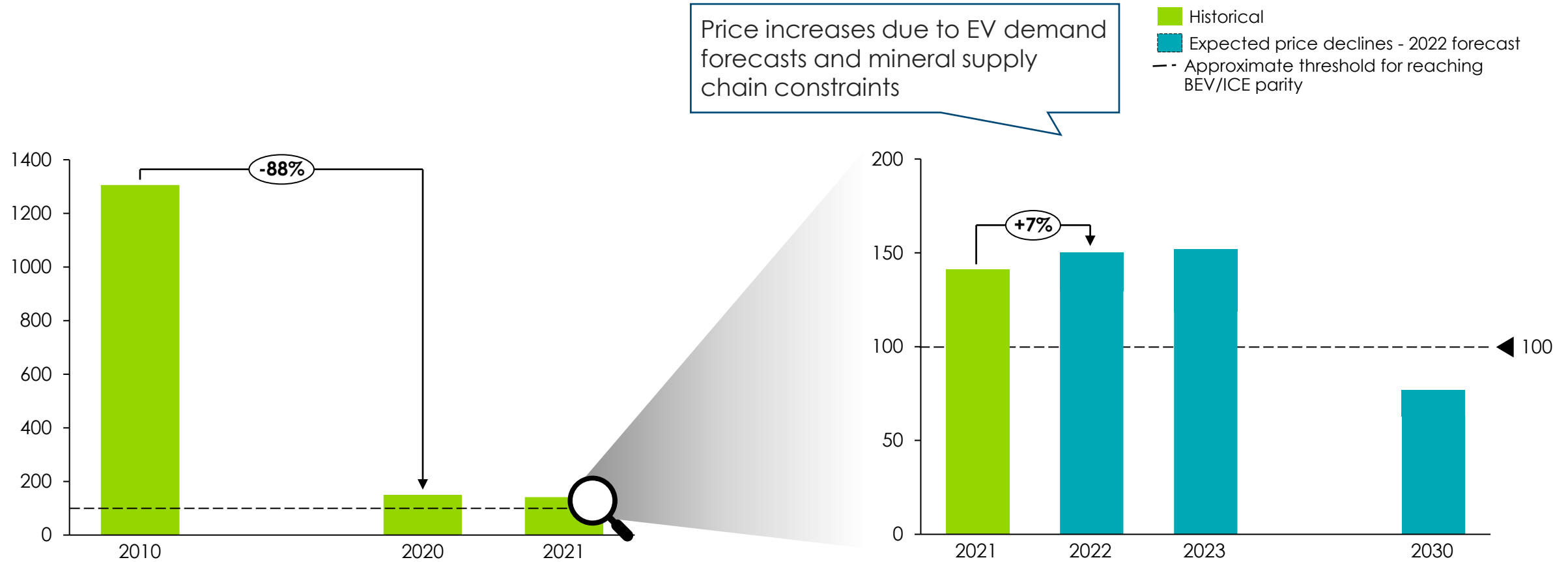
- IEA 2016 New Policies
- IEA 2018 New Policies
- IEA 2020 Sustainable Development
- IEA 2022 Net Zero by 2050
- IEA 2024 Net Zero by 2050

- World average
- China
- United States
- South Africa
- Germany

Note: 1. Based on solar PV tracking.
Sources: IEA World Energy Outlook, Bloomberg New Energy Finance 2023, 2H 2023 LCOE: Data Viewer Tool.

[Batteries] Despite temporary increases, battery prices continue their downward trajectory

Battery costs in EVs – past and projected
\$/kWh; 2022 nominal

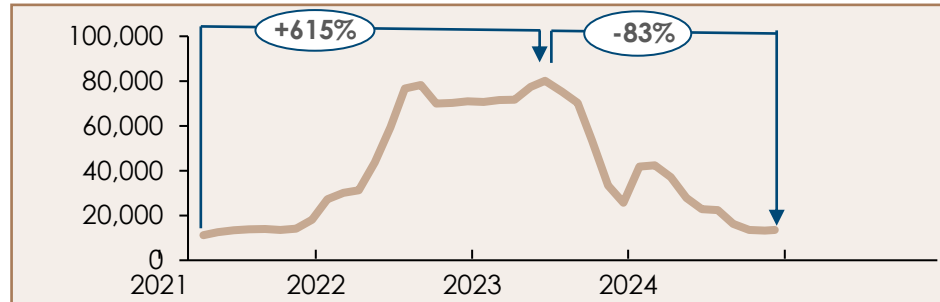


Source: Systemiq analysis for the ETC; BNEF (2023), Long-term electric vehicle outlook; BNEF (2022), Long-term electric vehicle outlook; ETC (2023); Better, faster, cleaner: Securing clean energy technology supply chains; BNEF (2023), Interactive data tool – battery manufacturing

[Batteries] Increases in prices between 2022-2023 were driven by mineral supply chain constraints and EV demand but have since dissipated

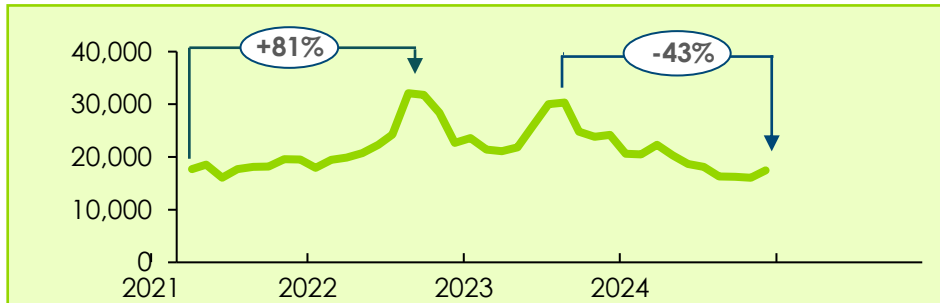
Mineral prices \$/tonne

Lithium



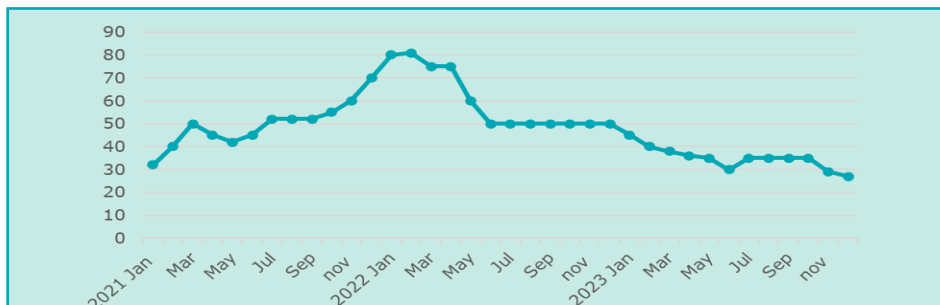
- Slowdown in EV demand relative to very high expectations
- New projects announced in EU , US , Australia, Chile, some subsequently postponed
- New technology Direct Lithium Extraction(DLI) from brine

Nickel



- Shift towards nickel-free LFP batteries
- Massive expansion of Indonesian supply (Chinese owned)

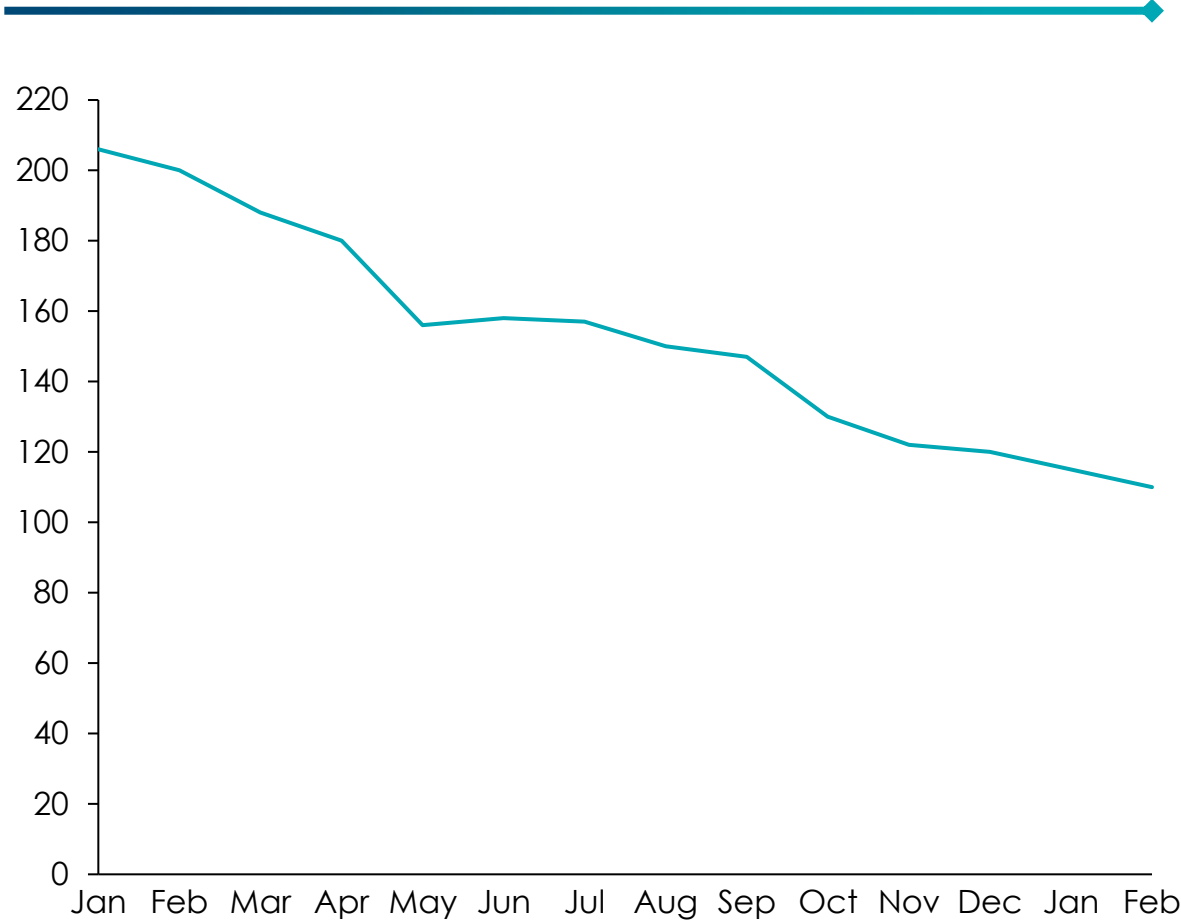
Cobalt



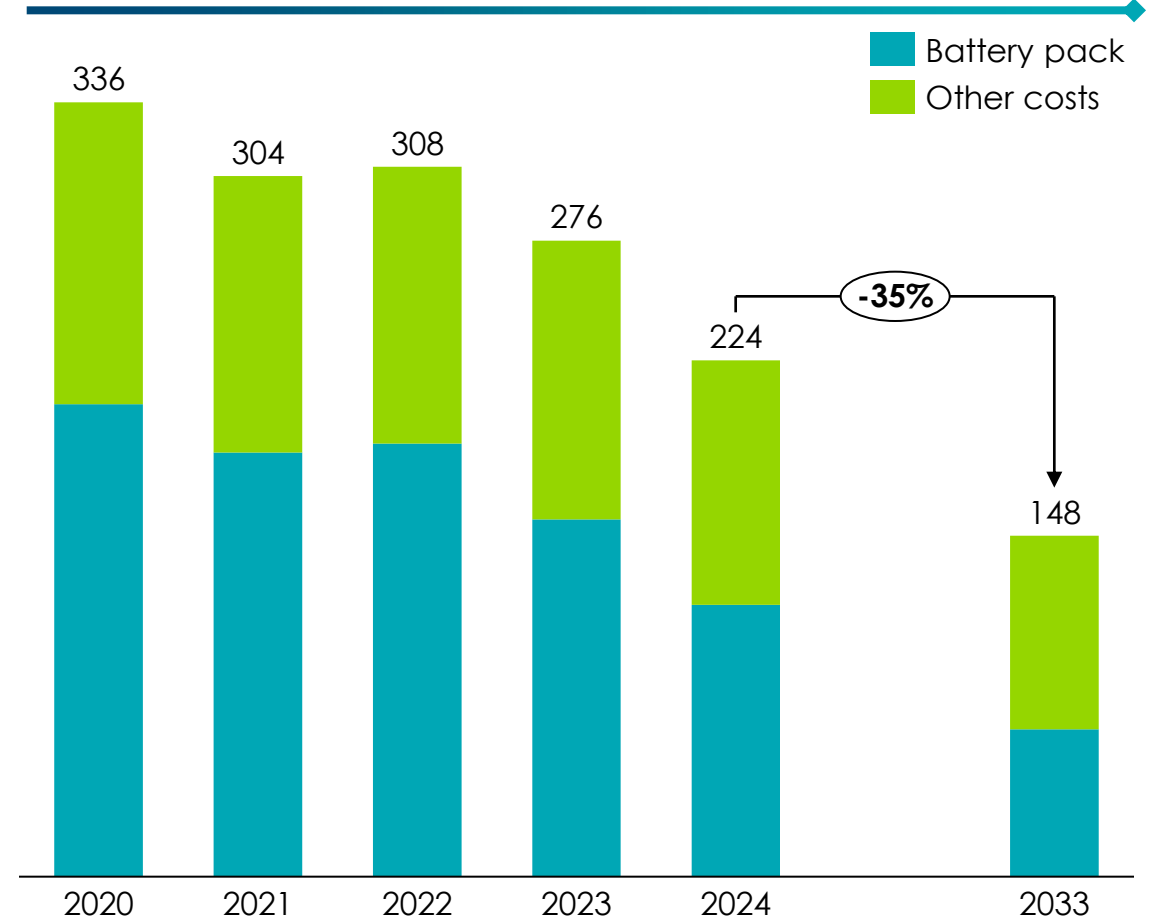
- Reduction of Co-proportion within NMC batteries
- Shift towards nickel and cobalt-free LFP batteries
- By-product of nickel development in Indonesia

[Batteries] As a result, battery costs are declining, too, driving further advancements in stationary storage

Chinese battery costs, Jan 2023 – Feb 2024
\$ per kwh



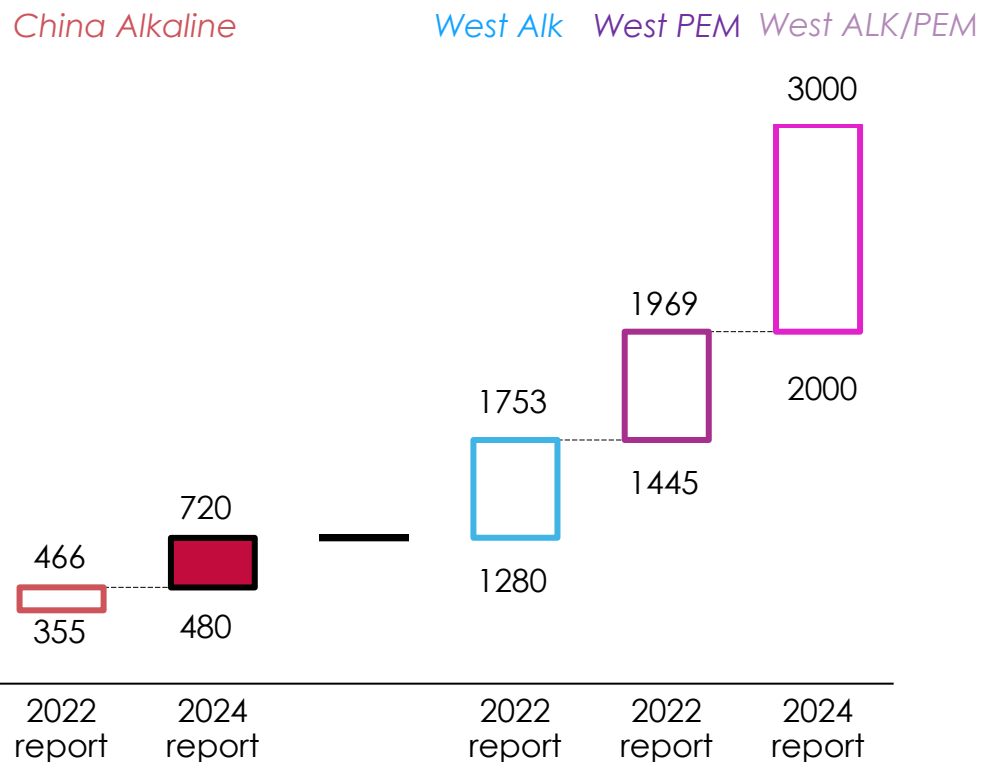
Full system cost of two-hour energy storage
\$ per kwh



[Hydrogen] Costs of hydrogen remain high, and anticipated to fall less steeply than anticipated in light of higher system capex

System capex forecast of large alkaline electrolysis projects

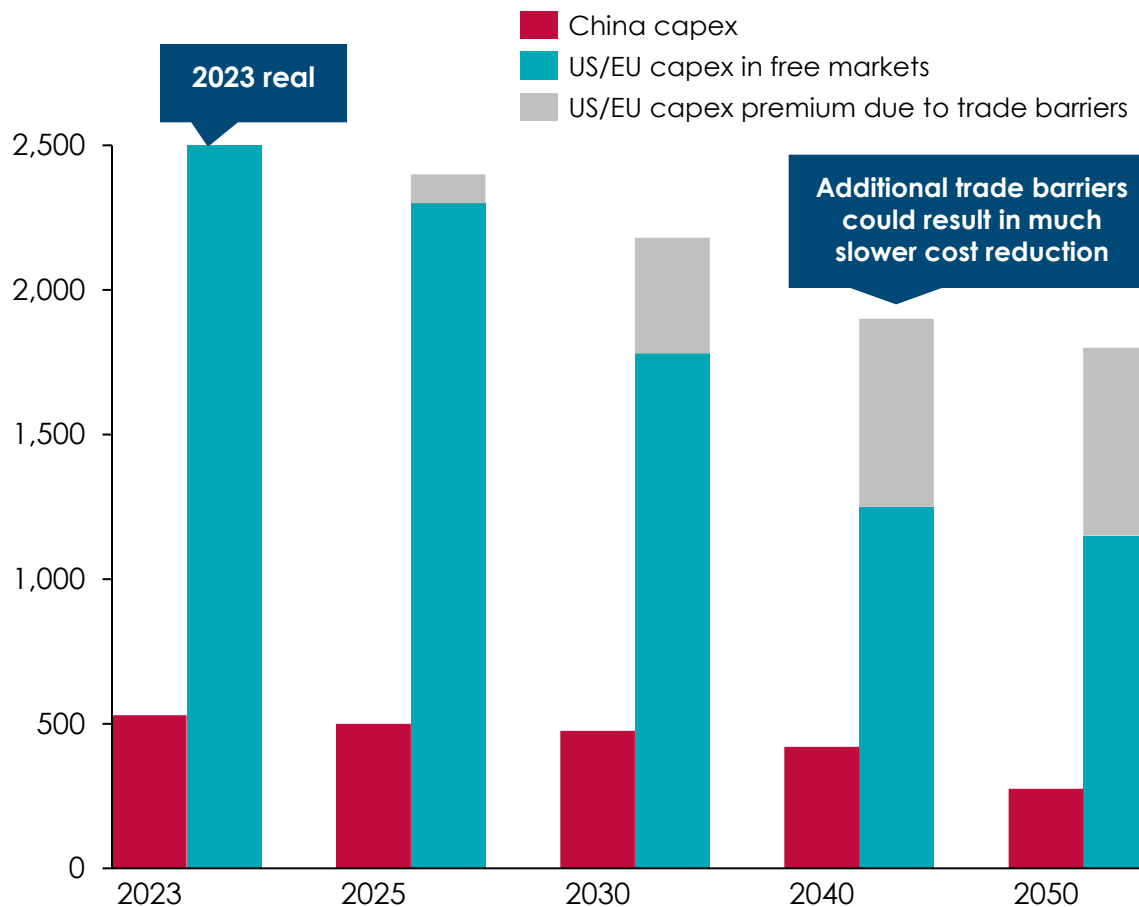
\$/kW



BNEF electrolyzer survey reports

Electrolyzer system costs

\$ per kw of hourly hydrogen yield



Additional trade barriers could result in much slower cost reduction

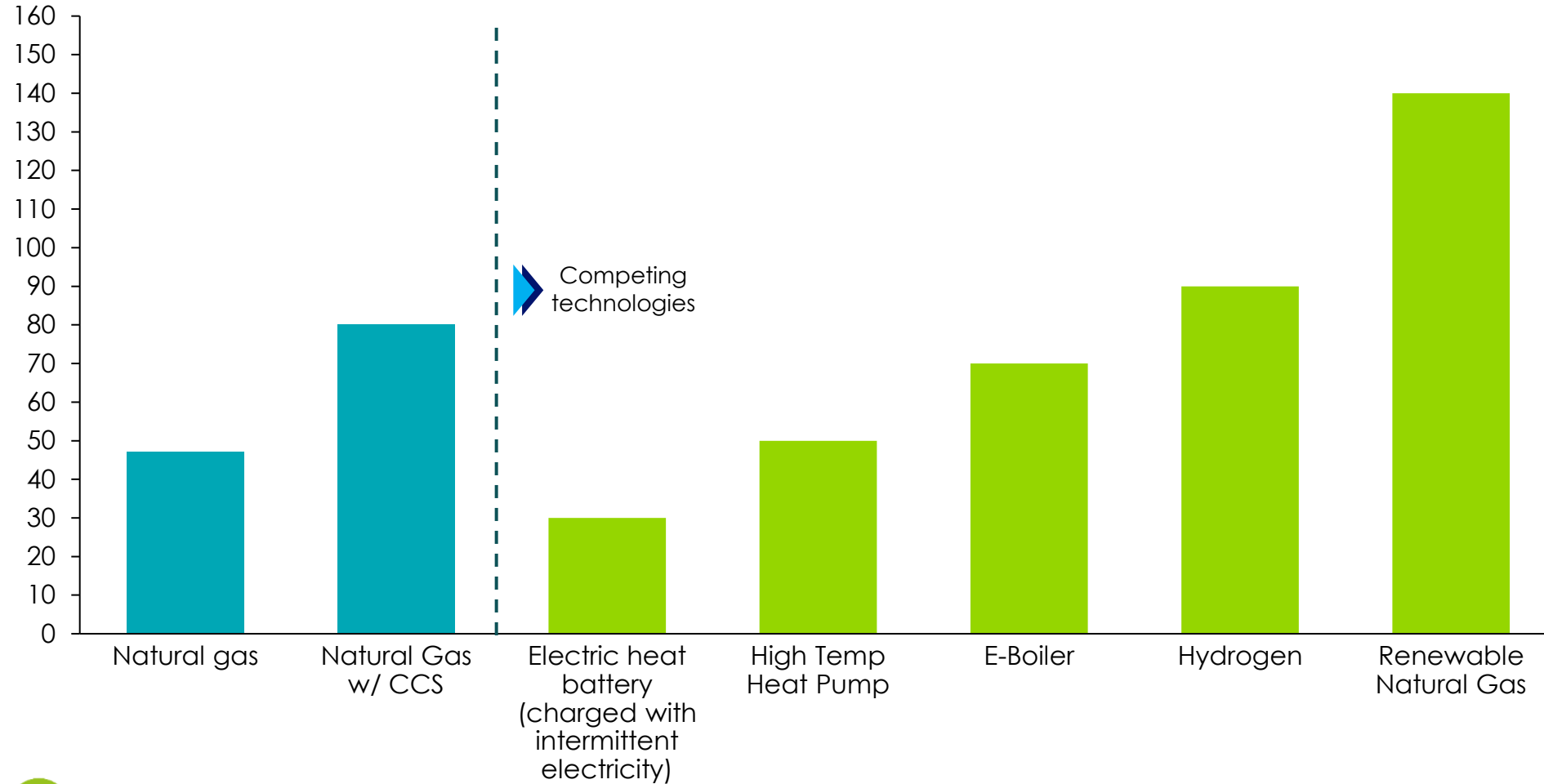
Note: Years refer to time of final investment decision (FID), engineering, procurement and construction bidding closure or equipment purchase. There was no trade barrier in 2023, so the 'premium due to trade barriers' was not available then. The unit '0.2Nm³/h' is equivalent to kw under the current industry consensus
 Source: Bloomberg (2024) BNEF Hydrogen Market Outlook



[Heat electrification] Estimates suggest that the cost of medium temperature heat electrified solutions can be competitive with more carbon intensive alternatives

Levelised Cost of Heat (LCOH) for temperatures >100 degrees Celsius

\$/MWh



Notes: LCOH reflects US prices; Natural gas LCOH is based on 2024 LNG price of \$40/MWh
Source: Rondo (2024) *Can a brick solve your heat challenge?*



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Changing trends for electrification and hydrogen

Disruption deep-dives



The potential of 8 key disruptions – our hypothesis on their role



How far can electrification go?

High potential electrification disruption



- 1 Industrial heat electrification (>600°C) (including electric steam cracking)
- 2 Electrification of iron-making

Disruption potential with less certainty



- 3 Li-ion solid state batteries
- 4 Advanced Direct Air Capture

Enablers of electrification



- 5 Sodium based batteries
- 6 Nuclear fission (Small and Micro reactors)




















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In an unconstrained electrified world – what would be the role of hydrogen?



Innovation is crucial: eight pivotal disruptions may change the electrification vs. hydrogen vs. carbon boundary

■ Enablers
 ■ Hydrogen
 ■ Potential but less certainty
 ■ High potential

	Technology disruption 	Assessment of disruption 	Sectors impacted 	
Sector specific	1 Industrial heat electrification (>600°C)	Make electrification feasible and cost-competitive with CCS for high temperatures and with H2	 (Heavy-) industry (cement)	
	2 Electrical steam cracking	Replace fossil-fuel cracking by electric cracking for ethylene and propylene	 Chemicals	
	3 Molten Oxide Electrolysis and Electrowinning	Enables fully electric primary steel production	 Steel	
	4 Li-ion solid state batteries	Outperforming other batteries in compactness, weight and charging speed	 Trucking	 Shipping
			 Aviation	
5 Advanced Direct Air Capture (DAC)	Boosts e-fuels (synfuels) efficiency and lowers costs, outcompeting biofuels, but also reduce cost of DACCS for fossil + CCS	 Industry	 Chemicals	
		 Aviation	 Power	
Cross sectoral	6 Sodium-based battery technologies	Enable low-cost, long-duration storage, other dispatchable generation	 Power  Industry	
	7 Small Nuclear Reactors (SMR), Nuclear Micro Reactors (NMR)	Provide ultra-cheap round-the-clock power generation	 Chemicals and other industry	
	8 White hydrogen and optimizing electrolyzer costs	Drives (green) hydrogen to cost parity with carbon fuels and CCS	 Power	 Chemicals
			 (Heavy-) industry	



Our understanding of the key disruptions will shape our scenarios

- During this workshop, we would look for your challenge and feedback on...
 - Our understanding of disruptions
 - The impact that these disruptions might have on a carbon/electricity/hydrogen boundary
 - How our story for these disruptions might change for constrained/unconstrained scenarios
 - The limitations we might encounter for these technologies

What is out of scope for this sprint

- Recycling, reuse and utilization of carbon will be covered in Sprint 2
- Land-use, grid build out and other considerations – for now, not considered as part of 'unconstrained' scenarios
- Focus is on demand, not supply



Industrial heat electrification

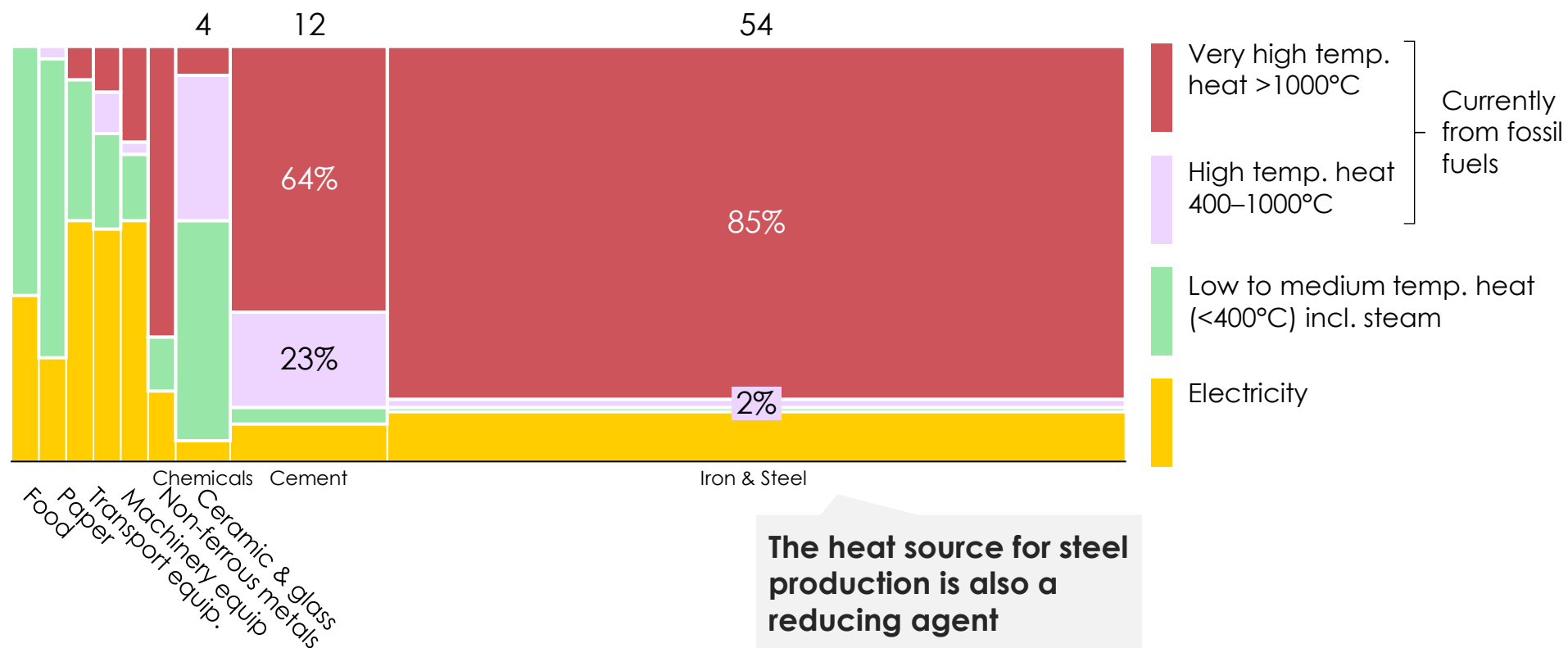


Electrifying high-temperature heat in the iron and steel, cement, and chemical sectors could significantly increase the role of low-carbon power in the industrial sector

Energy use by temperature and industry sector¹ in 2050

EJ

Illustrative as energy use by temperature and industry is based on European values in 2020



Key insight















Electrifying high-temperature heat (>100°C) could reduce fossil fuels use in industries by ~60EJ in 2050, particularly in energy-intensive sectors like **steel, cement and chemicals**

Notes: 1. Data representing energy split by temperature in EU across the sectors applied to a global level based on a study from Madeddu (20220) with adaptations for the chemical sector to include plastics from Coolbrook (2024).

Sources: Final energy demand in 2050 based on Systemiq analysis (2024) from ETC (2023), Fossil Fuels in Transition Report; Silvia Madeddu (2020), The CO₂ reduction potential for the European industry via direct electrification of heat supply. Coolbrook (2024), Electric cracking: RotoDynamic Reactor cuts 100% of CO₂ in steam cracking



New technologies currently under development could electrify industrial energy demand at high temperatures (over 400°C)

Technology ¹	Process	Sectors ²	TRL	Energy Efficiency	Company <i>Non-exhaustive examples</i>
Shock-wave heating	Rotation turbines employ an electric motor to spin blades and gas , where supersonic speed and rapid deceleration creates a shock-wave and turbulent gas, which generates high temperature heat	Cement, chemicals, steel, aluminum, other industry (glass)	6-7	50-95%	  
Arc and plasma heating	Two electrodes connected to a high-voltage power supply create an electric field that ionises the air, forming a plasma with electrons and positively charged particles . The applied electric field causes the ionized gas molecules to oscillate to generate heat	Cement, Steel, other industry (Machinery, transport equipment)	3-9	50-90%	   
Resistance	An electric current passes through resistive elements , causing electrons to collide with the atoms of the material, converting electrical energy into heat, the heat is then transferred by gas through convection or through radiation	Steel, aluminum, chemicals, other industry (glass, machinery, transport equipment)	6-9	50-95%	   
Microwave	Electricity powers a microwave generator , producing microwaves that cause molecules (especially water or other polar materials) to oscillate , generating collisions and with that heat	Steel (sintering), other industry (e.g., ceramics)	Unsure	50-85%	
Induction	High-frequency current passes through an induction coil (e.g., copper), creating a magnetic field . This process generates induced force and produces heat because of the electrical collisions in the material.	Steel, aluminum, other industry (machinery, glass, minerals, transport)	7-9	50-90%	 

Note: 1. Only includes the sectors where a technology can electrify a high temperature processes; 2. Other technologies can be implemented for industry electrification, e.g. ultraviolet (UV), infrared, thermoelectric cooling, electron beam, and laser heating but have a narrow field of application
 Source: [Silvia Madeddu \(2020\)](#), The CO2 reduction potential for the European industry via direct electrification of heat supply. [Fraunhofer ISI \(2024\)](#): Direct electrification of industrial process heat. An assessment of technologies, potentials and future prospects for the EU. Study on behalf of Agora Industry.



Most recent announcements of innovation are focused on shock-wave heating, arc and plasma heating, and resistance heating

Focus technologies

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Shock wave heating can create up 1,700°C through supersonic accelerations converting kinetic energy into heat

OVERVIEW OF SHOCK WAVE HEATING

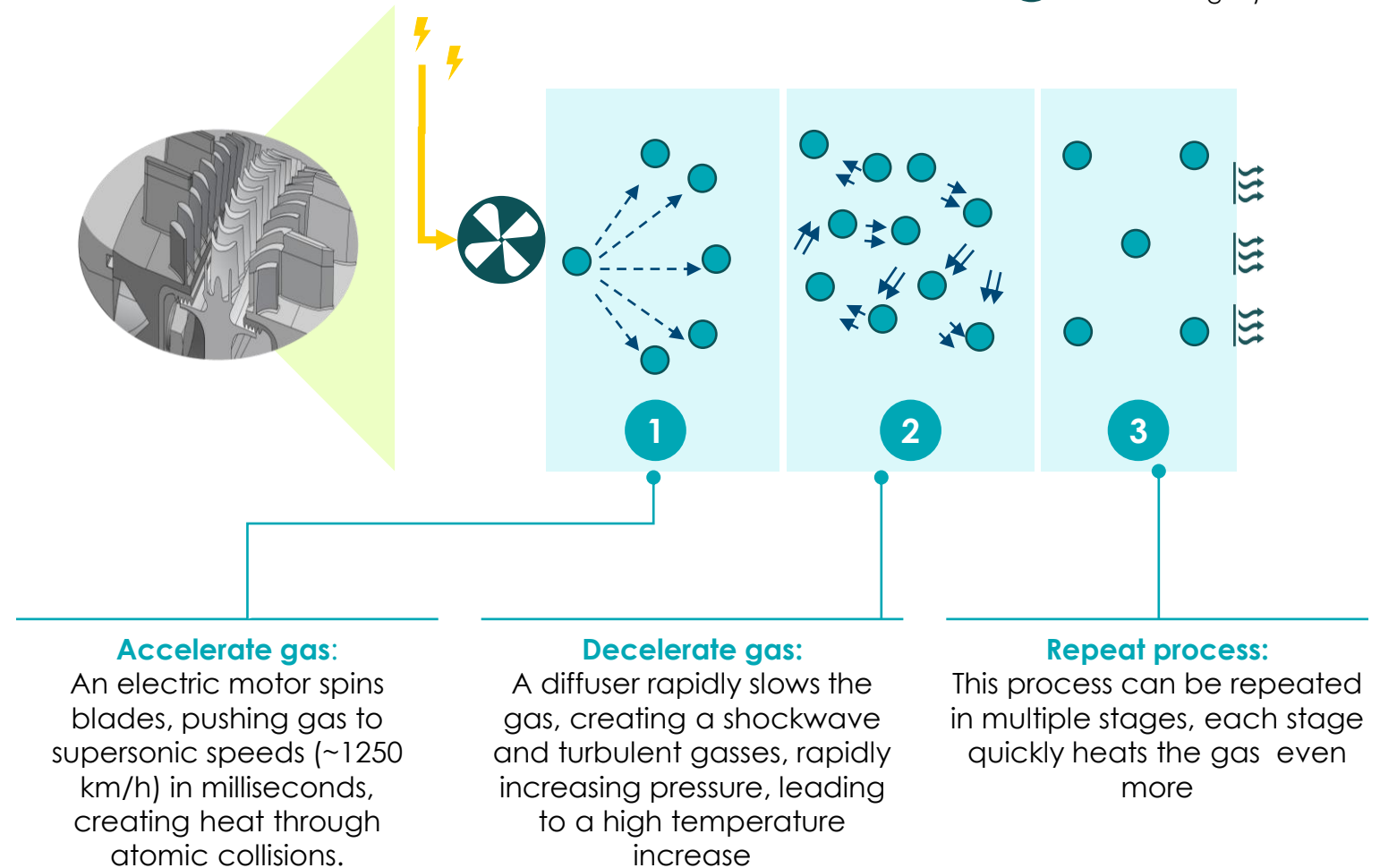
Current TRL & steps to get to TRL>7

- **Current TRL:** 5-6, launched a 0.8 MW pilot plant and completed testing for ~1000 °C. Plan to deploy 5-10 MW plants (for cement / steel sector) and 10-30 MW (for chemical sector) in 2024
- **Challenges:** significant upfront investment and supply of abundant low-cost power
- **Developed by:** Coolbrook, partnership with ABB, Linde, Brightlands, Shell, Ultratech, Cemex, ArcelorMittal, JSW and more

Advantages

- **Uniform high-temperature distribution** (up to 1,500-1,700°C) for high-quality production
- **High energy efficiency:** +90% as the rotational mechanism maximizes heat retention, minimizing energy loss and waste
- **Integration into existing production lines** with relative ease enabling retrofit of facilities

● Gas atoms (e.g., Naphtha, CO2 or nitrogen)



Arc and plasma heating can generate heat of over 7000°C through the collision of protons and electrons

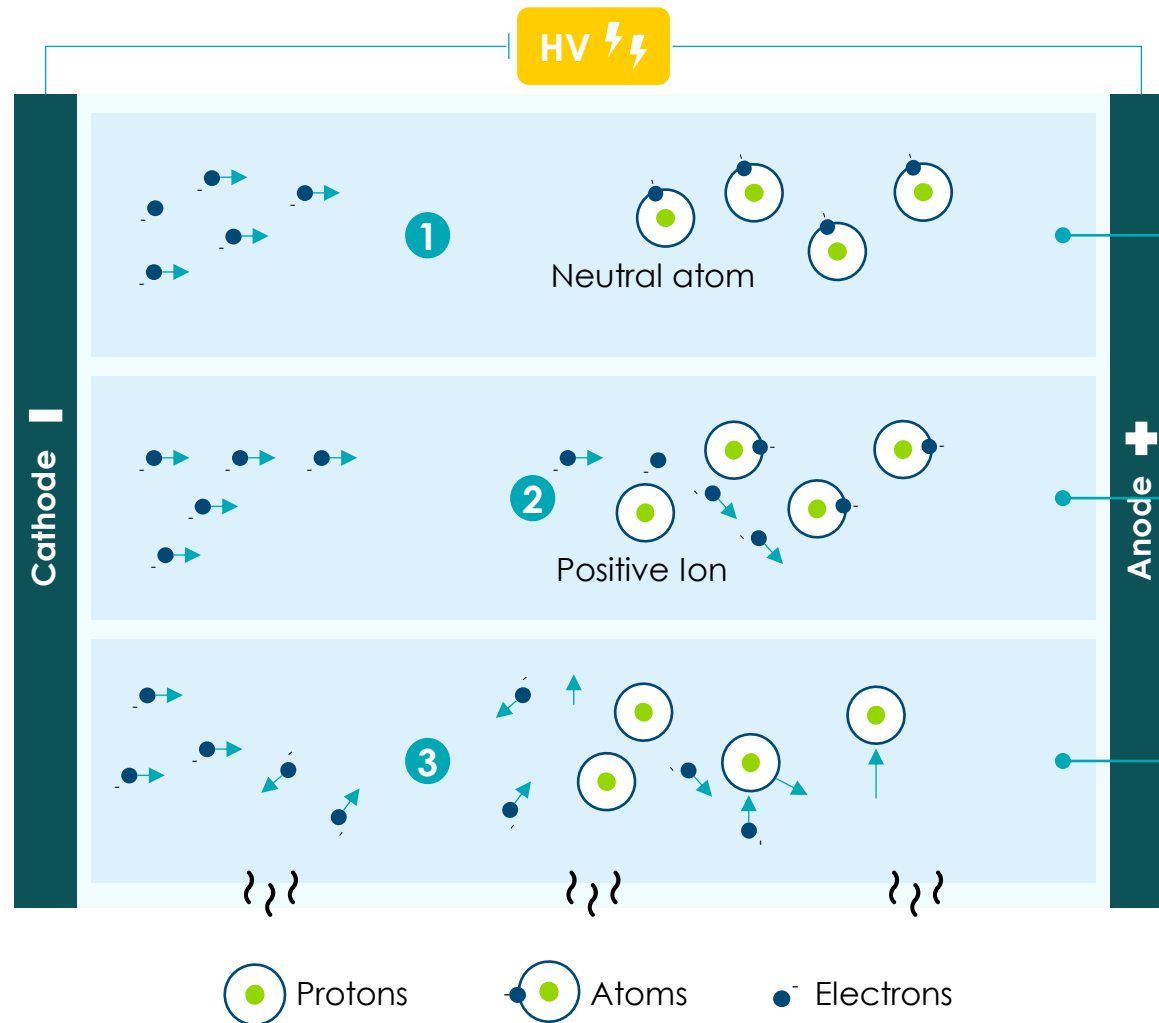
OVERVIEW OF ARC AND PLASMA HEATING

Current TRL & steps to get to TRL>7

- **Current TRL:** 7-9, 2MW up to 1500°C test facility commissioned in 2023 and already used for applications with small capacities
- **Challenges:** efficiency for the energy transfer, significant upfront investment and supply of abundant low-cost power
- **Developed by:** SaltX, Vattenfall & Dalmia Cement (CemZero)

Advantages

- **Precise temperature control** which can improve the end-product quality and energy efficiency
- **Integration potential with existing systems**, for example, retrofitting with existing pre-heater and pre-calciner system due to its modular nature



1 Accelerate electrons: High-voltage difference between the electrode and anode, creates a strong electric field across the gap. This field causes the electron to accelerate from the cathode to the anode

2 Ionise gas atoms: Fast-moving electrons collide with neutral gas atoms, transferring kinetic energy and knocking electrons out of these atoms, which turns them into positively charged ions

3 Generate heat with collision: Positive ions, electrons, and neutral atoms move rapidly and collide frequently. These forced collisions disperse kinetic energy, raising the temperature

Resistance can generate heat of over 800°C and crack hydrocarbons directly or indirectly

OVERVIEW OF RESISTANCE HEATING

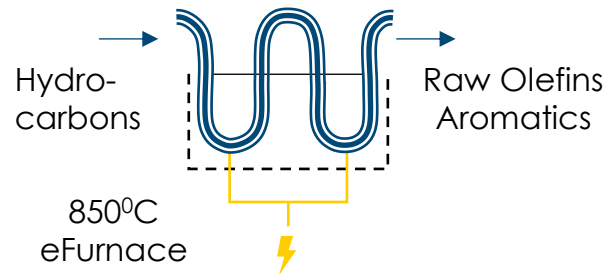
Current TRL & steps to get to TRL>7

- **Current TRL:** 7, two large-scale demonstration plant of 6MW, capable of processing 4 tons of hydrocarbons per hour in 2024.
- **Challenges:** securing supply of low-cost power
- **Developed by:** BASF, Linde & SABIC (project Starbridge); VoltaChem; Dow & Shell; BASF, Borealis, BP, LyondellBasel, Sabic and Total (Crackers of the Future)

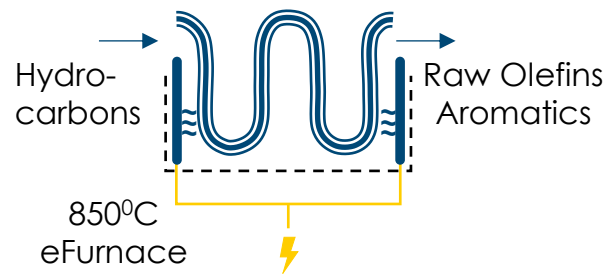
Advantages

- **Integrated into existing installations** reducing the need for entirely new facility
- **Improved energy efficiency** as requires only about 95% of the energy demand compared to fossil fuel crackers (absence of flue gas losses, no need for superheating)

Direct Heating



Indirect Heating



- 1 **Tube heating:** Tubes with the chemical feedstock (e.g., naphtha) (or in the indirect method a conductive material) are connected to electrodes, where electrical currents cause electron-atom collisions in the metal. These collisions generate vibrations, raising the tube temperature.
- 2 **Hydrocarbon heating of hydrocarbons**
Thermal energy from the heated metal tubes is transferred to hydrocarbons at the tube's inner surface through collisions, increasing the kinetic energy of the hydrocarbons as they interact with the hot tube and each other.
- 3 **Bond breaking / cracking:** When hydrocarbons absorb enough energy (around 850°C), the increased molecular vibrations break carbon-carbon bonds, initiating the cracking process to produce smaller molecules like ethylene.



The economics, technological readiness and operational implications will define the adoptability of different industrial heat technologies

Key barriers



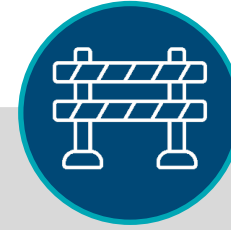
ECONOMICAL

- **CAPEX:** The upfront costs or retrofitting existing installation are significantly higher than other low-carbon alternative
- **Electricity costs:** Electricity price have to compete with low-cost fossil fuel costs + CCS, especially for the continuous, high-power demand of high temperature processes



TECHNICAL

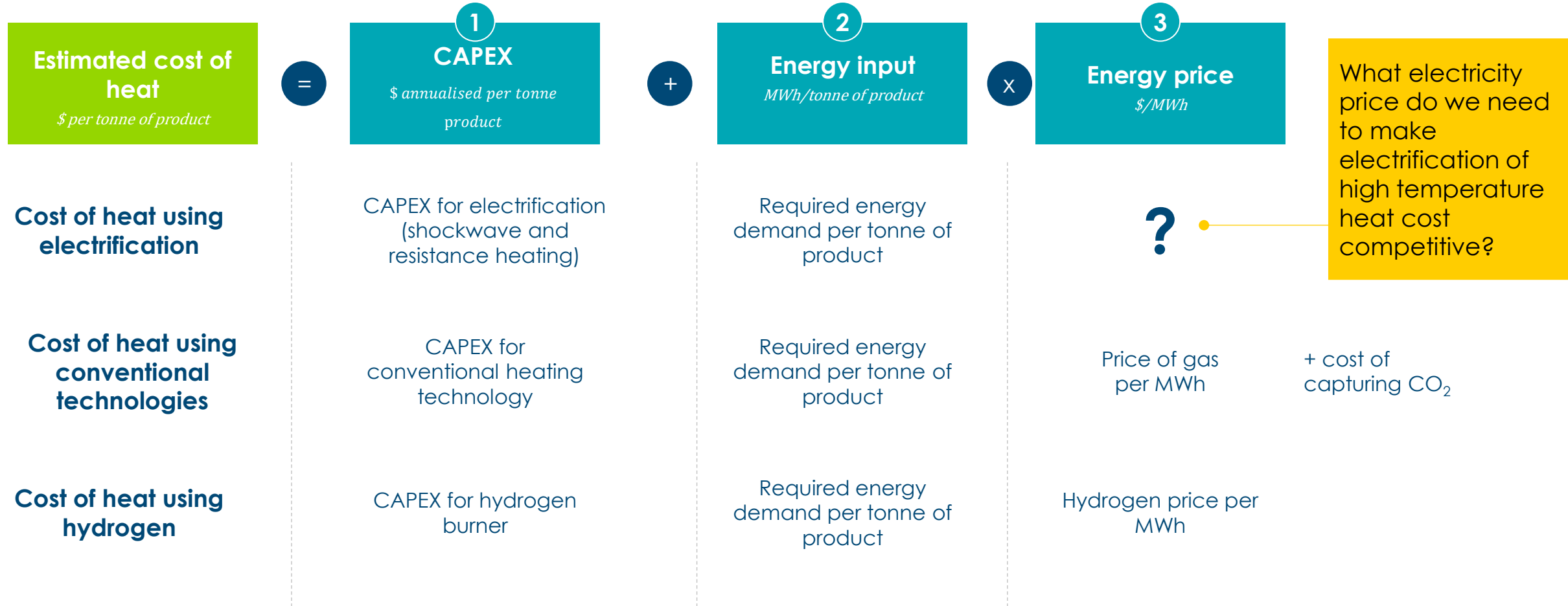
- **High temperatures:** Efficiently reaching and maintaining the temperatures
- **Heat resistant materials:** Developing materials that can reliably withstand the extreme temperatures over long operational lifetimes



ORGANISATIONAL

- **Firm 24/7 clean power source:** the energy-intensive process cannot be easily ramped up and down without significant losses
- **Integration with existing equipment:** it can be challenging to install the new equipment with the current infrastructure

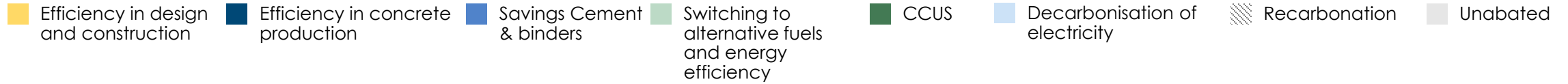
[Analysis focus] At which electricity price is high temperature heating cost efficient?



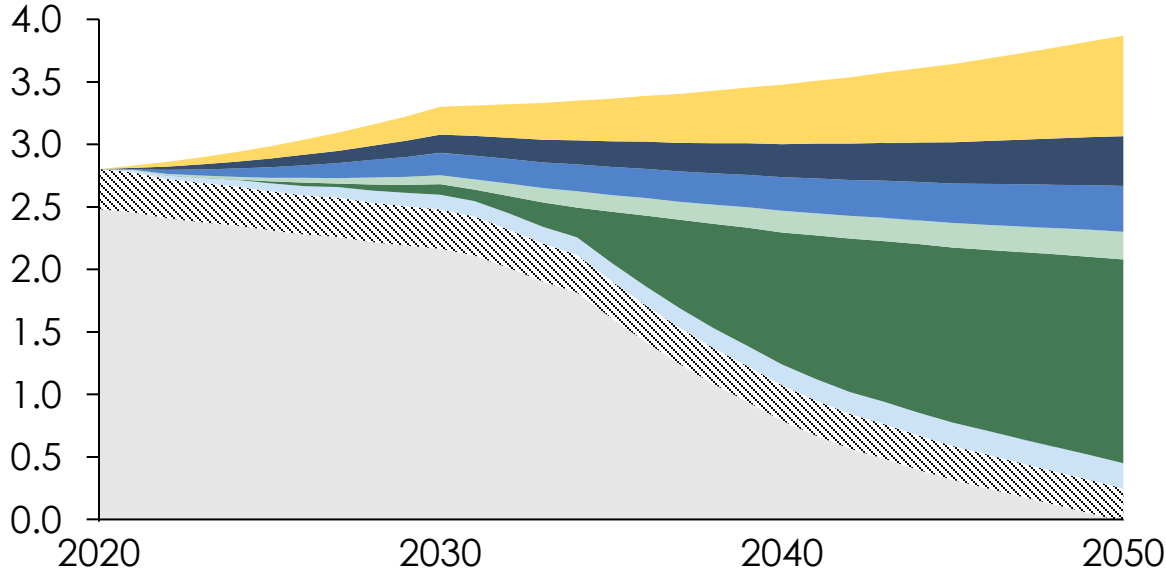
Cement – a use case for industrial heat



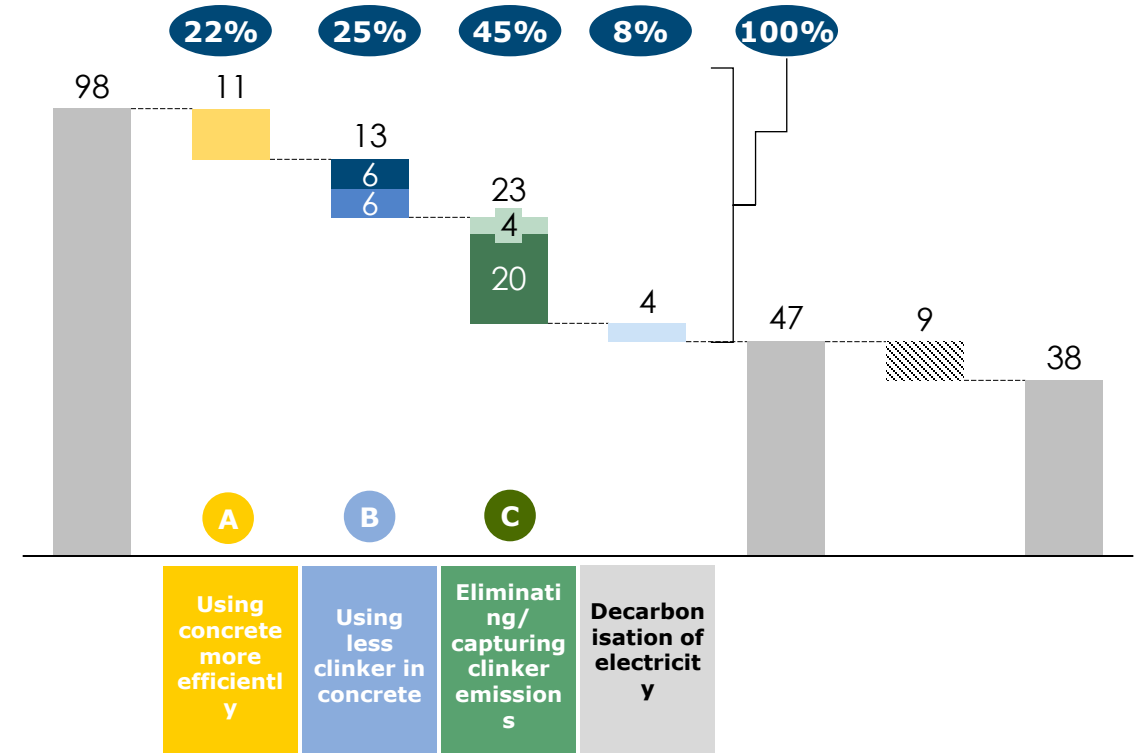
In cement, our FFIT scenarios did not include electrification technologies but 45% of the emissions reductions were reliant on CCS



Annual GHG emissions¹, in Gt CO₂



Cumulative GHG emissions between 2022 and 2050, in Gt CO₂



Notes: Includes scope 1 and 2 emissions. Scope 3 upstream would add approximately 3.8 Gt CO₂e of cumulative emissions from 2022 to 2050. "Savings and binders" include switching to new binders. Decarbonisation of electricity involves electricity demand for kilns, grinders and carbon capture. Source: MPP (2024). Making net zero Concrete & Cement possible



Recap: Shock wave heating can create up to 1,700°C through supersonic accelerations converting kinetic energy into heat

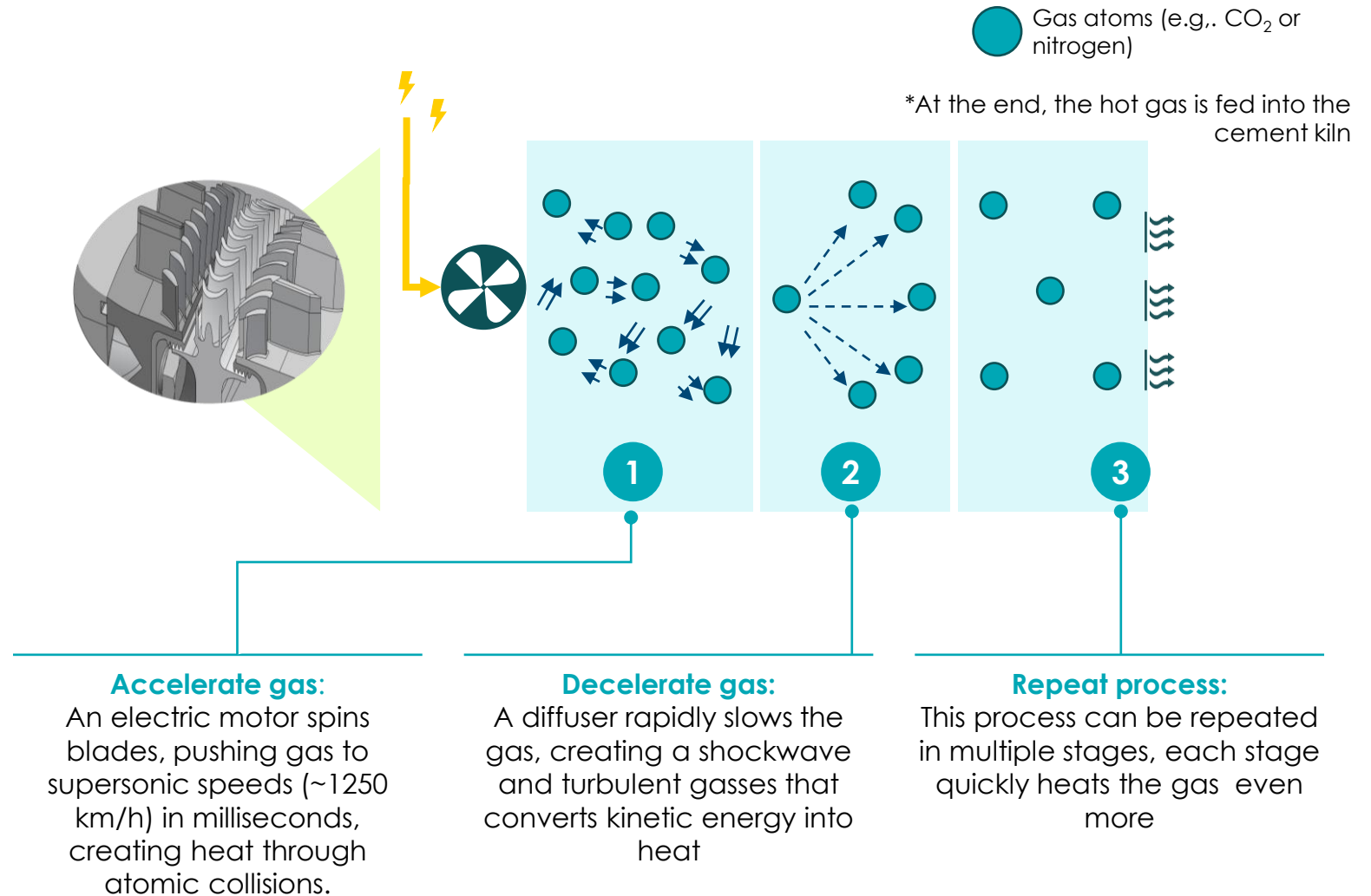
OVERVIEW OF SHOCK WAVE HEATING

Current TRL & steps to get to TRL>7

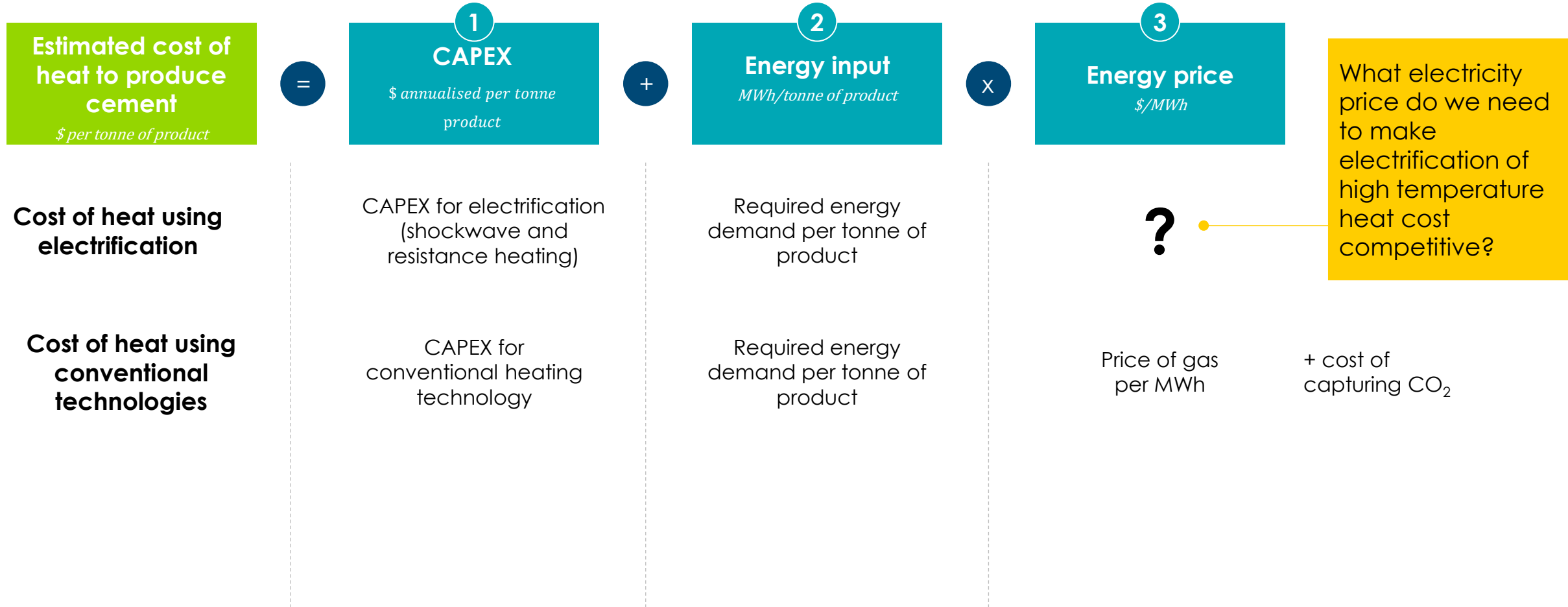
- **Current TRL:** 6-7, launched a 0.8 MW pilot plant and completed testing for ~1000 °C. Plan to deploy 5-10 MW plants in 2025
- **Challenges:** significant upfront investment and complex integration with existing plants
- **Developed by:** Coolbrook, partnership with Shell, Ultratech, Cemex, ArcelorMittal, JSW and more

Advantages

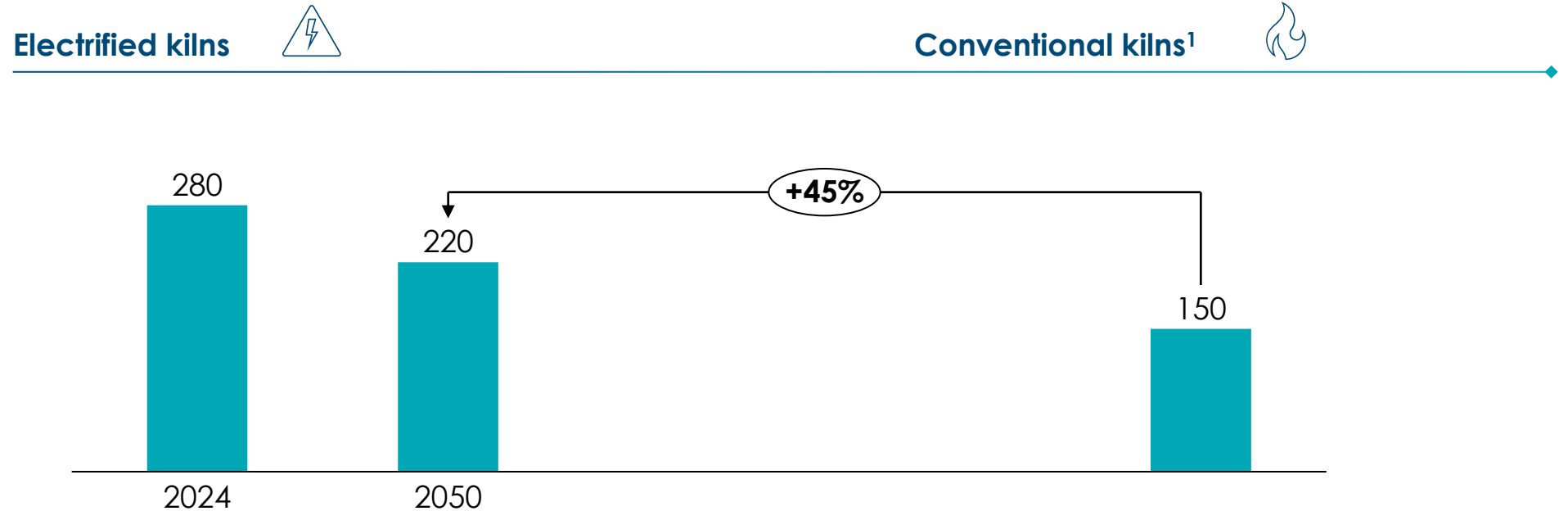
- **Uniform high-temperature distribution** (up to 1,500-1,700°C) for high-quality production
- **High energy efficiency** of +90% as the rotational mechanism maximizes heat retention, minimizing energy loss and waste
- **Integration into existing production lines** with relative ease enabling retrofit of facilities



[Recap] At which electricity price is high temperature heating cost efficient?



1 Preliminary estimates suggest that the CAPEX of electrified kilns would be ~45% higher than conventional gas burner



CAPEX
\$/t cement



Rationale

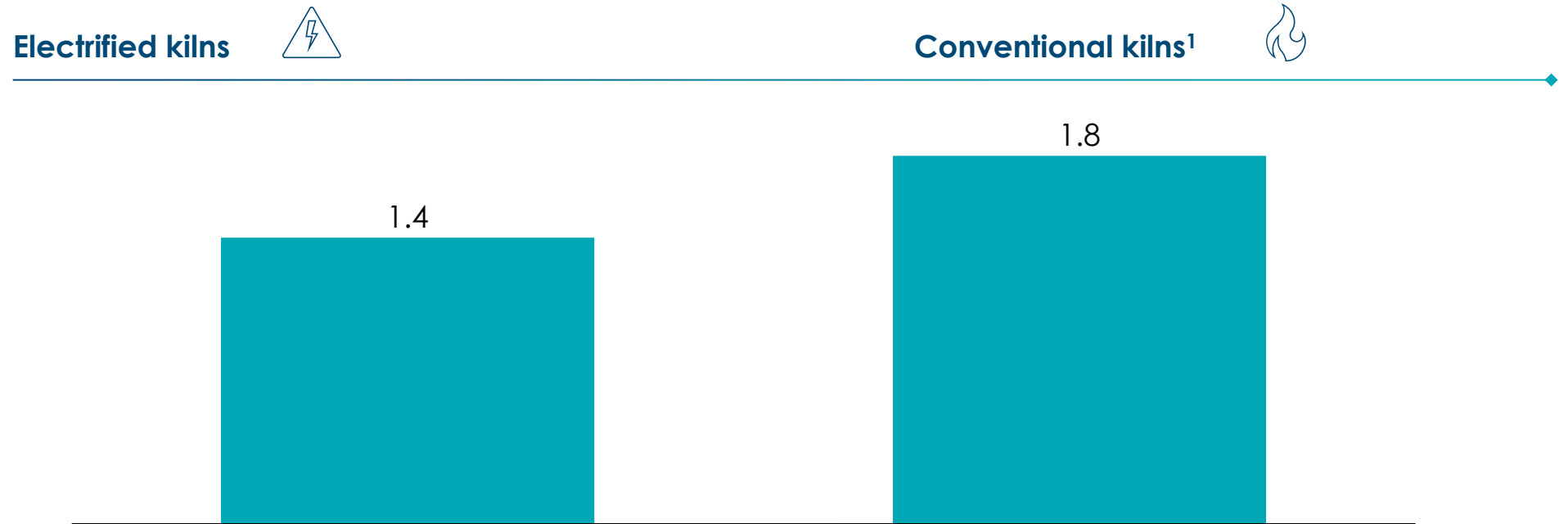


- Fossil alternative capex optimized and used widely across the industry, whereas electrification technology still nascent
- High temperature electrification technologies require use of durable materials that can withstand the conditions of the electrified kiln

1. CCU/S will be added as variable cost

Sources: BloombergNEF (2024), Cement Production Valuation Model. Parra (2023). Decarbonisation of cement production by electrification.

2 Early estimates suggest that the energy consumption of electrified kilns could be lower than other options



Energy consumption
(MWh/t cement)



Rationale

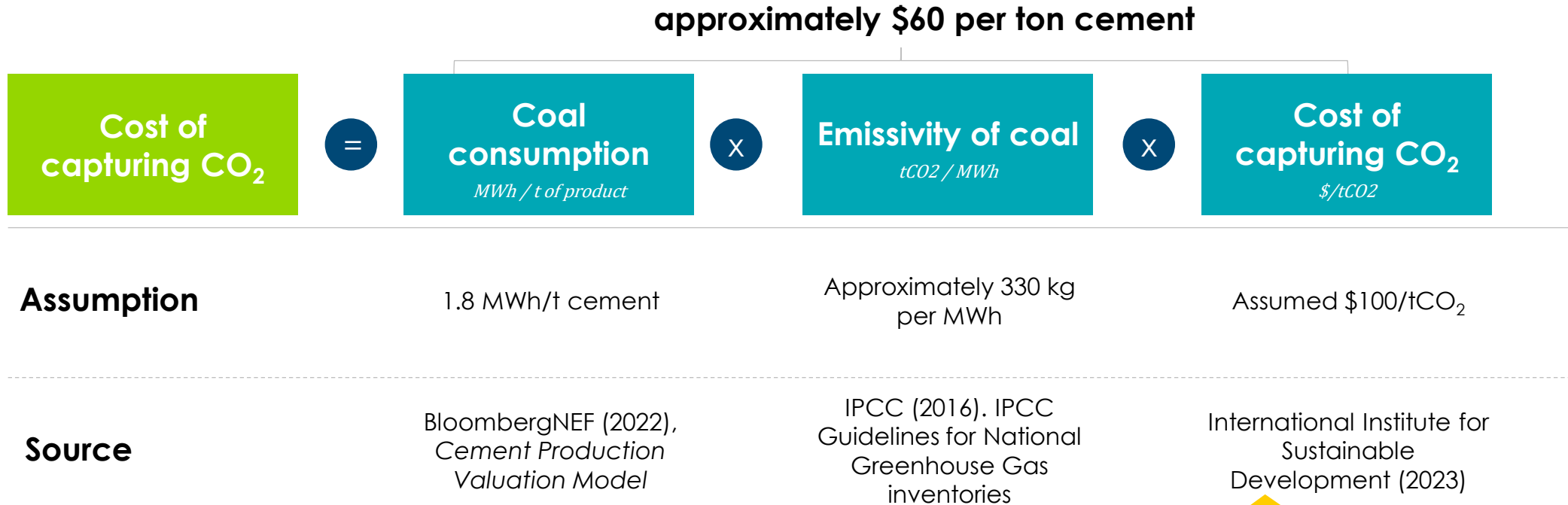


- Electrification technology can heat materials directly, avoiding inefficiencies that come with combustion of fossil
- Relative to conventional gas burners, they can also allow for more fast and precise temperature control

1. CCU/S will be added as variable cost

Sources: BloombergNEF (2024), *Cement Production Valuation Model*; [Parra](#) (2023). *Decarbonisation of cement production by electrification*.

3 The cost of CCU/S will add around \$60 per ton of cement to the conventional kiln



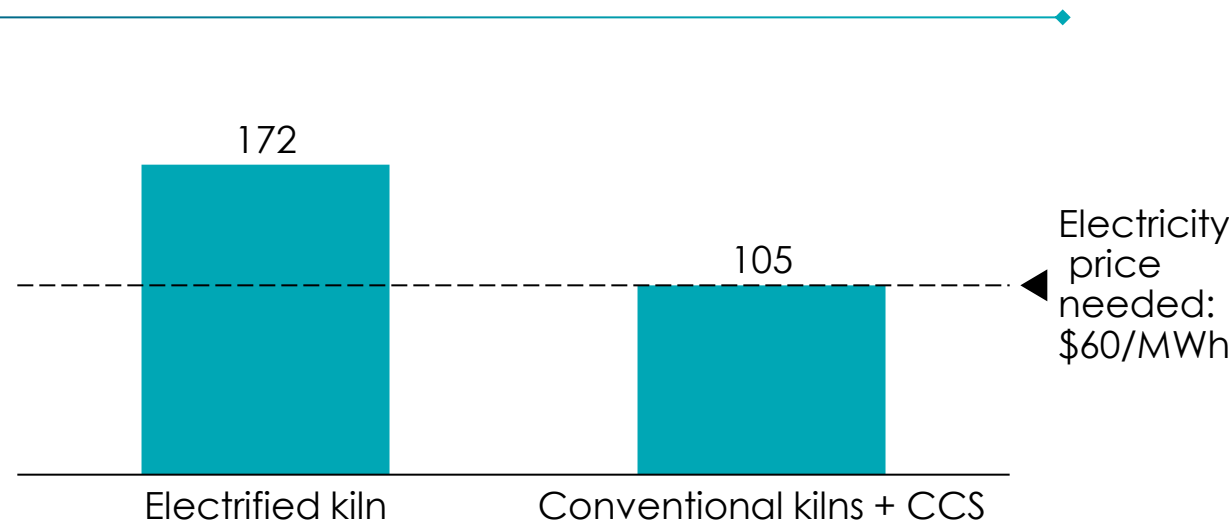
Cement's process emissions must be captured regardless of electrification but are excluded here as they impact both sides equally¹



1. Capturing cement process emissions is cheaper with electrification due to higher CO₂ concentration.
Source: BloombergNEF (2024), *Cement Production Valuation Model*; IPCC (2016). *IPCC Guidelines for National Greenhouse Gas inventories*

Switch to electric kilns could already be cost competitive with an electricity price of \$60/MWh

Levelised cost of heat in cement production by 2050, \$/t cement



Key outputs

Capex annualised ¹	\$22/t	\$15/t
Energy cost + CCU/S cost	\$150/t	\$30/t and \$60/t
Total	\$172/t	\$105

Key inputs

CAPEX	\$220/t	\$150/t
Energy requirements	1.4 MWh/t	1.8 MWh/t
Energy price and CCU/S cost	\$110/MWh (Assumed grid price in China 2050)	\$17/MWh and \$60/t

Notes: 1. Annualised over 10 years
Sources: BloombergNEF (2023). Cement production Valuation Model

A disruption of electric kilns could replace fossil fuels in the cement-making process, raising electricity needs from 2EJ to 7EJ

What we need to believe in

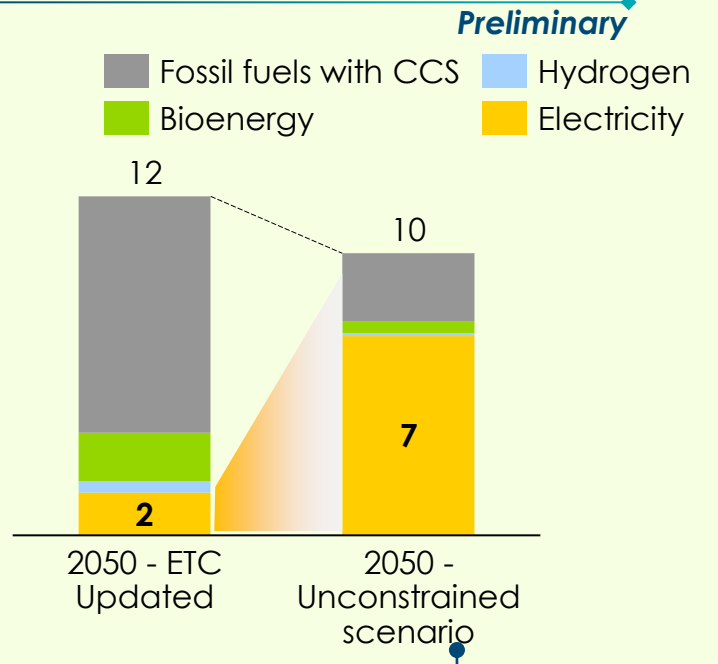
	Today	2050
TLR	5-6	9 (in 2035)

Electricity price to be competitive in China in 2050 (\$/MWh)	110	80
--	-----	----

- Barriers mitigated**
- High temperature requirements
 - Pilot testing and scaling up
 - Cost-competitive power prices

- Latest developments**
- In 2023, **COOLBROOK®** successfully completed test of 1000 C
 - **SaltX** working on an electric arc calciner
 - Several MoU with steel and cement producers (**CEMEX** , **UltraTech** , **Dalmia cement**) to electrify the manufacturing process

Impact on energy demand, EJ per year



Key assumption for the unconstrained scenario: Non-electrified cement kilns are replaced by electrified kilns after 2035



Note: Company websites
Sources: Mission Possible Partnership (2024) Making net zero Concrete and Cement Possible; Internal analysis

Electrical steam cracking – utilising industrial heat technology

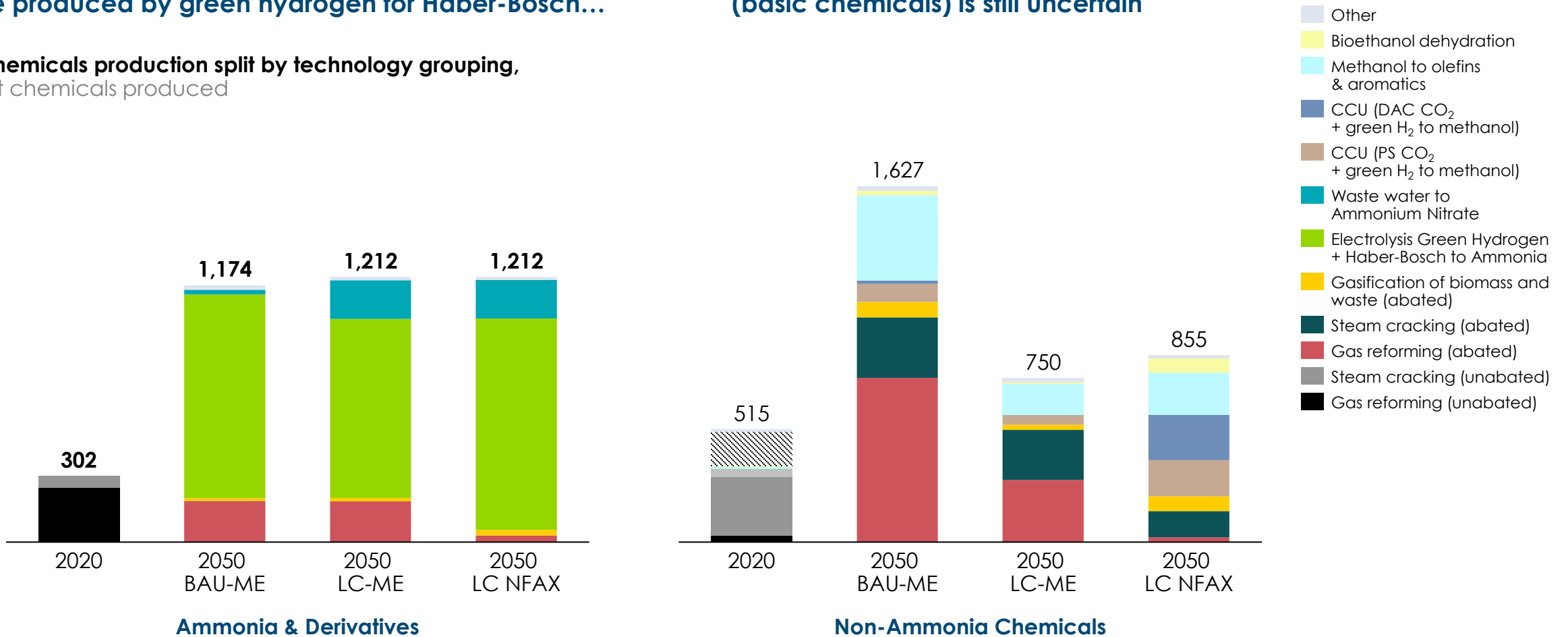


Ammonia's decarbonization route is clear, but for basic chemicals, it still much depends on the specific scenario

All previous scenarios shows that ammonia will likely be produced by green hydrogen for Haber-Bosch...

...While the future of olefins and aromatics (basic chemicals) is still uncertain

Chemicals production split by technology grouping,
Mt chemicals produced



Source: [Systemiq & Center for Global Commons](#) (2022). Planet Positive Chemicals



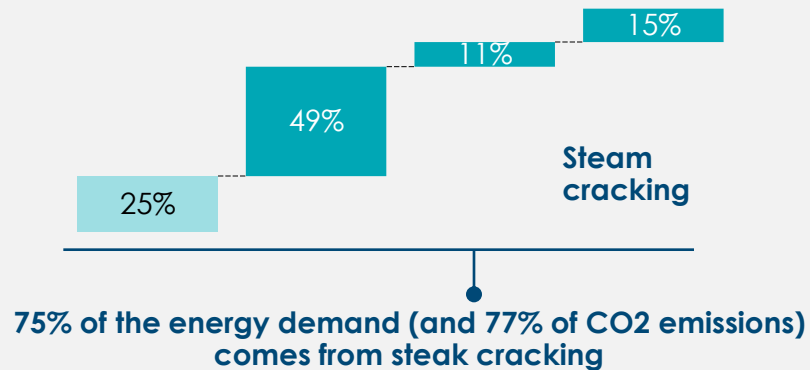
Majority of emissions in basic chemical production come from cracking, where electrification offers a solution

75% of the energy demand (and 77% of CO2 emissions) for basic chemical production come from steam cracking

Steps in primary chemicals production



Energy consumption, %



Electrification is one of the solutions to decarbonize the cracking process

Technology

CO₂ reduction potential for steam cracking process

Decarbonizing heating of crackers

- Electrification 97%
- Hydrogen firing 97%
- CCU/S² 97%

Decarbonise feedstock

- Substitute with chemical recycling (pyrolysis oil) 94%
- Substitute with Bio-naphtha 100%



Notes: 1. CCU/S = Carbon Capture Usage / Storage
Sources: BloombergNEF (2022), Decarbonising petrochemicals

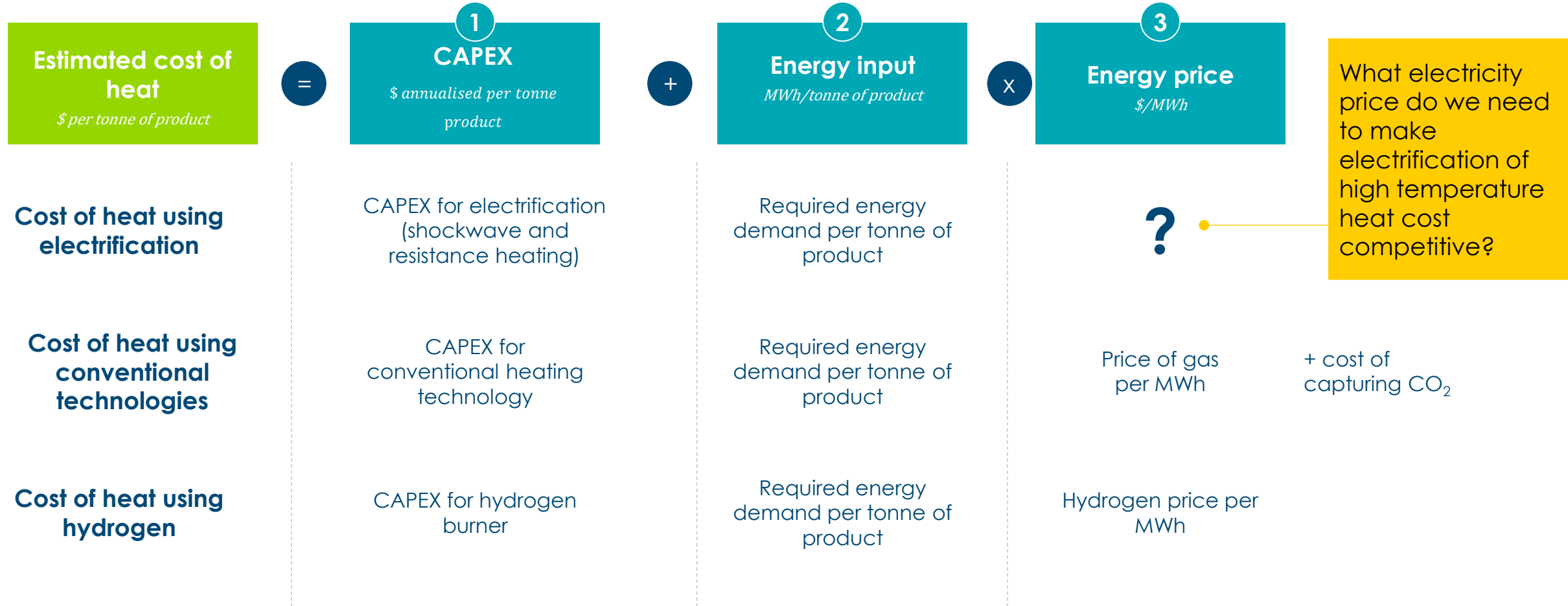
Electric crackers could use shock-wave and resistance heating technologies to electrify basic chemicals

Technology ¹	Process	Sectors ²	TRL	Energy Efficiency	Company <i>Non-exhaustive examples</i>
Shock-wave heating	Rotation turbines employ an electric motor to spin blades and gas , where supersonic speed and rapid deceleration creates a shock-wave and turbulent gas, which generates high temperature heat	Cement, chemicals, steel, aluminum, other industry (glass)	6-7	50-95%	
Arc and plasma heating	Two electrodes connected to a high-voltage power supply create an electric field that ionises the air, forming a plasma with electrons and positively charged particles . The applied electric field causes the ionized gas molecules to oscillate to generate heat	Cement, Steel, other industry (Machinery, transport equipment)	3-9	50-90%	
Resistance	An electric current passes through resistive elements , causing electrons to collide with the atoms of the material, converting electrical energy into heat, the heat is then transferred by gas through convection or through radiation	Steel, aluminum, chemicals, other industry (glass, machinery, transport equipment)	6-9	50-95%	
Microwave	Electricity powers a microwave generator , producing microwaves that cause molecules (especially water or other polar materials) to oscillate , generating collisions and with that heat.	Steel (sintering), other industry (e.g., ceramics)	Unsure	50-85%	
Induction	High-frequency current passes through an induction coil (e.g., copper), creating a magnetic field . This process generates induced force and produces heat because of the electrical collisions in the material.	Steel, aluminum, other industry (machinery, glass, minerals, transport)	7-9	50-90%	

Note: 1. Only includes the sectors where a technology can electrify a high temperature processes; 2. Other technologies can be implemented for industry electrification, e.g. ultraviolet (UV), infrared, thermoelectric cooling, electron beam, and laser heating but have a narrow field of application
 Source: [Silvia Madeddu \(2020\)](#), The CO₂ reduction potential for the European industry via direct electrification of heat supply. [Fraunhofer ISI \(2024\)](#): Direct electrification of industrial process heat. An assessment of technologies, potentials and future prospects for the EU. Study on behalf of Agora Industry.

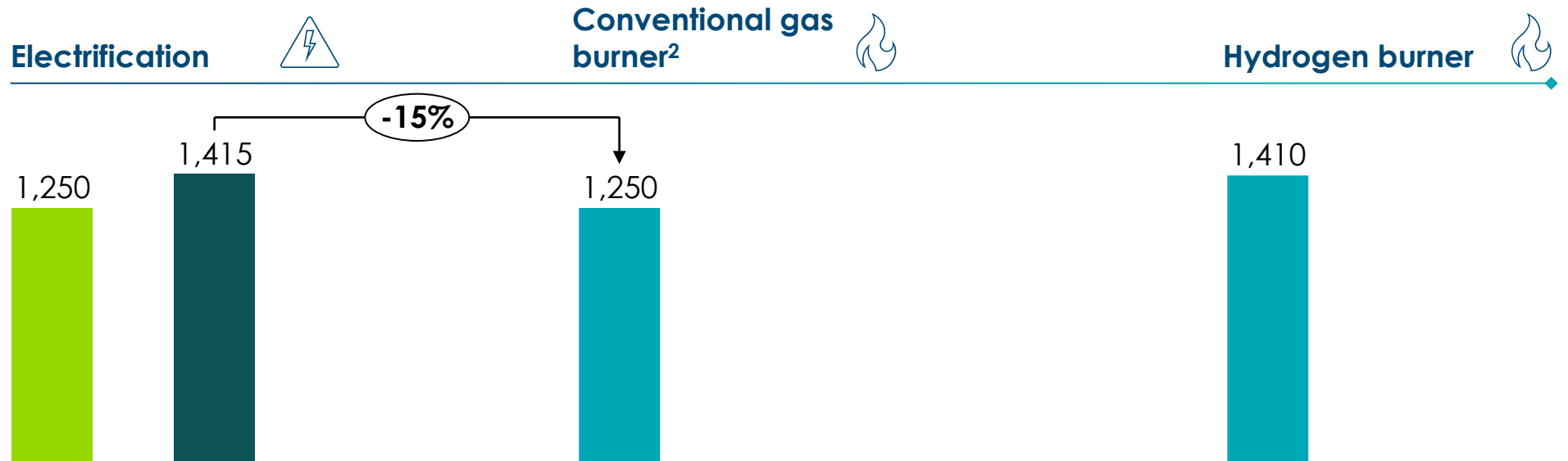


[Analysis focus] At which electricity price is high temperature heating cost efficient?



1 Preliminary estimates suggest that the CAPEX of electrification technologies could be within a 15% range of other low-carbon alternatives

Shockwave Resistance



CAPEX/t HVC¹
(in 2050)

Rationale

- Shockwave electrification is equal to conventional burner costs as higher furnace costs are offset with reduced downstream equipment
- Resistance heating costs are 10–15% higher, amongst other, due to large space needs for bigger applications

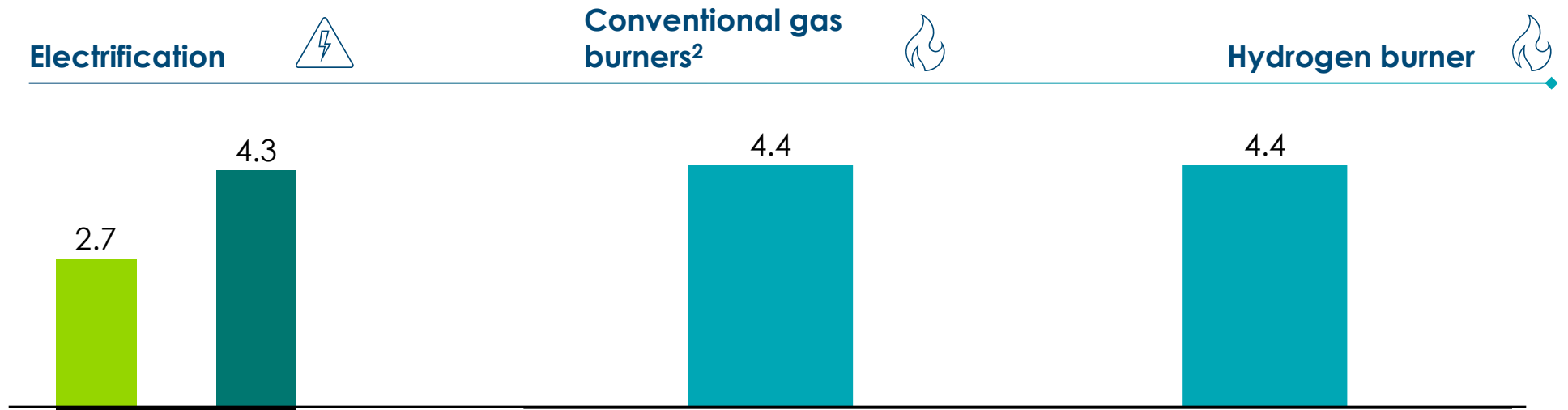
- Values based on SABIC Geleen Plant in EU
- No capex assumed for the required CCU/S, only included as OPEX later in the analysis

- Capex is higher than conventional gas burners due to added hydrogen pipelines, compressors, furnace adjustments, and NOx abatement equipment.

Notes: 1. High value chemical; All values are based on a case example for a Naphtha cracker to produce Ethylene. 2. Input price for gas will include CCU/S
Sources: BloombergNEF (2022), *Decarbonising petrochemicals*.

2 Early estimates suggest that the energy consumption of electrification technologies could be lower than other solutions

Shockwave Resistance



- E-crackers enhance heat control, reducing losses
- Shockwave technology improves yield, requiring less naphtha and increasing energy efficiency
- No additional energy consumption assumed for the required CCU/S, only included as OPEX later in the analysis
- Assumed similar as conventional gas burners

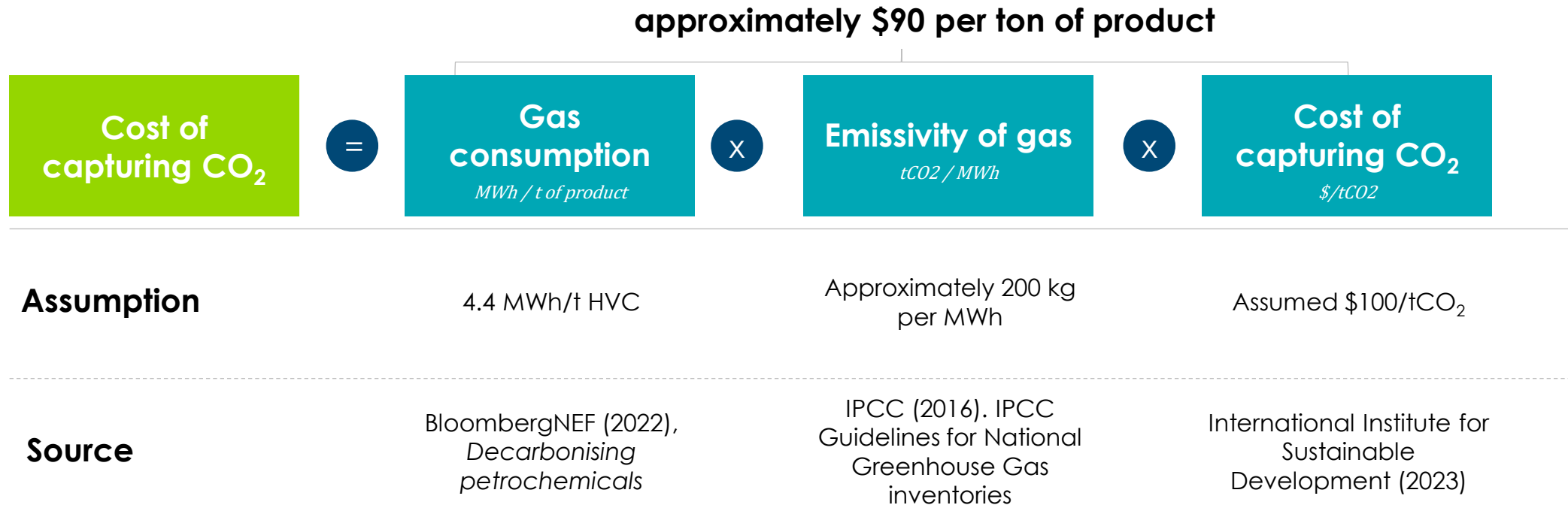
Energy consumption (MWh/t HVC¹)

Rationale

Notes: 1. High value chemical; All values are based on a case example for a Naphtha cracker to produce Ethylene. 2. Input price for gas will include CCU/S
 Sources: BloombergNEF (2022), Decarbonising petrochemicals. [Center for Global Commons & Systemiq](#) (2022), Planet Positive Chemicals.



3 The cost of CCU/S will add around \$90 per ton of product to the gas costs

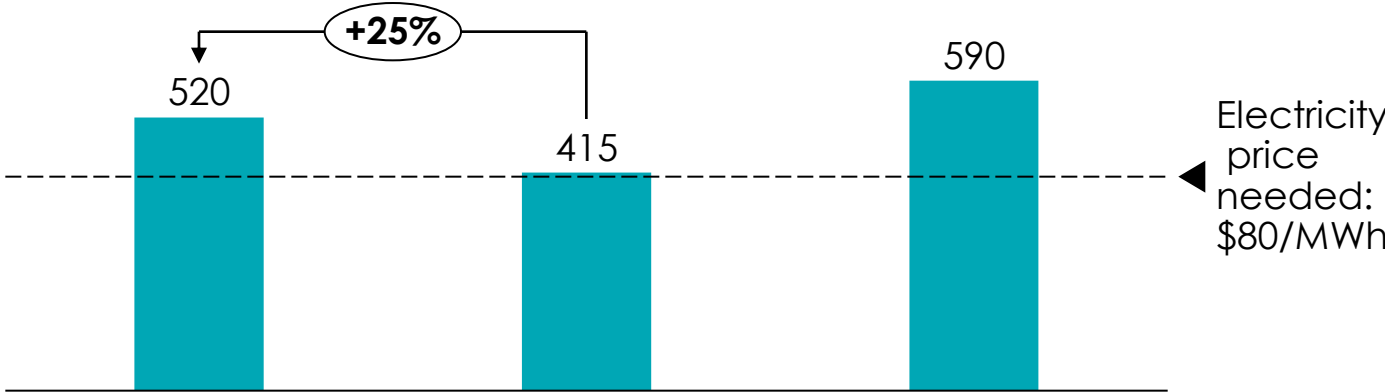


Source: IPCC (2016). *IPCC Guidelines for National Greenhouse Gas inventories*. International Institute for Sustainable Development (2023) *Why the Cost of Carbon Capture and Storage Remains Persistently High*



Switch to e-crackers could already be cost competitive with an electricity price of \$80/MWh

Levelised cost of heat in ethylene production in 2050, \$/t ethylene



Key outputs

	e-cracker	Fossil + CCS	H2 cracker
Capex annualized ¹	\$135/t	\$125/t	\$140/t
Energy cost + CCU/S cost	\$385/t	\$200/t + \$90/t	\$450/t
Total	\$520/t	\$415/t	\$590

Key inputs

CAPEX	\$1335/t ²	\$1255/t	\$1405/t
Energy requirements	3.5 MWh/t ²	4.4 MWh/t	4.4 MWh/t
Energy and CCU/S cost	\$110/MWh	\$45/MWh and \$90/t	\$102/MWh ³

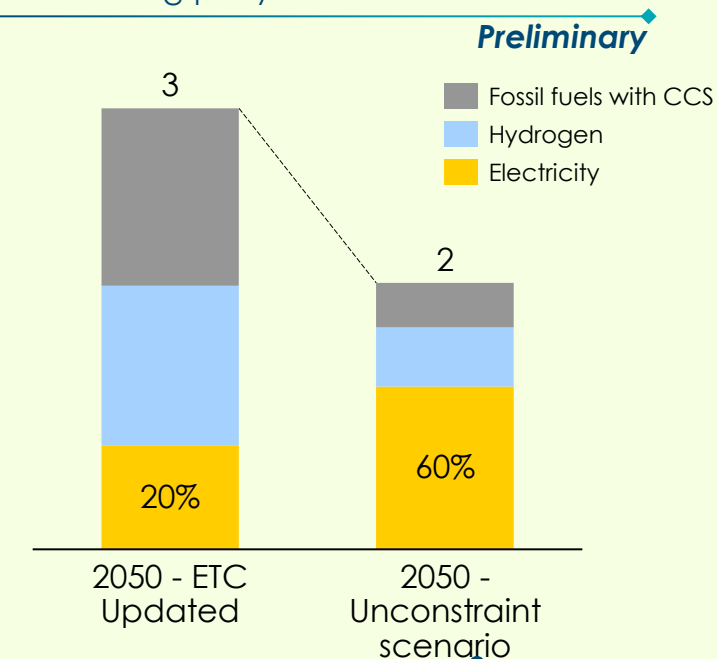
Notes: 1. Assumed over 10 years. 2. Average over different electrification technologies; 3. around \$3/kg H₂
 Sources: [Center for Global Commons & Systemiq](#) (2022), Planet Positive Chemicals. BloombergNEF (2022), Decarbonising petrochemicals

A disruption of electric crackers could significantly increase the relative proportion of electricity in the steam cracking process

What we need to believe in

	Today	2050
TLR	6-7	9 (in 2040)
Electricity price to be competitive in 2050 (\$/MWh)	90	80
Barriers mitigated	<ul style="list-style-type: none"> Proving high temperature heat at 850°C on a commercial scale Sufficient cost-competitive power Improving the business case (lower CAPEX and competitive power prices) 	
Latest developments	<ul style="list-style-type: none"> BASF is testing two 3 MW electric steam crackers, funded with €15 mln from the German government Dow and Shell secured Dutch government funding for an electric cracker Technip Energies, LyondellBasell, and Chevron plan an electric cracker at LyondellBasell's Texas facility 	






Impact on energy demand for basic chemicals (not including feedstock), EJ for cracking per year



Key assumption for the unconstraint scenario:

Fossil steam crackers are replaced by electric crackers after 2035

Electrification of high temperature heat, with competitive energy prices, could shift the industrial sectors towards electrification

Final energy demand type 	Impact on energy demand by 2050 
Electrification	 <p>Cost-competitive electricity (\$60-\$80 MWh) and technological advances could increase demand for electrons to power electric applications for the industrial sector</p>
Final hydrogen use/e-ammonia	 <p>Electrification of high temperature heat may reduce H₂ demand for H₂-based solutions.</p>
Carbon based fuels (e-SAF, methanol, fossil with and without CCS)	 <p>Could displace reliance on fossil + CCS alternatives for decarbonization</p>

Key questions/considerations

- High temperature heating technologies are advancing, bringing them closer to commercial readiness
- They may be less capital-intensive than other decarbonization options
- Also, high temperature industrial electrification solutions offer better energy efficiency than alternatives
- However, the business case for electrification of heat remains sensitive to fossil fuel prices



For discussion: what electricity prices might be feasible?

What electricity prices might be possible to enable industrial heat technology



- 1** If we need a constant power source, what is average prices can we expected from the grid?
- 2** What electricity prices are we currently seeing for around the clock renewable (e.g., \$50/MWh in India) and could this be brought down?
- 3** Should we focus on grid at low prices or dedicated solar? Can these technologies run flexibly when electricity prices are cheap?

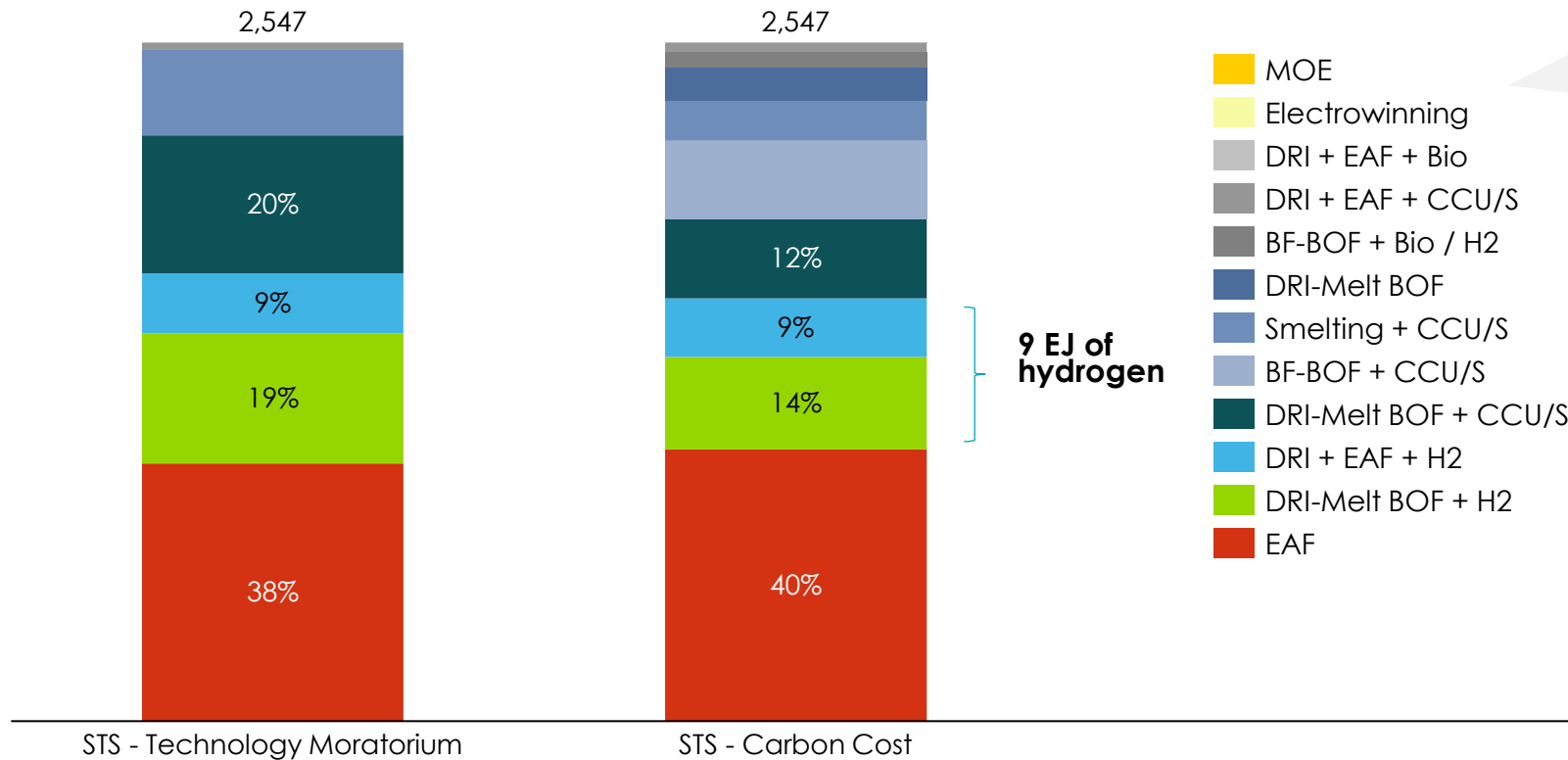


Electrification of iron-making



Previous iron and steel decarbonisation scenario shows no uptake of MOE and electrowinning before 2050 (and high percentage H₂)

Global technology mix for steel making in 2050, Mt steel



- MOE
- Electrowinning
- DRI + EAF + Bio
- DRI + EAF + CCU/S
- BF-BOF + Bio / H₂
- DRI-Melt BOF
- Smelting + CCU/S
- BF-BOF + CCU/S
- DRI-Melt BOF + CCU/S
- DRI + EAF + H₂
- DRI-Melt BOF + H₂
- EAF








MOE and electrowinning were included in the STS, but the business cases did not support any uptake by 2050

9 EJ of hydrogen



Source: [Mission Possible Partnership](#) (2022), Making Net-Zero Steel Possible

Electrowinning and Molten Oxide Electrolysis (MOE) could potentially disrupt the iron-making process

Technology	Process	TRL	Energy Efficiency	Company <i>Illustrative examples</i>
Molten Oxide Electrolysis (high temperature electrolysis)	<ul style="list-style-type: none"> • Dissolved iron ore: Iron ore (Fe_2O_3) is liquified by the heat of a molten oxide-based electrolyte bath (e.g., silicon oxide) of around 1600°C • Electrolysis : A current is passed through the molten electrolysis causing the iron ore to break down into Fe^{3+} ions, where the Fe^3 ions move towards the cathode, gain an electron and form iron and oxygen is released at the anode • Accumulation: The iron is tapped at the bottom as a liquid metal 	5	20% more efficient¹	 
Electrowinning (low temperature electrolysis)	<ul style="list-style-type: none"> • Suspension of iron ore: Iron ore (Fe_2O_3) is suspended in an alkaline sodium hydroxide solutions at about 100-110°C. • Ion movement: A current passes through the solution, the iron ions are attracted to the cathode, where electrons reduce the ions to iron. Afterwards, the iron is fed into the EAF¹ with a small amount of coke to make liquid crude steel. 	4-5	25% more efficient¹	    

Notes: 1. More efficient than the low-carbon alternative, in this example: Direct Reduced Iron and Electric Arc Furnace (DRI-EAF)
 Source: [ARENA](#) (2024). Fortescue – low temperature direct electrochemical reduction for zero emissions iron. [Agora Industry](#) (2024), Low-carbon technologies for the global steel transformation. [The Chemical Engineer](#) (2024). Boston Metals' electrified process starts extracting valuable metals from mining slag. [Carbon Commentary](#) (2023). Decarbonising steel: hydrogen or metal oxide electrolysis. [Fast company](#) (2024). This Boston startup wants to make the steel industry go green. [IEA](#) (2024), ETP Clean Energy Technology Guide. [Recycling Today](#) (2024). Electra launches pilot plant for low-carbon iron production. [INO](#) (2020). Low temperature electrowinning for steelmaking;



Molten Oxide Electrolysis (MOE) offers a one-step solutions to produce low-carbon iron, cutting multiple steps

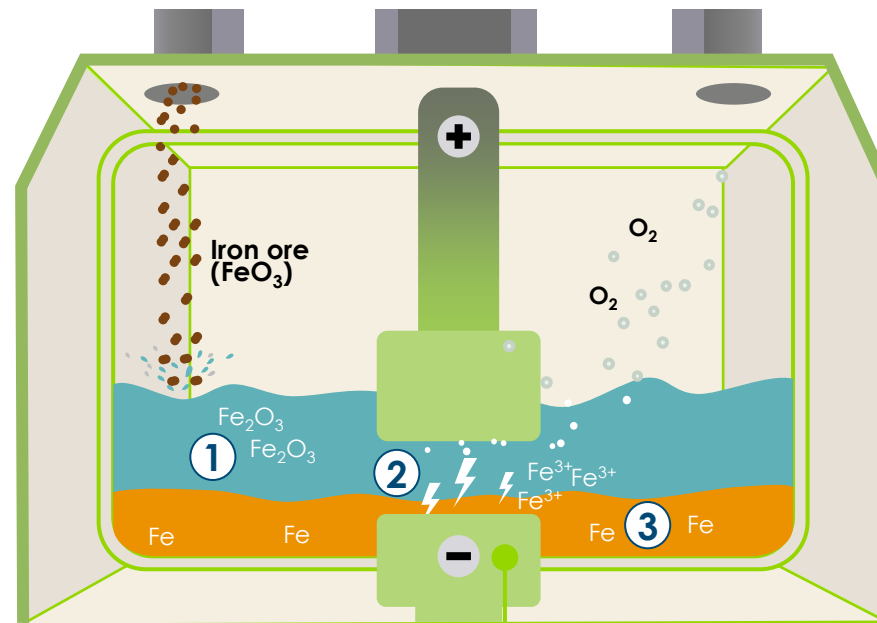
OVERVIEW OF MOLTEN OXIDE ELECTROLYSIS (MOE)

Current status

- **TRL:** 5, producing tens of kg (scaling up 25 kt this year)
- **Challenges:** managing 1600°C temperatures, corrosion, and heat distribution
- **Developed by:** Boston Metal & MIT (raised \$370 million to date, including from Arcelor Mittal)

Advantages

- **Modular:** Each module is bus-sized, allowing scalable expansion by adding more units
- **Not feedstock restrictive:** Capable of processing various grades of iron ore but impact of higher gangue¹ contents on efficiency is unclear
- **Does not require additional EAF unit:** as the iron product is melted already in this production step



1 Dissolved iron ore: Iron ore (Fe₂O₃) is liquified by the heat of a molten oxide-based (e.g., silicon oxide) electrolyte bath of around 1600°C

2 Electrolysis to iron: A current is passed through the molten electrolyte, causing the iron ore to break down into Fe³⁺ ion, where the Fe³⁺ ions move towards the cathode and gain an electron and form iron

3 Electrolysis: The iron is tapped at the bottom as a liquid metal

Notes: 1 Gangue materials are impurities in the iron ore (e.g., silicates, alumina)

Sources: [Carbon Commentary](#) (2023). Decarbonising steel: hydrogen or metal oxide electrolysis. [Fast company](#) (2024). This Boston startup wants to make the steel industry go green. [MIT](#) (2024). Making steel with electricity

Electrowinning offers an alternative decarbonization method to convert iron ores to iron with low temperature electrolysis

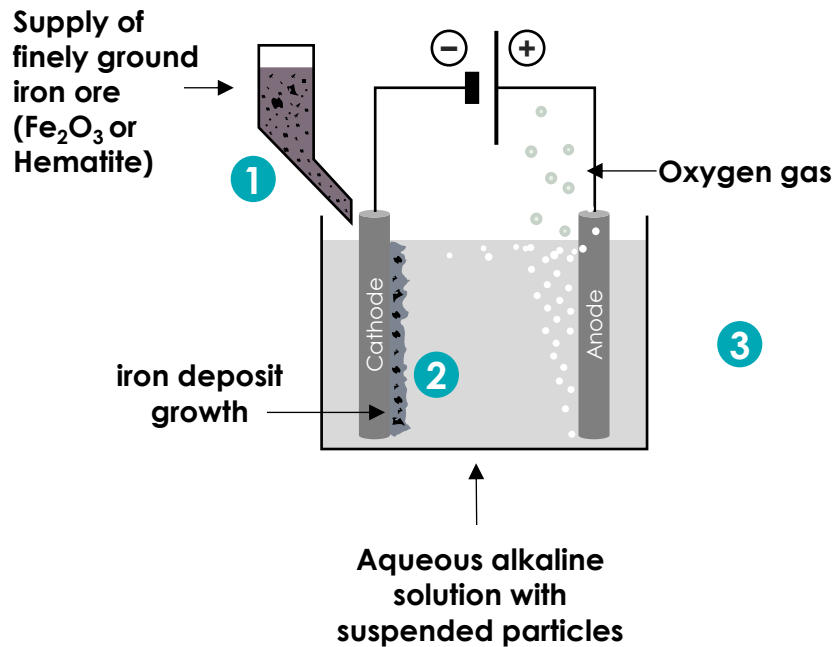
OVERVIEW OF ELECTROWINNING (Alkaline Iron Electrolysis)

Current status

- **TRL:** 4-5, 40-80 kt steel/year plant will start production in 2027
- **Challenges:** low-cost power supply, managing waste products, corrosion
- **Developed by:** John Cockerill & ArcelorMittal's Volteron (Siderwin previously), Electra (raised \$85 million to date)

Advantages

- **Flexible operations** aligned with intermittent renewables due to its low temperature operation (110 °C)
- **Separation of gangue¹ at the ironmaking stage** which makes further handling in the EAF more efficient
- **Efficiency:** potentially more efficient than DRI-EAF



1 Suspended: Iron ore (FeO_3) or Hematite is suspended in an alkaline sodium hydroxide solution at a temperature of 110°C

2 Ion movement: A current is passed through the solution Fe^{3+} to move towards the cathode and forming crystals on the surface.

3 Cathode harvesting: The cathode is removed from the electrolytic cell and the product is mechanically gathered, a process called "Cathode harvesting".

Several key technological and economical challenges need to be overcome to bring MOE and/or Electrowinning to commercial readiness

Key barriers



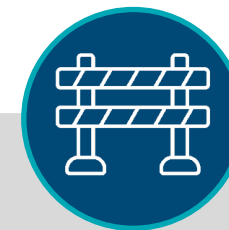
ECONOMICAL

- **CAPEX:** initial capital expenditures are significant
- **Energy cost:** Process requires large amounts of energy, and it will have to outcompete the cost for DRI-EAF and fossil + CCU/S
- **O&M:** The lifetime of the equipment should be extended to reduce O&M costs



TECHNICAL

- **Scalability:** current technologies are still in the early stages
- **Material durability:** The equipment need to withstand high temperatures and corrosive environments

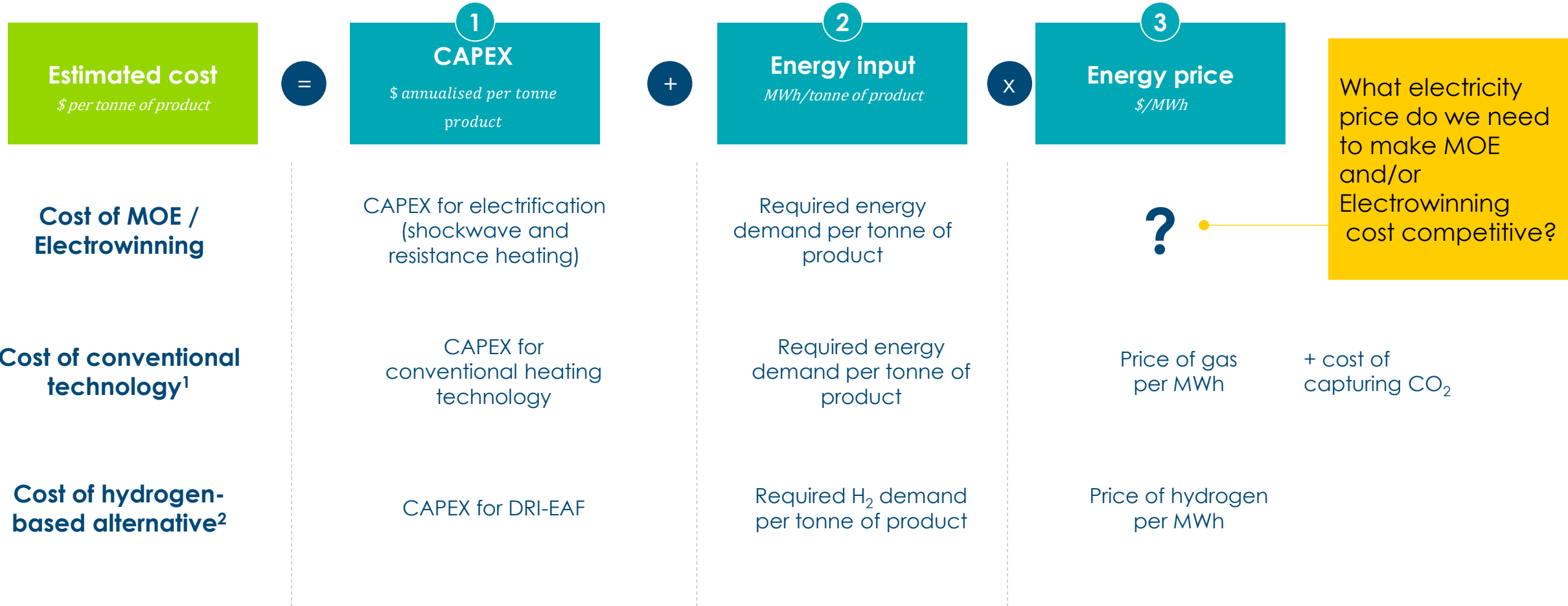


ORGANISATIONAL

- **Stable power supply:** achieving and maintaining a temperature of 1650°C is challenging and time-consuming for the MOE process. If the feed cools down and solidifies, it may impact the electrolyser modules' performance and stability



[Analysis focus] At which electricity price is high temperature heating cost efficient?



Notes: 1. Blast Furnace – Basic Oxygen Furnace; equipment includes coking plant, sintering plant, pelletizer plant, blast furnace, basic oxygen furnace; 2. Direct Reduced Iron – Electric Arc Furnace.
Sources: Mission Possible Partnership (2022). *Making net-zero steel possible*

1 Preliminary estimates suggest that the CAPEX of electrification technologies could be within the same price range as DRI-EAF

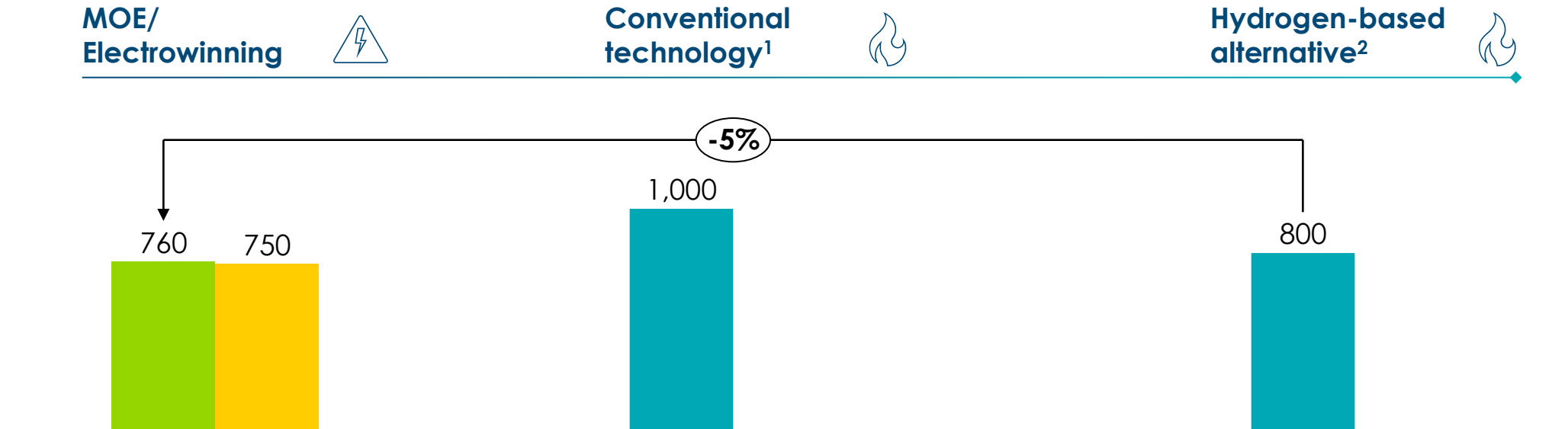
CAPEX/t steel
(in 2050)



Rationale



MOE
Electrowinning



Requires less equipment than conventional technologies

Requires more equipment compared to electrification technologies and more space

Requires less equipment than conventional technologies

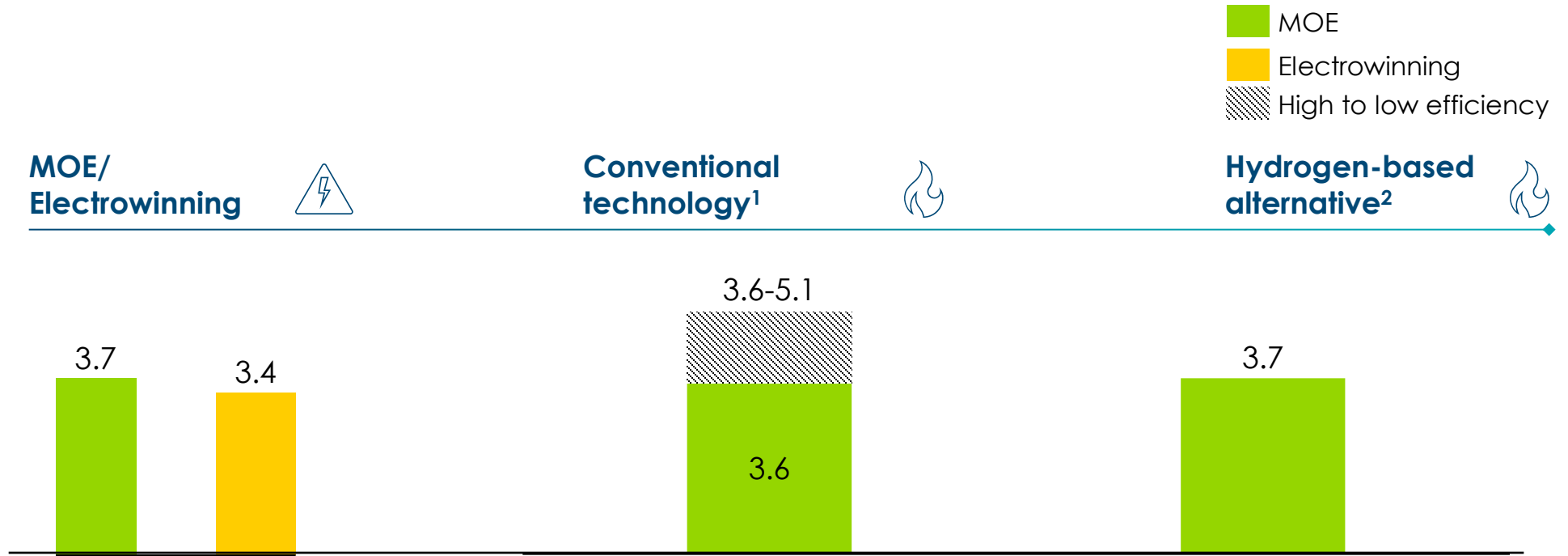


Notes: 1. Blast Furnace – Basic Oxygen Furnace; equipment includes coking plant, sintering plant, pelletizer plant, blast furnace, basic oxygen furnace; 2. Direct Reduced Iron – Electric Arc Furnace.

Sources: Mission Possible Partnership (2022). *Making net-zero steel possible*

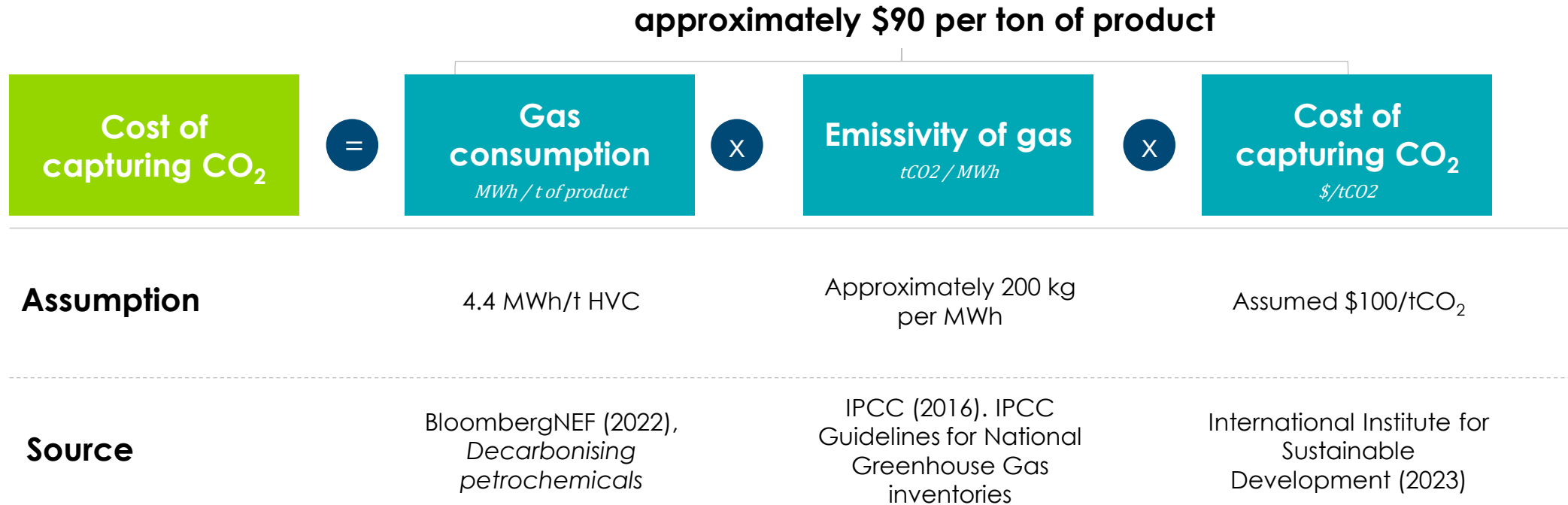
2 Early estimates suggest that the energy consumption of electrification technologies could be lower than other solutions

Energy consumption (MWh/t steel)



Notes: 1. Blast Furnace – Basic Oxygen Furnace; 2. Direct Reduced Iron – Electric Arc Furnace.
Sources: [Mission Possible Partnership](#) (2022). *Making net-zero steel possible*

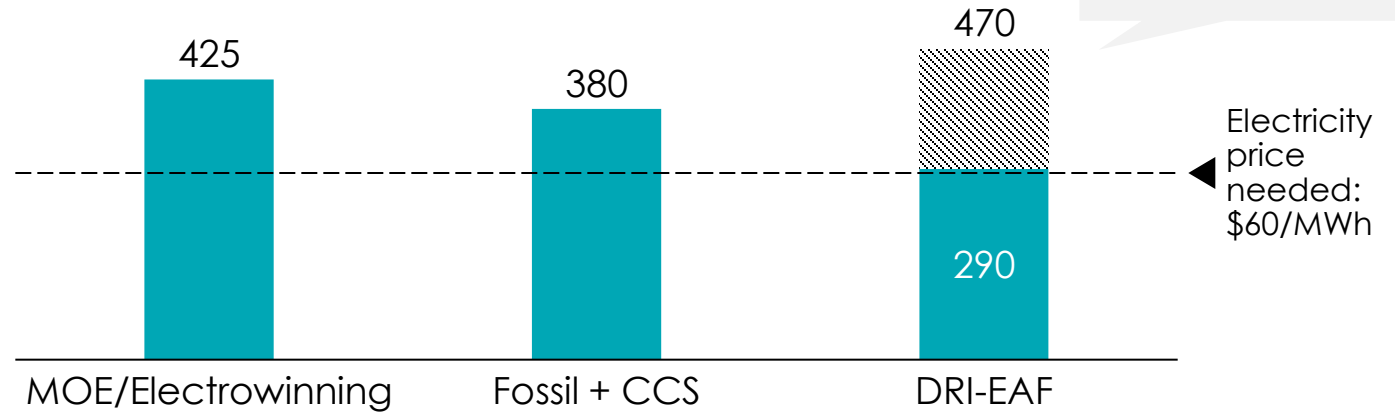
3 The cost of CCU/S will add around \$90 per ton of product to the conventional solution



Source: IPCC (2016). *IPCC Guidelines for National Greenhouse Gas inventories*. International Institute for Sustainable Development (2023) *Why the Cost of Carbon Capture and Storage Remains Persistently High*

The cost increase for electrowinning and MOE compared to DRI-EAF is expected to be around 30%

Levelised cost of heat for steel production in 2050, \$/t steel



MPP assumed a low-price of \$0.7/kg H₂ but could be less competitive with today's estimates - \$3/kg H₂

Electricity price needed: \$60/MWh

	MOE/Electrowinning	Fossil + CCS	DRI-EAF
Capex annualized ¹	\$75/t	\$100/t	\$80/t
Energy cost + CCU/S cost	\$350/t	\$100/t + \$180/t	\$210/t
Total	\$425/t	\$380/t	\$290

Key inputs

CAPEX	\$755/t ²	\$1000/t ³	\$800/t
Energy requirements	3.5 MWh/t	5 MWh/t ⁴	2.4 MWh/t (H ₂) + 1.7 MWh/t (Elec.)
Energy and CCU/S cost	\$100/MWh	\$20/MWh and \$180/t ⁴	\$18/MWh ⁵ (H ₂) + \$100/MWh (Elec.)

Notes: 1. Assumed over 10 years. 2. Average over different electrification technologies. 3. Average BF-BOF assumed; 4. 11.7 GJ/t steel for coking coal and 6.8 GJ/steel for lower-grade steel. 5. Emissivity for best available technology assumed 1.8 tCO₂/t steel and a capture price of \$100/t CO₂. 6. \$0.7/kg H₂

Sources: [Mission Possible Partnership](#) (2022), Making Net-Zero Steel Possible. BloombergNEF (2022), *Decarbonising petrochemicals*

A disruption of MOE and electrowinning could reduce the hydrogen and fossil demand and increase the direct electricity demand from 8 to 16 EJ

What we need to believe in

	Today	2050
TLR	4-5	9 (in 2035)
Electricity price to be competitive in China in 2050 (\$/t MWh)	75	60

Barriers mitigated

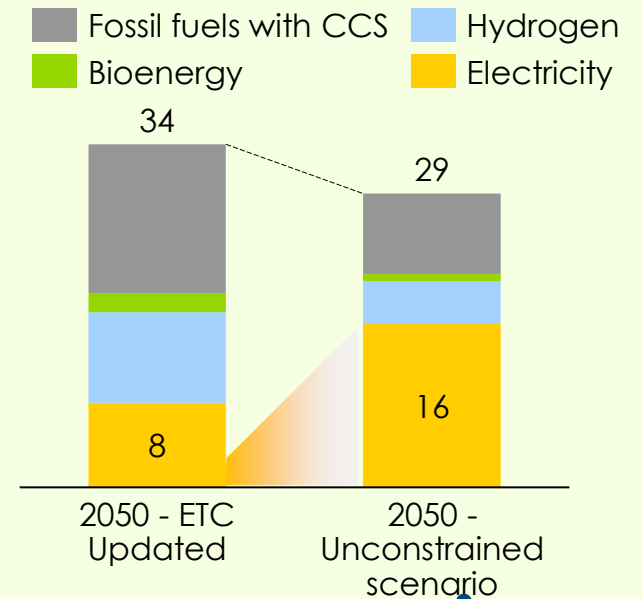
- Accessing a **competitive power supply**
- Proving commercial viability through piloting and demonstrating it can be scaled economically
- Scaling up the technology, improving energy efficiency, ensure long-term anode stability

Latest developments

- **MOE:**  (backed by ) raised **\$262** mln in series C **funding** and is building a demo plant of **25 kt** metal per year to come online in 2024
- **Electrowinning:**  commissioned its pilot plant earlier this year in Boulder.
- **Electrowinning:**  &  's **Volteron plant** will start production in 2027, targeting **40–80 kt/year**
- **Electrowinning:**  is doing a research funded by the Australian government agency

Impact on energy demand, EJ per year





Highly preliminary



Key assumption for the unconstrained scenario:

All fossil-based steel making plant are replaced by MOE/Electrowinning after 2035

With competitive energy prices, the production of H₂-DRI could shift towards MOE or electrowinning

Final energy demand type 	Impact on energy demand by 2050 
Electrification	 Cost-competitive electricity and technological advances could increase demand for electrons to produce iron in the iron and steel sector
Final hydrogen use/e-ammonia	 MOE and electrowinning may reduce H₂ demand for H₂-based DRI .
Carbon based fuels (e-SAF, methanol, fossil with and without CCS)	n/a

Key questions/considerations

- MOE/electrowinning technologies are advancing, bringing them closer to commercial readiness
- They may be less capital-intensive than other decarbonization options
- Also, MOE and electrowinning could offer better energy efficiency than alternatives
- However, the business case for MOE and electrowinning remains sensitive to fossil fuel prices



Li-ion solid state batteries (SSB)

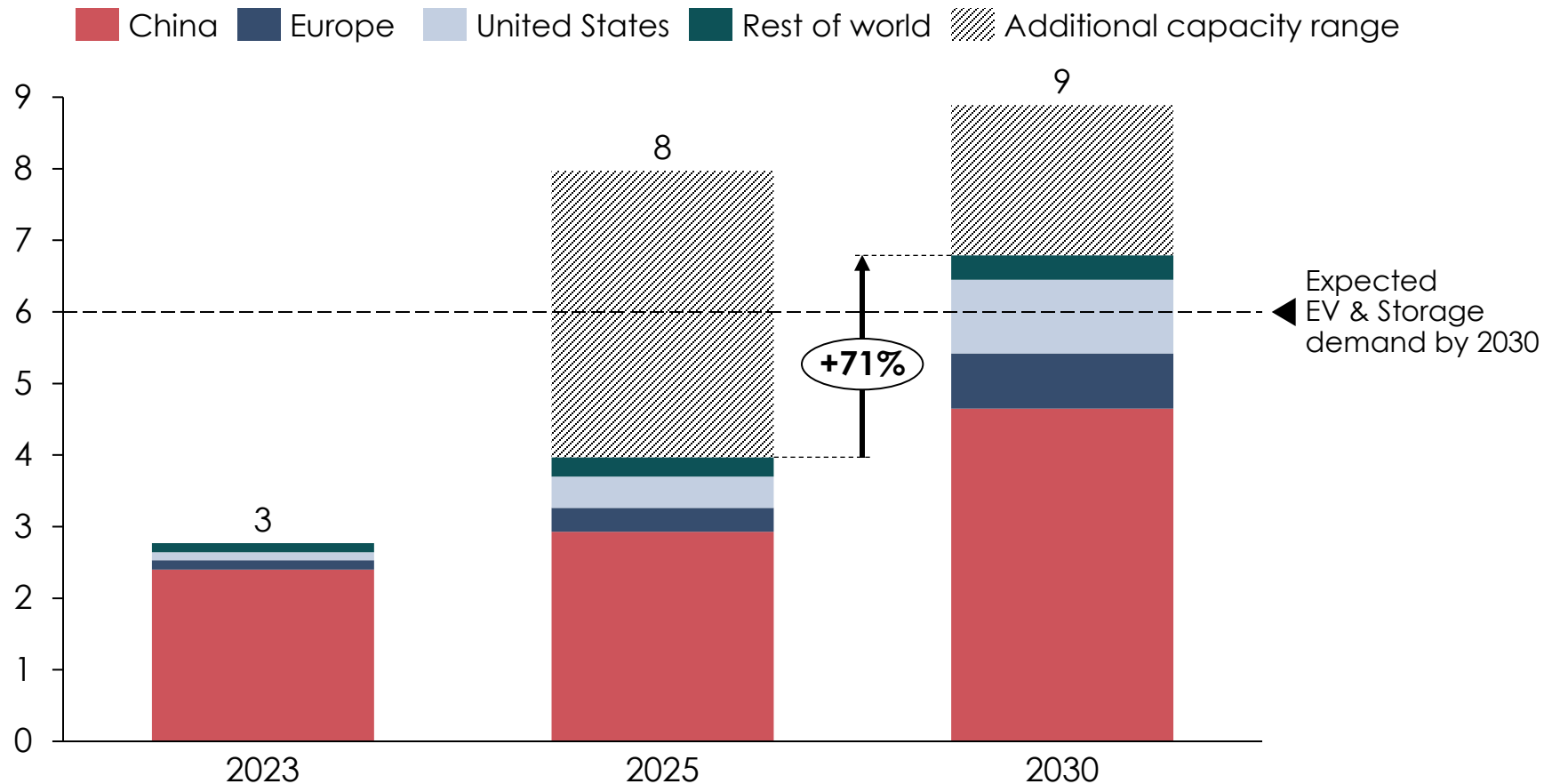


The immense manufacturing scale and growing demand create a landscape where diverse battery chemistries can both co-exist and overlap

Battery manufacturing capacity

TWh/ year

Implications



- The **battery industry** is **ready to produce the batteries** needed to achieve road transport electrification and stationary storage **by 2030**
- The **projected scale of capacity** can further **support battery demand diversification** (e.g., in mobile applications)
- **Next-generation batteries**, including solid-state, are expected to **emerge as alternatives to lithium-ion** by 2030 **due to expanding applications and market needs**

Source: ETC analysis based on IEA (2024), Global EV Outlook 2024, and BNEF (2024) China Already Makes as Many Batteries as the Entire World Wants. By April 2024, BNEF was tracking 7.9 TWh of annual battery manufacturing capacity announced for the end of 2025

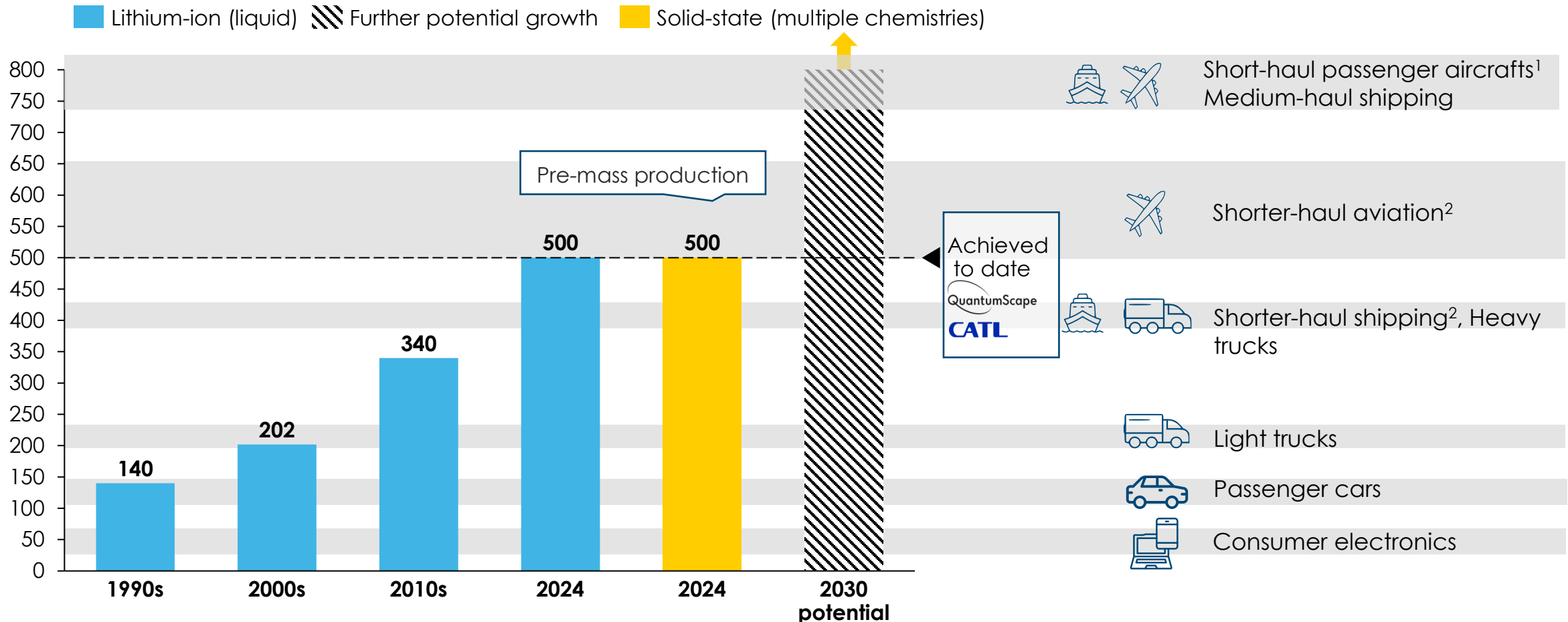
Solid-state batteries have the potential to further accelerate electrification in mobility by significantly enhancing energy density

Top-tier battery cell energy density by decade and today

Gravimetric densities, Wh/kg

Minimum viable energy density










Examples



Notes: Currently dominant lithium-ion batteries use liquid electrolytes, current solid-state batteries predominantly use lithium, other ions (e.g., sodium) can be used; Minimum density at which first full battery-electric models are feasible, 1) Typical twin-engine narrowbody aircraft with a range of 600 miles would require 800 Wh/kg, larger models 1000 Wh/kg, 2) Uptake in niche, shorter haul segments. At an energy density of 1,000 Wh/kg, most regional (~1,000 nautical miles) aviation can turn full electric. Sources: ETC analysis based on RMI (2023) X-Change: Batteries, Zu and Li (2011) for 1990s-2000s, BNEF (2024) Global EV Outlook for 2010s and 2020s

Solid-state batteries (SSBs) outperform non-SS LIBs on energy density levels, but lifetime and fast charging capability are tech KPIs with biggest drawback

■ Different to current tech ■ Surpassing current tech

Technology	Process	TRL	Energy density <i>Ranges</i>	Life cycles <i>Before signs of degradation</i>	Fast charging capability	Companies <i>Illustrative examples</i>
Lithium-ion Solid State Batteries (SSB) ¹	Stores and releases energy through the movement of ions in an electrolyte between the anode and cathode to create a current. The use of solid materials (e.g., ceramic) and different chemistry mixes (e.g., lithium) , enabling faster charging and more compact design	7	350-500 Wh/kg 750-1000 Wh/l	2,000 – 3,000; 6,000 for semi-solid state	higher potential, but facing limitations	 TOYOTA      
Lithium-ion batteries (LIBs) ²	Stores and releases energy through the movement of ions in an electrolyte between the anode and cathode to create a current. Classic battery design with liquid electrolyte and different chemistry mixes, dominated by lithium-iron-phosphate (LFP)	10	200 - 500 Wh/kg 600 - 850 Wh/l	4,000 – 12,000	can charge from 10% to 80% in under 10 minutes	 

Note: 1) For SSB, Li-metal as anode with oxide (+NMC cathode) or polymer (+LFP cathode) are considered as most promising cell concepts, 2) LIBs with liquid electrolyte include LFP (Lithium-iron phosphate), NMC (Nickel Manganese Cobalt Oxide), NCA (Nickel Cobalt Aluminum Oxide)
 Sources: Company websites for logos, Fraunhofer ISI (2023) Solid State Battery Roadmap, ETC (2024) Energy and Storage workshop based on BNEF (2024) and IEA (2024), BloombergNEF (2024) Solid-State Battery Tech Update 2024, Cautious Optimism



Solid-state LIBs outperform other non-solid-state batteries in compactness, weight and charging speed making them the preferred solution in transport

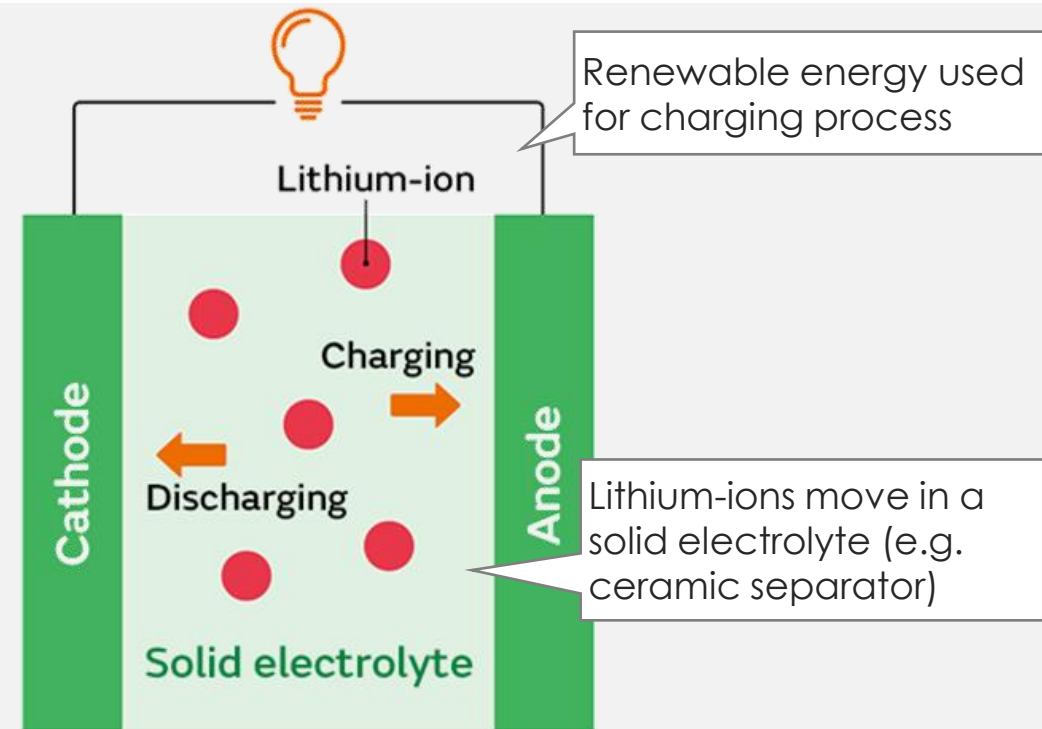
Key performance advantages

- **Higher energy density:** Extends range and improves payload capacity
- **Fast charging:** High-temp resistant SSBs offer quicker charging than LIBs
- **Safer:** Non-flammable components reduce leak and fire risks
- **Long lifespan:** Solid electrolytes degrade slower than liquid counterparts
- **Flexible design:** Easily shaped into smaller, thinner forms
- **Temperature resistance:** Performs better in extreme heat or cold conditions

Current status

- **Manufacturing scale:** Early-stage commercial production with select pilot projects underway, targeting 15 GWh of annual capacity by 2025
- **Company Example:** Stellantis plans a test fleet of EVs with solid-state batteries by 2026
- **Funding & Market Forecast:** \$6.9 billion in VC/PE and grants for 49 startups raised to date

Stores and releases energy through the movement of lithium-ions in an electrolyte between the anode and cathode to create a current







- No metallic separator between cathode and anode required
- Silicon-based anodes, lithium-metal anodes have highest potential to improve battery performance

Notes: SSB = Solid-state batteries

Sources: Diagram (adjusted) from Murata (2022), What are solid-state batteries?, Fraunhofer Iisi (2023) Alternative Battery Technologies Roadmap 2030+

Solid-state batteries technological potential represents the continued evolution of the non-solid-state lithium-based battery technologies

SSB performance areas spilling over to conventional Li-batteries¹

 Higher energy density	High-capacity anodes (lithium-metal, silicon) utilized by SSBs improve energy density also for current versions of lithium-ion batteries
 Enhanced safety	Non-flammable solid electrolytes in SSBs eliminate the risk of fire and thermal runaway; these safety innovations lead to safer liquid and hybrid electrolytes in conventional batteries
 Broader temperature range	Material insights from SSBs help develop new additives and coatings that enable conventional Li-batteries to perform better in harsh conditions
 Improved stability	Advances in stable and conductive interfaces help reduce cycle degradation in conventional batteries, enhancing their longevity and reliability

SSBs could enable further **steady performance improvements** of **7-8%²** for all battery chemistries



New 'semi-solid' and **'condensed'** batteries like CATL's 'Shenxing' offer **big performance gains**, achieving **500 Wh/kg** and fast 10-minute recharging for 400 km

Notes/ Sources: 1) Includes all other lithium batteries than solid-state, 2) ETC estimates based on average learning rates for advanced batteries

The challenge is primarily about industrialising at massive scale and acceptable cost for mobile applications

Key barriers



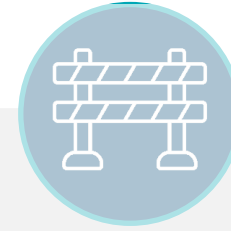
ECONOMICAL

- **High Initial Costs:** Higher production costs compared to LIBs due to small volumes and new production technologies
- **Investment Needs:** Parallel development requires large investments
- **Market Entry Barriers:** Cost-effective only for premium markets initially



TECHNICAL

- **Scale-Up Issues:** Challenges in scaling materials and ensuring component compatibility at mass production levels, impacting battery life



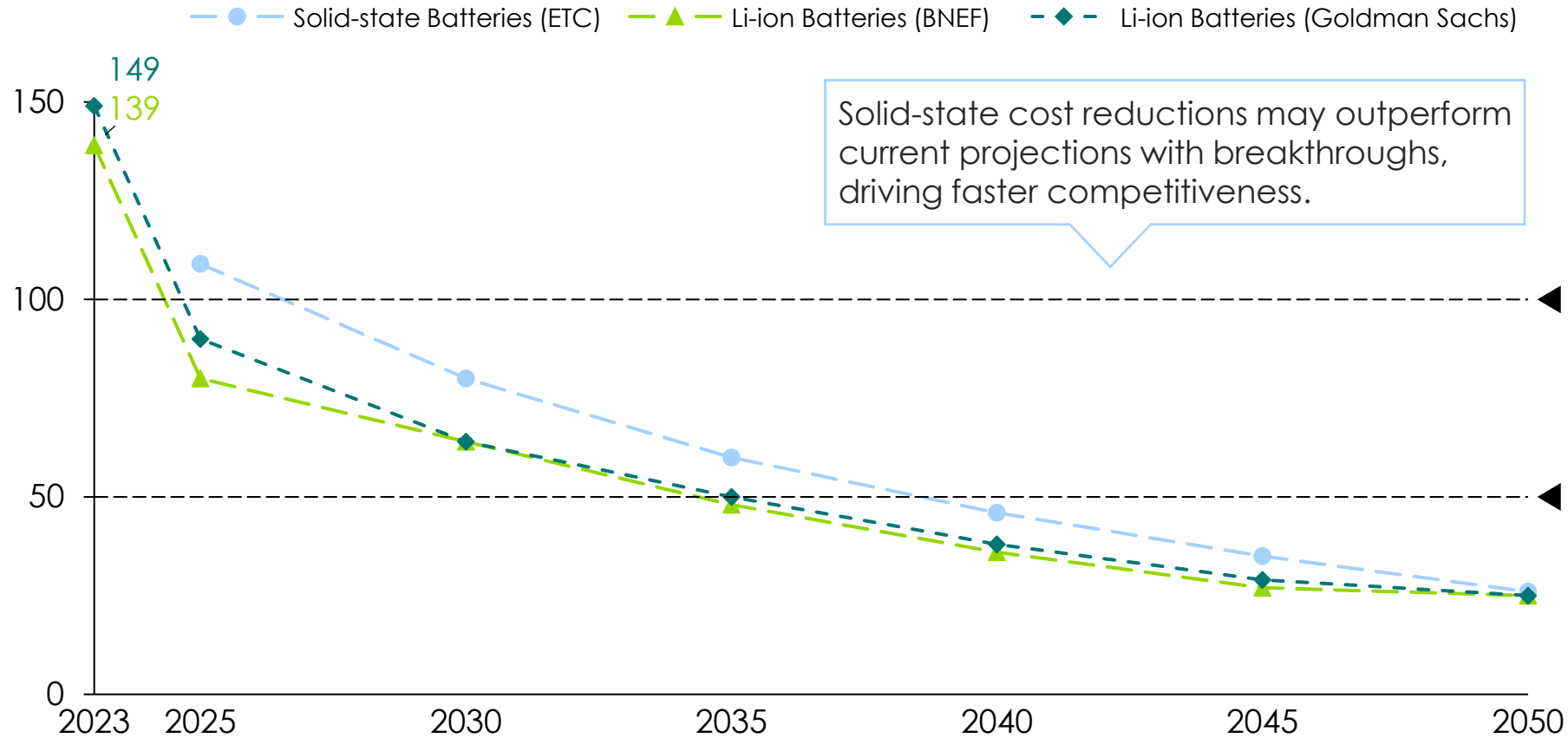
ORGANISATIONAL



Rapid declines in battery costs could open a range of electrification pathways for mobility, potentially accelerating beyond anticipated levels

Average battery pack price
\$/kWh, actuals and projections^{1,2}

Mobility example
Battery pack price, shipping³



At battery prices of **\$100/kWh**; Battery-electric ships could be competitive with fuel oil ships (<1,500 km)

If battery prices reach **\$50/kWh**: Widespread economic viability for medium-range battery-electric ships (~3,000 km)

1) Methodology for price projections: For solid-state based on Fraunhofer: annual 6% cost improvement rate applied to EU price goals for solid-state batteries by 2025 and 2030 (<100 €/kWh) and 2030 (<75 €/kWh); for Li-ion price projections based on BNEF: price projection adapted from BNEF up to 2035: 6% cost improvement rate applied to years up to 2050: for Li-ion price projections from Goldman Sachs (GS): price projection adapted from GS up to 2030, thereafter 6% cost improvement rate applied to years up to 2050;
 2) Sources: Goldman Sachs (2024) Electric vehicle battery prices are expected to fall almost 50% by 2026, based on company data, Wood Mackenzie, SNE Research, Goldman Sachs; BNEF (2024) 2023 Lithium-Ion Battery Price survey, BNEF (2024) New Energy Outlook; Fraunhofer ISI (2024) Solid-state batteries roadmap 2035+
 3) RMI (2023) Xchange: Batteries The Battery Domino Effect



Higher density, low-cost batteries are shifting trucking, toward electrification with some potential to increase feasible electric range for ships and airplanes

Estimated influence of innovation on final energy mix



- **Increasing certainty** that with **current density levels**, lower-cost batteries and reduced TCO compared to ICE, the **vast majority** of trucking can be **electric**.








- The combination of **cheaper** and **more energy-dense batteries** will **gradually push** the limits of **electrification in shipping** applications
- While near-term innovation may lead to competitiveness in specific use cases (e.g., short to medium distances), the extent of electrification will be **limited** by **battery density constraints**



- **Solid-state** and **other battery technologies** may **slightly extend the range** for electric or hybrid-electric aviation, but significant electrification remains distant
- An increase in scope could be expected with **long-term transformative breakthroughs**, such as **liquid air energy storage** or other innovations, that would materialize **post 2050**

Sources: ETC based on RMI (2024) XChange Batteries, Fraunhofer ISI (2024) Solid-state battery roadmap 2035+, Fraunhofer ISI (2023) Advanced battery technologies roadmap 2030+, The International Council on Clean Transportation (2023) A total cost of ownership comparison of truck decarbonization pathways in Europe, Maersk McKinney Moeller Center (2024) Understanding the potential of battery-powered vessels for deep-sea shipping: a pre feasibility study

Low-cost batteries with improving performance are shifting trucking, shipping, and aviation toward electrification

Final energy demand type 	Impact on energy demand by 2050 
Electrification	 <p>Steady advancements in battery technology could increase demand for electrons across all road transport and even short-to-medium haul aviation and shipping</p>
Final hydrogen use/e-ammonia	 <p>Battery-electric solutions for medium-haul transport may cut hydrogen demand in trucking and medium-haul aviation but keep H2 essential for hybrid and long-distance use</p>
Carbon based fuels (e-SAF, methanol, fossil with and without CCS)	 <p>Batteries could help eliminate demand for carbon-based fuels in road transport and short-to mid-haul aviation and shipping. Remaining long-haul demand will rely on either carbon or hydrogen-derived fuels</p>

Key questions/considerations

- How does this assessment of shifting demand for batteries and fuels in transport compare with your perspectives and experience?
- What cost levels do you believe batteries must and can reach to enable widespread adoption and take over key transport segments?
- What key factors, next to technical performance and cost, do you believe will significantly impact fuel transitions for transport?

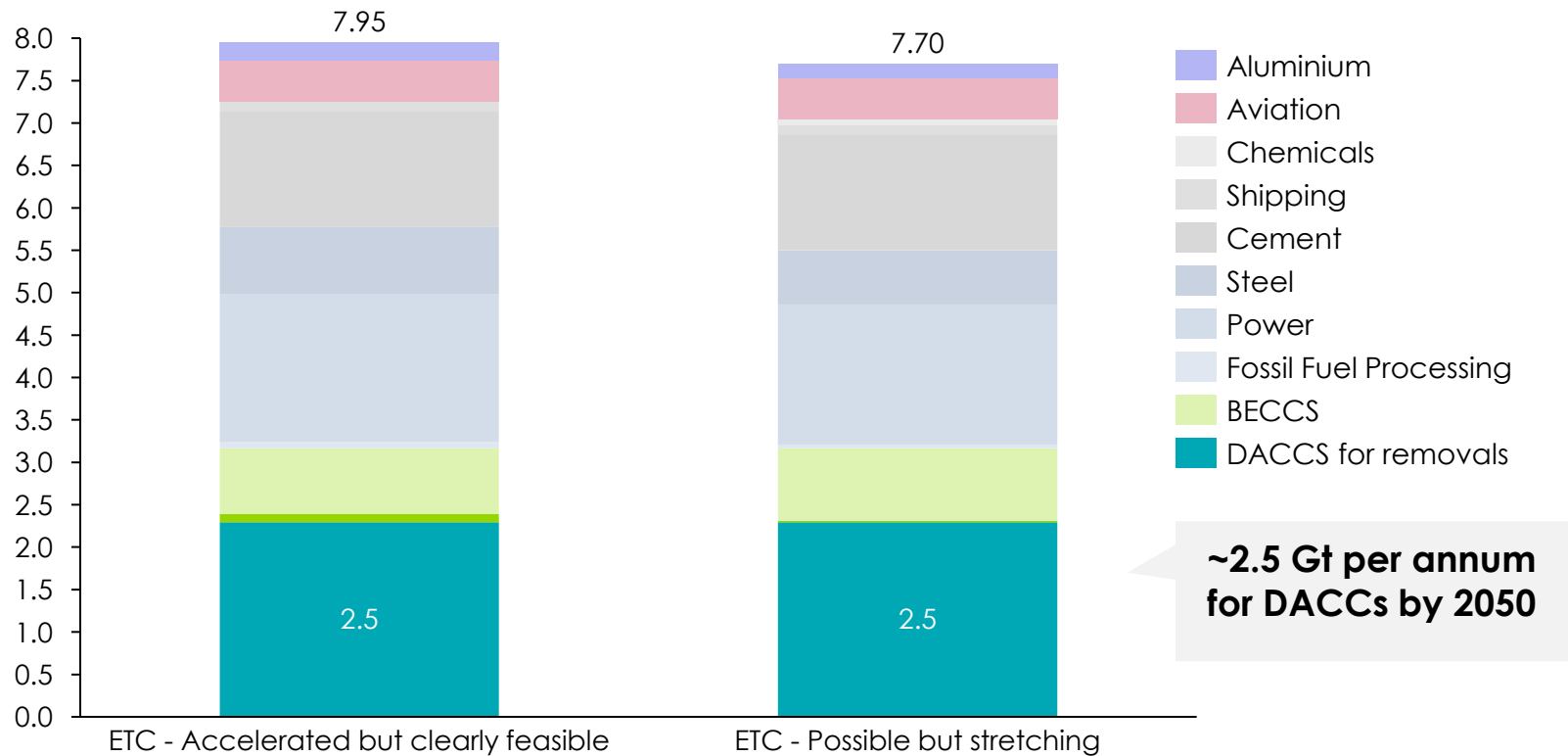


Advanced Direct Air Capture (DAC)



ETC estimated a role for DACCs of ~2.5Gt per annum of carbon removals by 2050

CCUS demand by sector in 2050, GtCO₂



Note: total captured emissions include both utilized carbon and carbon that is permanently stored. *Volumes in ACF and PBS are same as 'ETC – Previous Lower Bound'. Source: Systemiq analysis for the ETC (2023); ETC (2022), Carbon capture, utilization and storage in the energy transition.



DAC is currently a costly option at around \$1,000 per tonne of CO₂, with some believing this could drop to \$100 per tonne

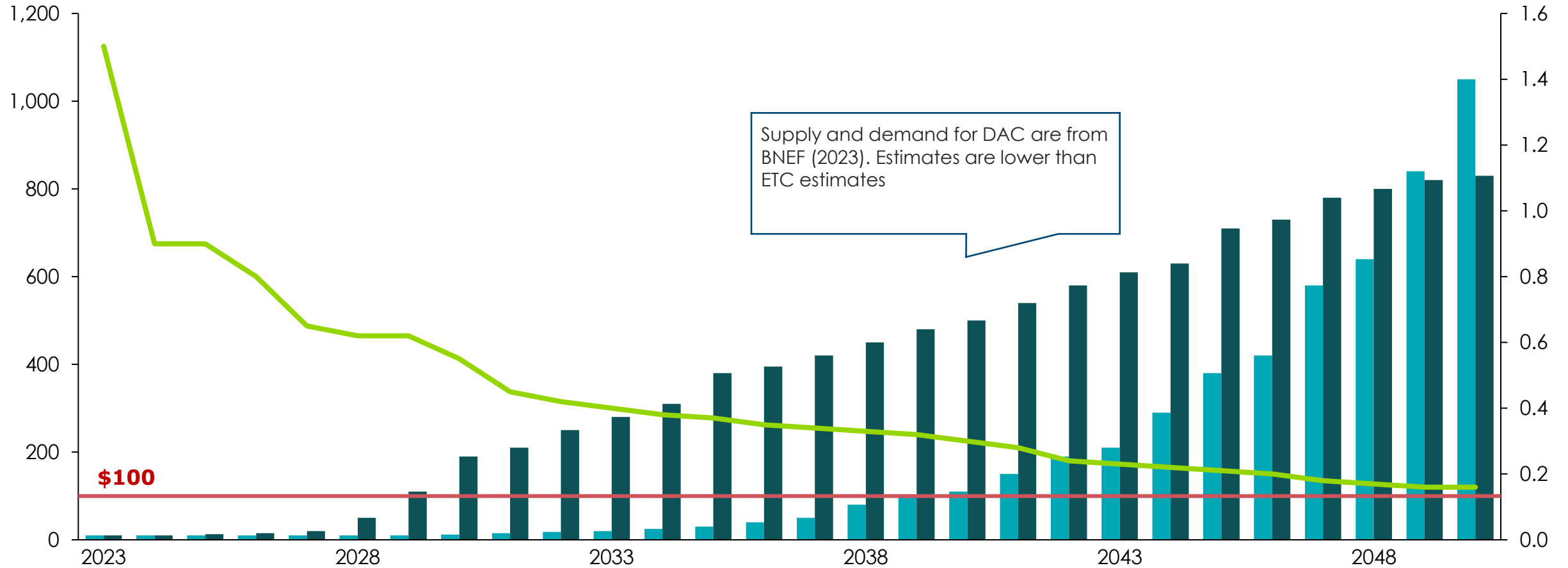
Unit price of DAC Outlook, 2023-2050

\$/tCO₂

Supply Demand Cost










\$/tCO₂

GtCO₂



Source: BNEF (2023) *What is the future of carbon removal*

The next generation of DAC technologies could reduce energy consumption, improve scalability, and enable further cost optimization

Technology	Process	TRL	Companies
Electrochemical DAC	Uses electrochemical cells to capture and release CO ₂ . Operates at lower temperatures relative to conventional thermal or pressured-based DAC. Involves adsorption of CO ₂ onto a reactive material, which is then desorbed using an electric current. This method could reduce energy consumption and enhances scalability compared to conventional thermal or pressure-based DAC systems.	5-7	 VERDOX  MissionZero  Greenlyte
DAC in combination with waste heat	Utilization of excess heat from industrial processes, such as data centers. Waste heat is used in the DAC process to regenerate sorbent materials and has potential to reduce operational costs.	5-7	 28Cearth
DAC and AI	Utilizing machine learning to analyze factors that impact the effectiveness of DAC units, such as climate conditions, energy prices and the state of the absorbent material attracting the CO ₂ from the air. This allows for faster predictions to be made about how materials will behave in the DAC process.	N/A	 NEG8 CARBON  Orbital Materials  cusp.ai <small>Unlocking the future of materials with AI.</small>
Modular and scalable set-ups	Designing modular, standardized units enables easy integration with existing infrastructure and efficient scaling of DAC systems, for example, standardizing, permitting and engineering processes shifts focus from individual projects to scalable products, where replicating smaller units instead of scaling up a single large system reduces CAPEX.	N/A	 carbyon  CarbonCapture™

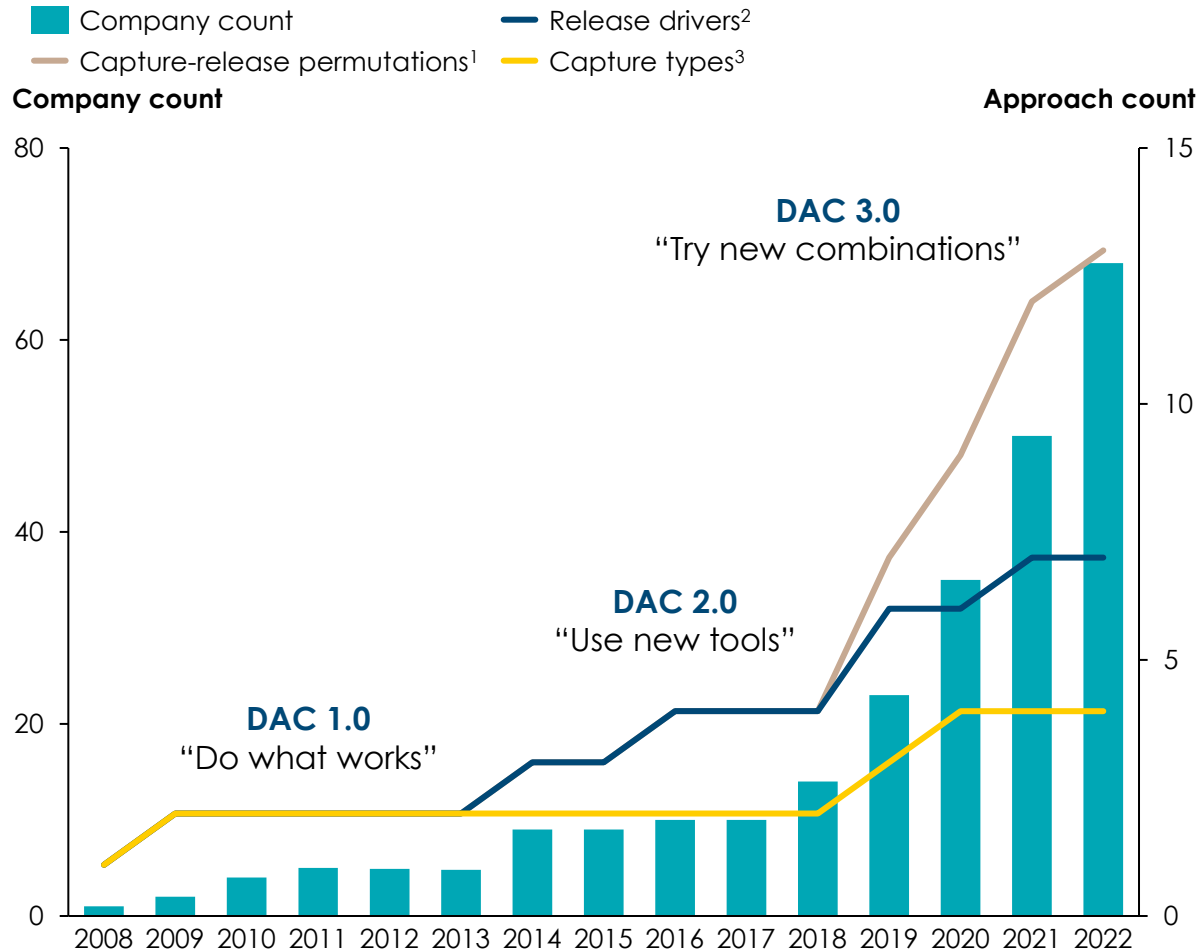


Source: [Axios](#). (2024). Exclusive: Company to unveil first CO₂ capture module for mass production; [Carbon Herald](#). (2024). NEG8 Teams up with Walton Institute on AI Direct Air Capture project

However, studies are suggesting that even with the next generation of DAC innovations, reaching \$100/t CO₂ by 2050 could be challenging

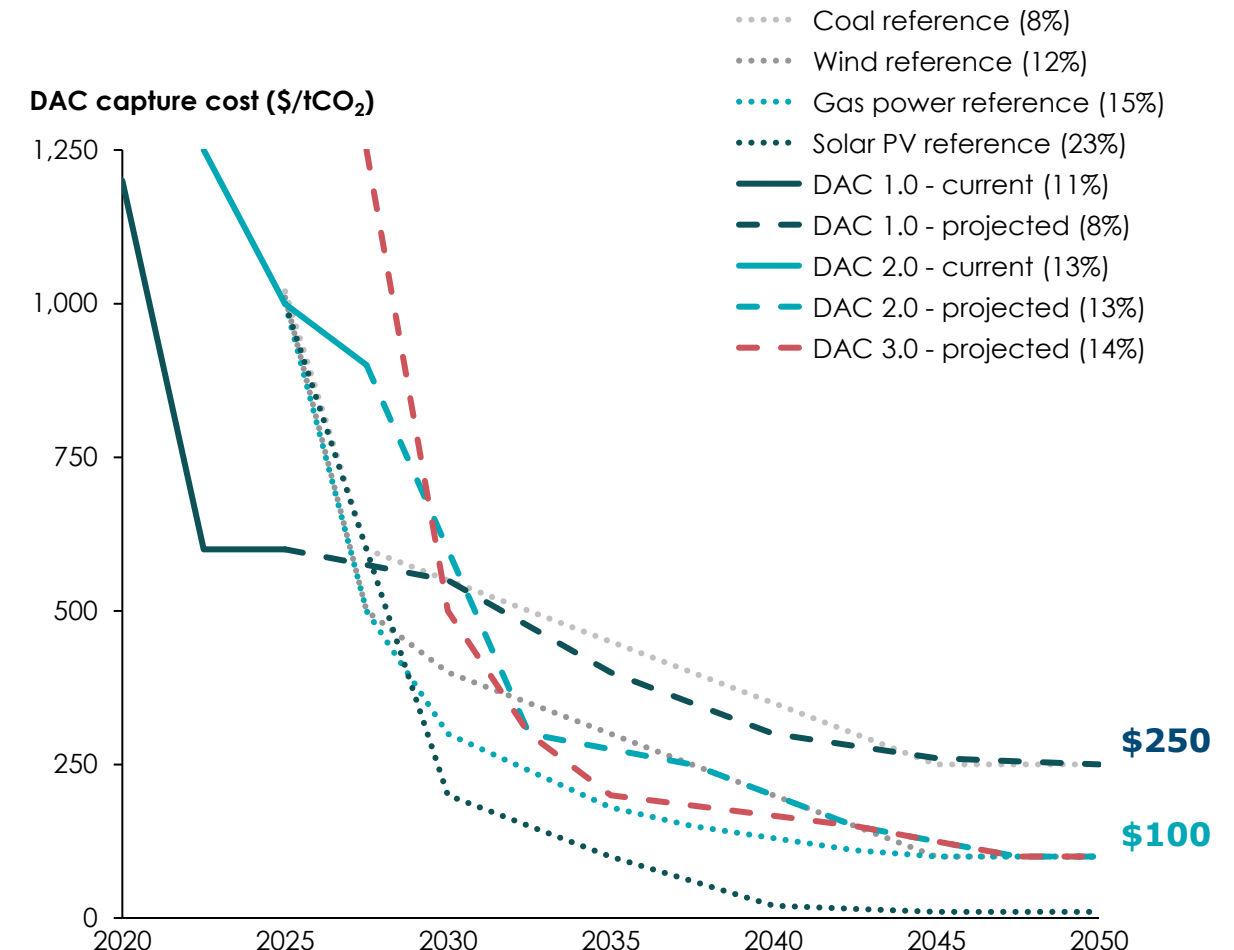
DAC companies and approach combinations over time

Numbers



Potential DAC cost paths by reference learning rates

In 2024 USD



1. Combining various methods for capturing and releasing CO₂, such as replacing thermal techniques with liquid solvent capture and electrochemical release; 2. Applying alternative CO₂ release methods, including pH or voltage control; 3. Developing innovative capture technologies like membranes.

Source: Statista, Exantia Analysis; Note: learning rate is the cost reduction per doubling of cumulative installed capacity

There are technical, economical and organisational barriers that must be overcome

Key barriers



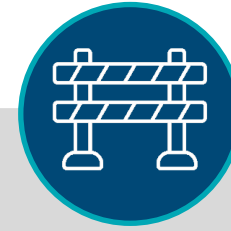
ECONOMICAL

- **High CAPEX:** Large, costly plants needed to process high air volumes due to low CO₂ concentration
- **Electricity costs:** High energy demand for DAC processes and sorbent regeneration
- **Sorbent costs:** Expensive CO₂-capturing materials with significant replacement costs



TECHNICAL

- **Material durability and stability:** Develop efficient, long-lasting sorbents for CO₂ capture
- **Equipment durability at scale:** Ensure reliable operation of large-scale DAC plants with long lifetimes
- **Performance in varying weather:** Enable consistent operation across different temperatures and humidity levels







ORGANISATIONAL

- **Limited storage options:** Few suitable CO₂ storage projects available for DAC utilization
- **Regulatory uncertainty:** Lack of clear policies and incentives for DAC projects hinders investment



Advancements reducing DAC costs could lower reliance on electrification and strengthen the case for carbon-based fuels or for fossil plus DACCS offset

Final energy demand type 	Impact on energy demand by 2050 
Electrification	 Lower-cost DACCS can increase the role of fossils in combination with CCS for some sectors, reducing the reliance on electrons
Final hydrogen use/e-ammonia	Unclear In some sectors, increased use of DACCS may reduce reliance on green hydrogen
Carbon based fuels (e-SAF, methanol, fossil with and without CCS)	 Lower-cost DAC could provide a more affordable, sustainable carbon source for synthetic fuels and chemicals, while also driving larger adoption of fossil + CCS technologies

Key questions/considerations





- Technological advancements could significantly reduce the cost of DAC, prompting questions such as:
 - How low can DAC costs realistically go?
 - How will these cost reductions impact the cost-competitiveness of low-carbon technologies (e.g., the trade-off of using DAC versus e-fuels in aviation)?
 - When will these innovations become commercially viable?



Sodium based batteries (SIB)



Battery innovation addresses a critical issue in a RE-dominated economy: daily and weekly balancing of power

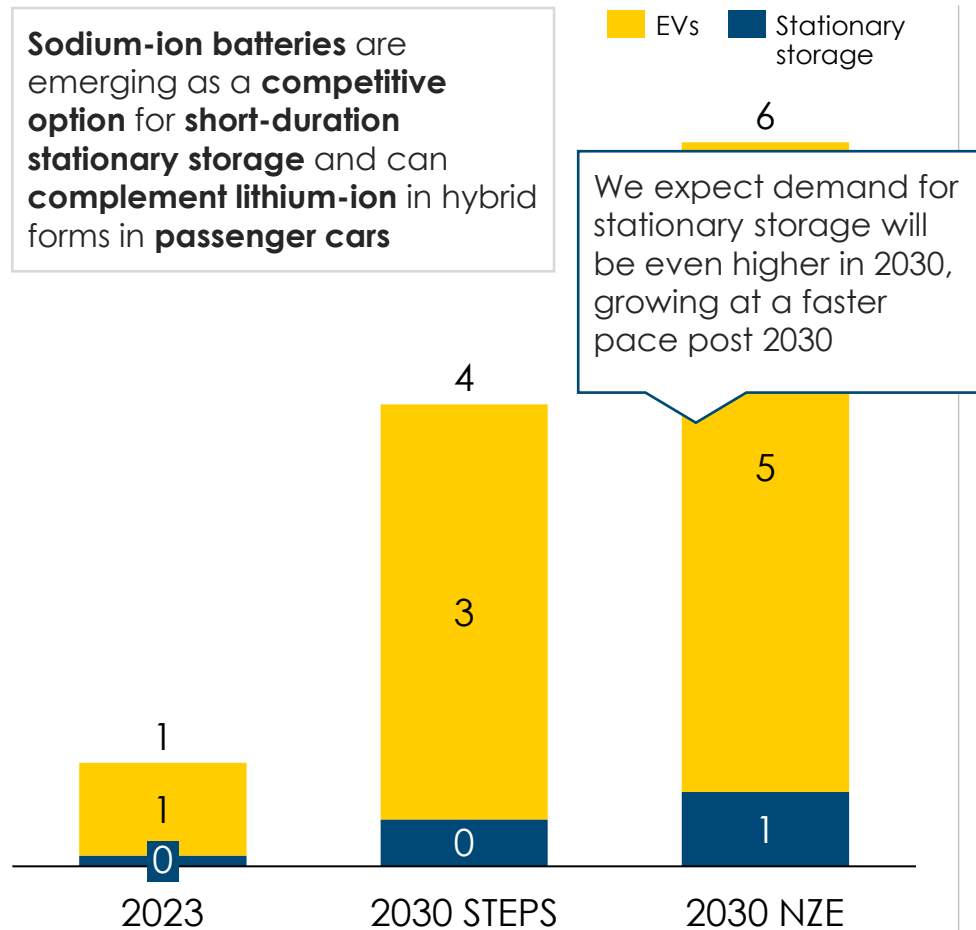
Types of balancing			System operation	Predictable Daily	Unpredictable Daily	Seasonal	Unpredictable week by week
Dispatchable generation 	Other zero carbon	Hydro, nuclear ¹	✓	✓	✓	✓	✓
	Fossil	Fossil (or bioenergy) + CCS	✓	✓	✓	✓	✓
		Fossil – low/very low utilisation	✓	✓	✓	✓	✓
Interconnection 		Accessing complementary weather patterns and time shifting generation		✓	✓	✓	
Energy storage 	Mechanical (pumped hydro)		✓	✓	✓	✓	✓
	Electro-chemical (batteries)		✓	✓	✓	✓	✓
	Other technologies		✓	✓	✓	✓	✓
	Chemical (hydrogen)		✓	✓	✓	✓	✓
Heat storage		Heat battery		✓	✓		
Demand side flexibility 	EV (smart charging, V2G)			✓	✓		
	Heating load ⁵			✓	✓		
	Industrial load ⁶				✓		✓

Focus

Notes: 1. Limited nuclear capacity for flexible ramping. 2. Battery storage is utility-scale and behind-the-meter. 3. Other technology might include gravitational storage and molten sands storage. 4. Examples of Power-to-X include the production of H2 from electrolysis and re-conversion of hydrogen in power via gas turbines or fuel cells. 5. Residential and commercial standard heating needs. 6. Including hydrogen electrolysis, where production can be shifted to optimal times. Source: Adapted from Climate policy Initiative for the Energy Transitions Commission (2017), *Low-cost, low-carbon power systems*

Batteries are key for stabilizing renewable energy in stationary storage, complementing their dominant role in passenger cars

Annual battery demand by application TWh





Stationary storage technologies in a net-zero economy

Mechanical 	Pumped-storage hydropower	<ul style="list-style-type: none"> • Most widely used storage technology with significant additional potential in several regions (outside EU)
Electro-chemical 	Batteries	<ul style="list-style-type: none"> • Most scalable type of grid-scale storage • Market has seen strong growth in recent years with major cost improvements further increasing their share
Chemical 	Power-to-X (i.e., Hydrogen)	<ul style="list-style-type: none"> • Potential for seasonal storage though outpaced in terms of cost and efficiencies by new battery chemistries
Thermal 	Molten salt storage	<ul style="list-style-type: none"> • Play a comparatively small role in current power systems

Notes: STEPS = Stated Policies Scenario, NZE= Net zero Emissions by 2050 Scenario, both produced by the IEA
Source: IEA (2024) Annual battery demand by application and scenario, 2023, and 2030

Together, SIB and LIB advancements reflect emulation, not competition, suggesting future convergence in technical performance and scalability

Technology	Process	TRL	Life cycles <i>Before signs of degradation</i>	Energy Efficiency	Companies <i>Illustrative examples</i>
Sodium-ion batteries (SIBs)	Sodium ions move between a sodium-based cathode and a hard carbon anode via a sodium salt electrolyte to store and release energy	7	5,000 – 11,000	90-95%	
Lithium-ion batteries (LIBs)¹	Lithium ions travel between a lithium-based cathode and graphite anode through a lithium salt electrolyte to charge and discharge the battery	10	4,000 – 12,000	93-95%	



Lithium-ion dominates the stationary energy market as sodium-ion batteries are not yet commercialized while technical KPIs are in similar ranges

See detailed overview of technical KPIs in Appendix

Note: Lithium-ion batteries include LFP (Lithium-iron phosphate), NMC (Nickel Manganese Cobalt Oxide), NCA (Nickel Cobalt Aluminum Oxide), Lower c-rates reduce stress on the battery, extending cycle life and ensuring the battery's capacity over time

Sources: BloombergNEF (2024) 2H 2024 Energy Storage Market Outlook, ETC (2024)



Sodium-based batteries could provide a more cost effective, robust solution for energy storage due to use of abundant, low-cost materials

Category	Technology	Typical cost of capacity (2024), \$/kWh
Electro-chemical	Sodium-ion battery ¹	<ul style="list-style-type: none"> 90-200, with costs btw. 30-80 for the cells
	Lithium-ion battery ²	<ul style="list-style-type: none"> Global: ~210 and ~150 by early 2030s likely China: well below 200 and falling fast, -40% turnkey cost reduction this year US: 350 <p><i>Note: fully installed system costs, incl. grid connection</i></p>
Chemical	Hydrogen in CCGT	<ul style="list-style-type: none"> \$100-200/MWh LCOS
Mechanical	Pumped Hydro	<ul style="list-style-type: none"> ~260
Mechanical	A-CAES	<ul style="list-style-type: none"> China ACAES: 280, purpose built 340 China Tank: 460 Non-China CAES: 280
Thermal	Molten Salt	<ul style="list-style-type: none"> China: 200 Non-China: 300

Sodium ion cells produced at scale could be **20% to 30% cheaper than LFP**, the dominant stationary technology due to abundant sodium, low extraction and purification costs

Notes: 1) Assuming battery energy storage system costs are 2-3x the cell cost 2) Fully installed system costs, incl. grid connection for 2-hour LFP storage system; Hydrogen in CCGT = Hydrogen storage in combined-cycle gas turbine systems (CCGT), A-CAES = Advanced Compressed Air Energy Storage
 Source: BNEF (2024), 2024 long-duration energy storage cost survey; Pacific Northwest National Laboratory (2023), Energy Storage Cost and Performance Database; IEA (2024), ETP Clean Energy Technology Guide; other sources from ETC Energy Storage deep-dive on energy storage



Technical barriers make LIBs currently more attractive for stationary storage applications, but SIB's benefits offer promise as technology advances

Key barriers



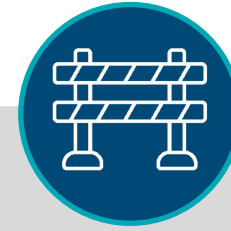
ECONOMICAL

- **Current production costs:** Current low production volumes of sodium-ion batteries lead to higher per-unit costs.



TECHNICAL

- **Lower energy density:** Storage utilization is constrained by low energy density compared to LIB, limiting widespread application options
- **Shorter cycle life:** Improving the cycle life and overall performance is necessary for stationary storage



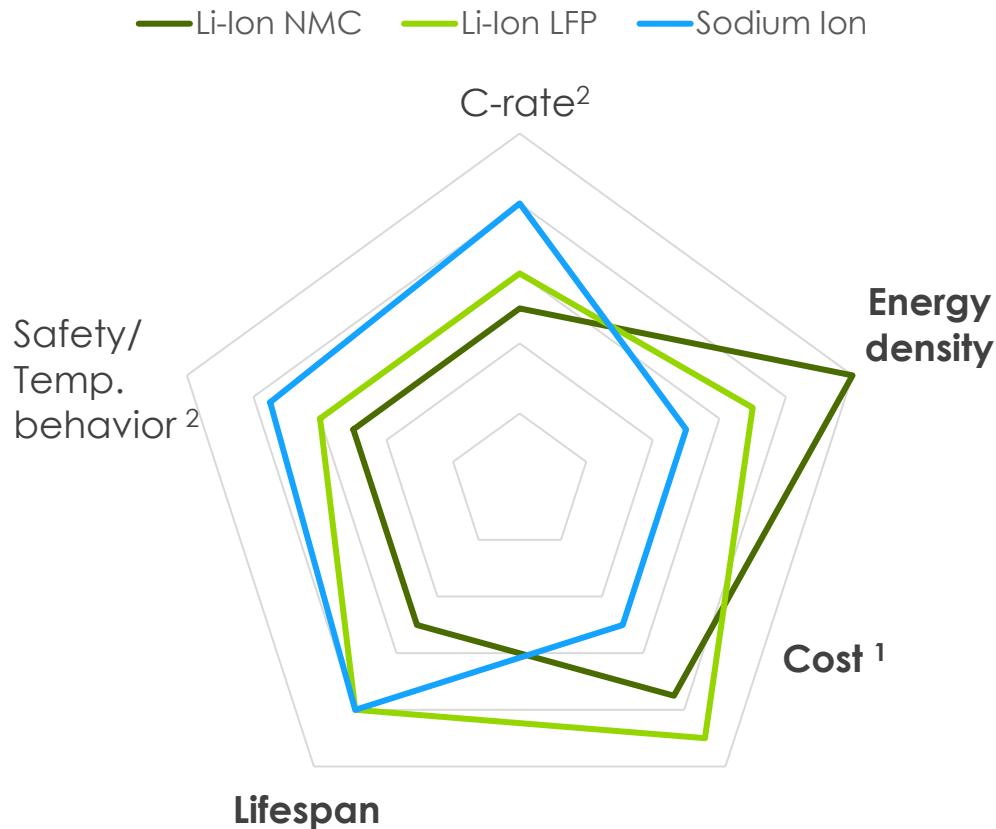
ORGANISATIONAL

- **Manufacturing infrastructure:** Sodium-ion battery manufacturing is less mature than lithium-ion, with fewer established processes and economies of scale



Recent advancements are narrowing the energy density gap between sodium-ion and LIBs, making SIBs increasingly viable for diverse applications

Radar chart of relevant dimensions of SIBs compared to LIBs








Category	Sodium-ion	Lithium-ion batteries (LIBs)
C-rate	2 – 4 C	4 – 6 C
Gravimetric energy density	~200 Wh/kg announced by CATL in 2024	~500 Wh/kg via condensed battery cell announced by CATL
Volumetric energy density	~ 400 Wh/l	600-750 Wh/l
Raw-material cost	Sodium hydroxide is \$300-\$800 per metric ton	Lithium hydroxide is \$15,000 per metric ton
Lifespan	Cycle-life similar to LIBs	Steady performance over a high number of cycles

Key technical challenges for SIBs in stationary storage:

- **Boost energy density and cycle life** to rival lithium-ion batteries.
- **Optimize stable, non-toxic materials** to minimize capacity fade and extend lifespan

Notes: 1) Cost of Sodium expected to be 20-30% lower compared to LFP once technology is scaled 2) C-rate and safety being less of a concern for stationary applications compared to mobile application
 Source: ETC analysis based on Fraunhofer ISI (2023) Battery technology advancements 2030+ roadmap, Volta Foundation (2024), IRENA (2024) Critical materials: batteries for electric vehicles

The lower cost of sodium can offer a significant economic advantage, accelerating and reinforcing the electrification of the power system

Final energy demand type 	Impact on energy demand by 2050 
Electrification	 <p>Sodium further reinforces the scalability and economic viability of battery storage solutions to potentially complement stationary storage options</p>
Final hydrogen use/e-ammonia	 <p>Sodium batteries can excel at short-term balancing, while hydrogen may remain for long-duration energy resilience and flexibility</p>
Carbon based fuels (e-SAF, methanol, fossil with and without CCS)	 <p>New battery chemistries add to potential storage solutions, allowing more renewables to displace fossil in the grid</p>

Key questions/considerations







- How does this assessment of shifting demand for batteries and hydrogen compare with your perspectives and experience?
- What do we need to believe for batteries to rule out hydrogen for long-duration storage?
- Can sodium-batteries be optimized to extend beyond short-to-medium-term applications? By when?



Small Nuclear Reactors (SMR), Nuclear Micro Reactors (NMR)



With rising renewables penetration, grid balancing becomes crucial, where nuclear can provide a zero-carbon solution

Types of balancing			System operation	Predictable Daily	Unpredictable Daily	Seasonal	Unpredictable week by week	
Focus	Dispatchable generation 	Other zero carbon	Hydro, nuclear ¹	✓	✓	✓	✓	✓
		Fossil	Fossil (or bioenergy) + CCS	✓	✓	✓	✓	✓
			Fossil – low/very low utilisation	✓	✓	✓	✓	✓
Interconnection 		Accessing complementary weather patterns and time shifting generation			✓	✓	✓	
Energy storage 	Mechanical (pumped hydro)		✓	✓	✓	✓	✓	
	Electro-chemical (batteries)		✓	✓	✓			
	Other technologies		✓	✓	✓	✓	✓	
	Chemical (hydrogen)		✓	✓	✓	✓	✓	
Heat storage		Heat battery			✓	✓		
Demand side flexibility 	EV (smart charging, V2G)			✓	✓			
	Heating load ⁵			✓	✓			
	Industrial load ⁶			✓	✓	✓		

Notes: 1. Limited nuclear capacity for flexible ramping. 2. Battery storage is utility-scale and behind-the-meter. 3. Other technology might include gravitational storage and molten sands storage. 4. Examples of Power-to-X include the production of H2 from electrolysis and re-conversion of hydrogen in power via gas turbines or fuel cells. 5. Residential and commercial standard heating needs. 6. Including hydrogen electrolysis, where production can be shifted to optimal times. Source: Adapted from Climate policy Initiative for the Energy Transitions Commission (2017), *Low-cost, low-carbon power systems*

Nuclear energy is back, driven by Big Tech's demand for clean, dispatchable power to ensure a reliable and affordable energy system

Tech players announcements

Post 2030

Google set to power its AI data centres with mini nuclear reactors

500 MW PPA with Kairos Power

Microsoft hires energy mavericks in quest for nuclear-powered datacenters

20 year PPA with Constellation Energy of Three Mile Island Nuclear plant

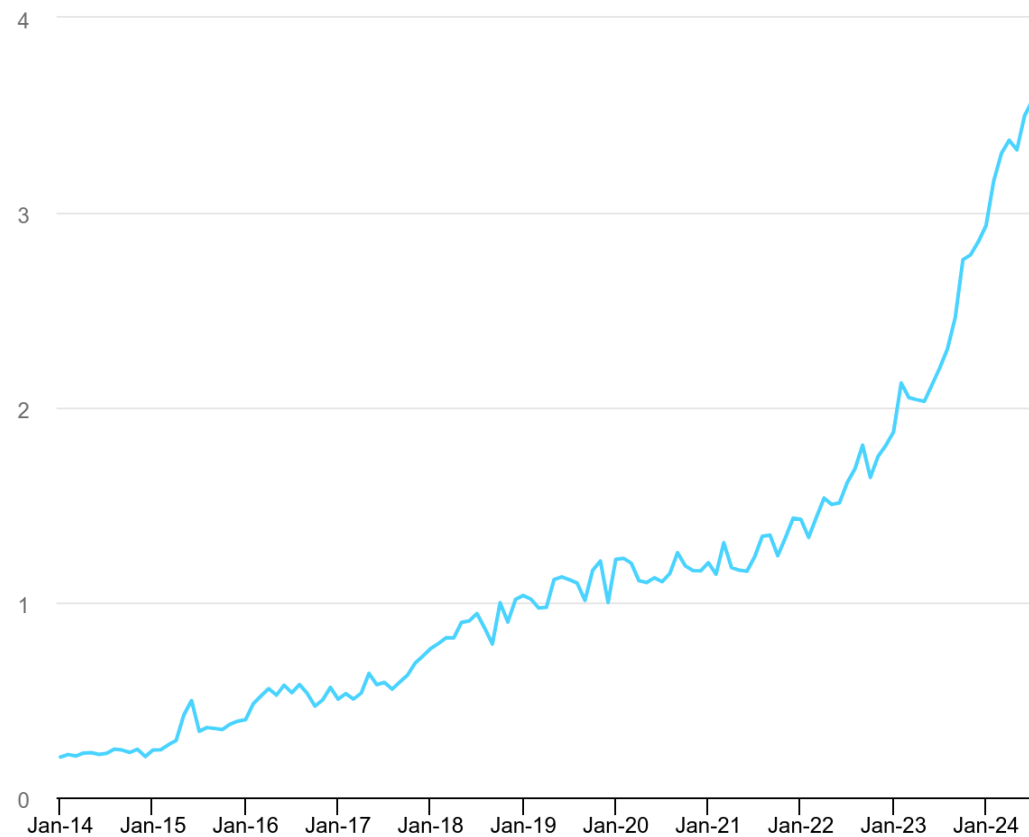
Amazon goes nuclear, to invest more than \$500 million to develop small modular reactors

\$500 M financing led by Amazon for X-Energy
320 MW PPA with Energy Northwest
Acquired 960 MW data center campus

Investment in data centres in the United States

2014-2024

Index December 2019 = 1







Nuclear startups received **>50%¹** of **global VC/PE funding** in H2 '24 for clean power equipment as electricity demand from data centers is increasing



PPA = Power Purchase Agreement, SPS = Stated Policies Scenario 1) Equals \$476 MN in second half of 2024. Since nuclear technologies are capital-intensive, they tend to close larger rounds of funding.

Source: BloombergNEF (2024), IEA (2024) What the data centre and AI boom could mean for the energy sector

Smaller reactors offer scalable, highly flexible nuclear solutions with reduced investment needs and possibly shorter lead times than traditional reactors

Technology	Process	TRL	Companies
Small Modular Reactors (SMR) <300 MW	High-temperature gas reactor (HTGR) HTGRs use helium coolant and graphite moderation , operating at high temp, using TRISO-coated fuel . Enables efficient power and heat generation for versatile energy applications.	7	
	Light-water small modular reactor (LWR) LWRs use uranium fuel, water as both a coolant and moderator . They operate at lower temperatures and pressures , using uranium fuel . Often designed for scalable, modular deployment	6-7	
	Other advanced reactors Designs like molten salt (MSRs) , fast reactors , and liquid lead-cooled types (LFRs) . They offer higher efficiencies, flexible fuel use , and inherent safety features , often operating at high temp. for diverse energy and industrial process heat applications	3-5	
Nuclear Micro Reactors (NMR) <50 MW NMRs focus on compact, simplified, transportable designs and rapid deployment and niche applications with greater efficiency and flexibility, tailored to their small size and specific use cases	n/a		

Sources: BloombergNEF (2024), International Atomic Energy Agency (2023)

SMRs/ NMRs offer a compact, flexible, and modular nuclear power solution for zero-carbon baseload, yet question persists which ones will be the first

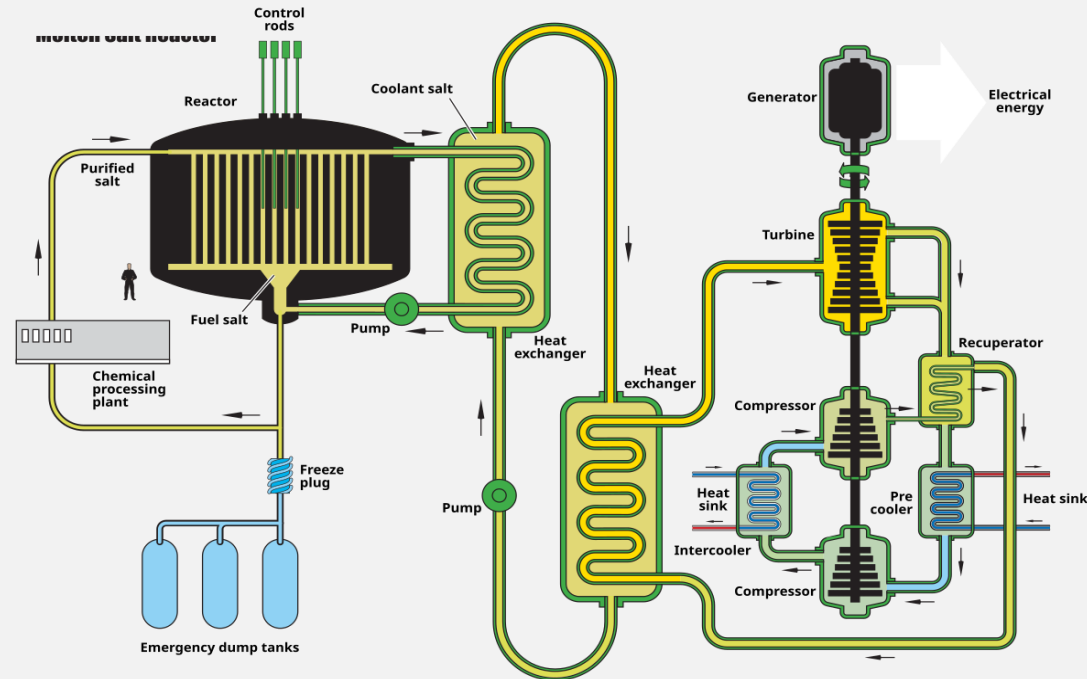
Key advantages

- **Scalable & flexible:** Modular, site-specific deployment
- **Enhanced safety:** Some moderators have inherent safety features
- **Higher efficiency:** Other fuels feasible, potentially leading to less waste
- **Lower costs:** Can lead to cost-effective, modular production and be deployed incrementally
- **Reliable, zero-carbon baseload:** supports a range of uses¹

Current status

- Small modular reactor deployment remains nascent with 80 SMR designs under development (majority <300 MW)
- Two operating SMRs in 2024
- By 2030, first SMR expected to be on the North American grid
- Pledge at COP28 to triple global capacity by 2050

Example: Molten Salt Reactors (MSRs) operate by circulating a **mixture of molten salts**, either as **coolant or as fuel-coolant** combination containing fissile material, at high temperatures through a reactor core to produce **heat for electricity** generation



- **Core:** Fuel² goes into the core and undergoes nuclear fission to produce heat, then transferred to a coolant (e.g., heavy water or molten salt)

Notes: 1) Supports a broad range of uses, including electricity generation, heat production for industrial processes, hydrogen production through high-temperature electrolysis, and power supply to remote or off-grid sites 2) HTGRs and LWRs use TRISO fuel/ Uranium-235, advanced reactors employ a range of fuels including TRISO, HALEU, metal fuels, molten salt, mixed oxides, thorium-based fuels Sources: BloombergNEF (2024) Advanced Nuclear. Much promise, but patience needed

Significant costs, lengthy reactor licensing, low technical readiness, and an unestablished supply chain are key barriers for new nuclear

Key barriers



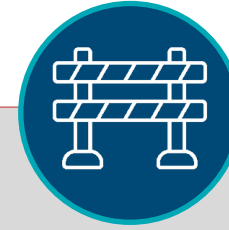
ECONOMICAL

- **High initial costs:** Development and approval are expensive due to limited suppliers and scalability challenges
- **Competition from faster-to install renewables + batteries:** Falling costs of renewables and storage require NMRs to demonstrate distinct advantages to gain market share



TECHNICAL

- **Supply chain and resource availability:** Sourcing the specialized nuclear fuel (e.g.) remains challenging
- **Lead times:** Long lead time and often-poor record of on-time delivery
- **Waste management:** logistical challenges for nuclear waste management on a small scale, including final disposal



ORGANISATIONAL

- **Regulatory hurdles:** New reactor types may require updated safety standards and licensing, varying by country
- **Safety and security concerns:** Potential radiological hazards and national security risks remain, with many designs being unpopular among citizens

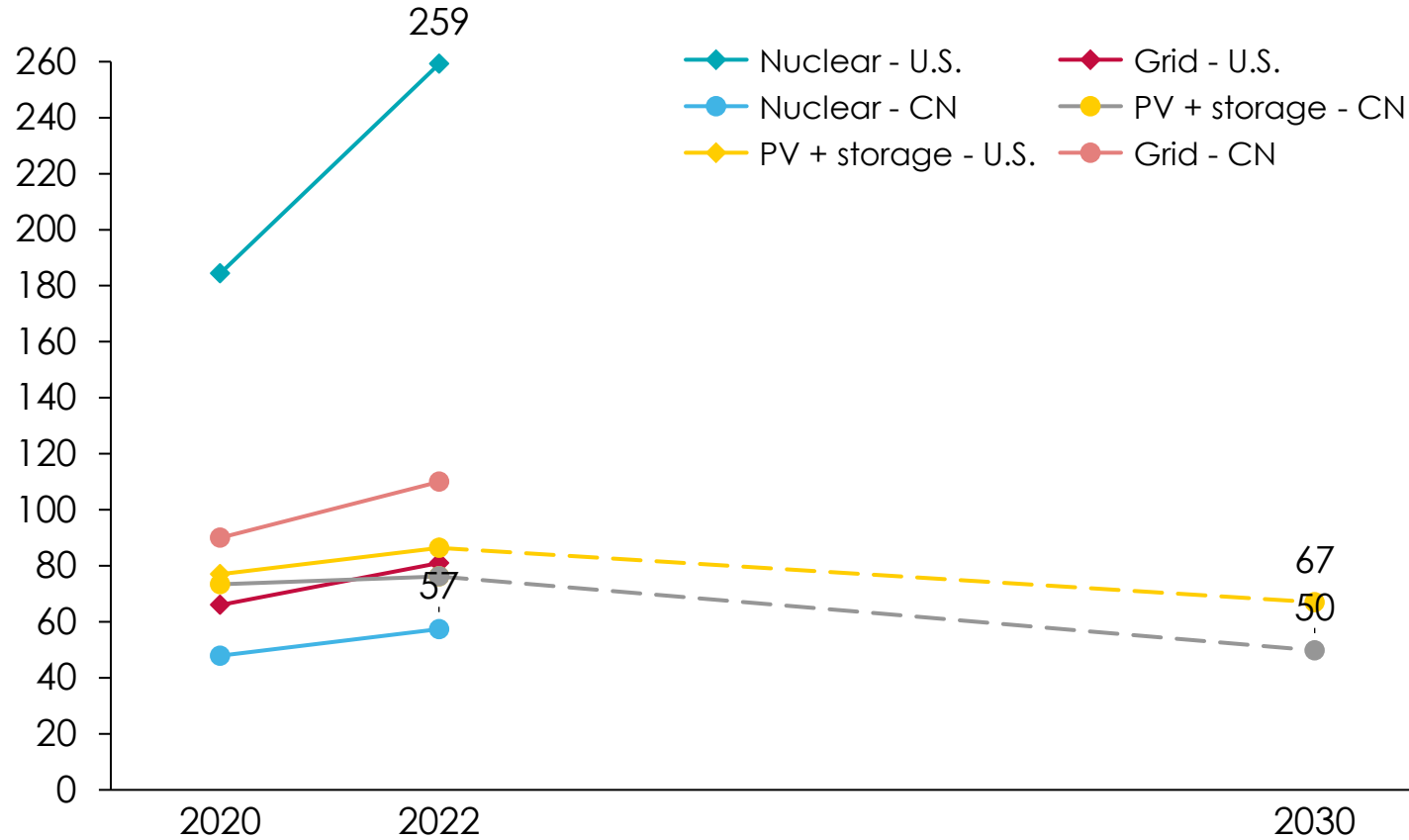




Hypothetically, nuclear has the potential to be a cost-competitive and flexible energy in certain regions, but other renewables are cheaper

LCOE comparison Nuclear, PV + Storage, Grid¹

\$/MWh



Key considerations

On the cost of Nuclear



LCOE of nuclear **varies heavily by region**, with **U.S. reactors being among the world's most expensive** and **China's the cheapest**²



SMRs and NMRs have potential to **lower LCOEs**³, but with **nascent tech readiness**, advanced reactors **won't be online until post-2030**



With **faster-than-predicted declines in LCOEs** of dedicated renewables and battery storage, it is **unlikely that nuclear can achieve similar levels in the near future**

Notes: 1) LCOE mid scenario taken from BNEF For battery storage the LCOE includes a charging costs. LCOE include carbon pricing in markets where policies are already implemented. LCOE of nuclear does not further specify between conventional reactors or SMRs/ NMRs, Average CN, U.S. grid prices for industry applied, 2) due to differences in regulatory environment, construction practices, labor costs and market dynamics, 3) reasons include factory manufacturing, reduced construction time, simplified regulation

Sources: ETC analysis based on BNEF (2023) LCOE H2 2023

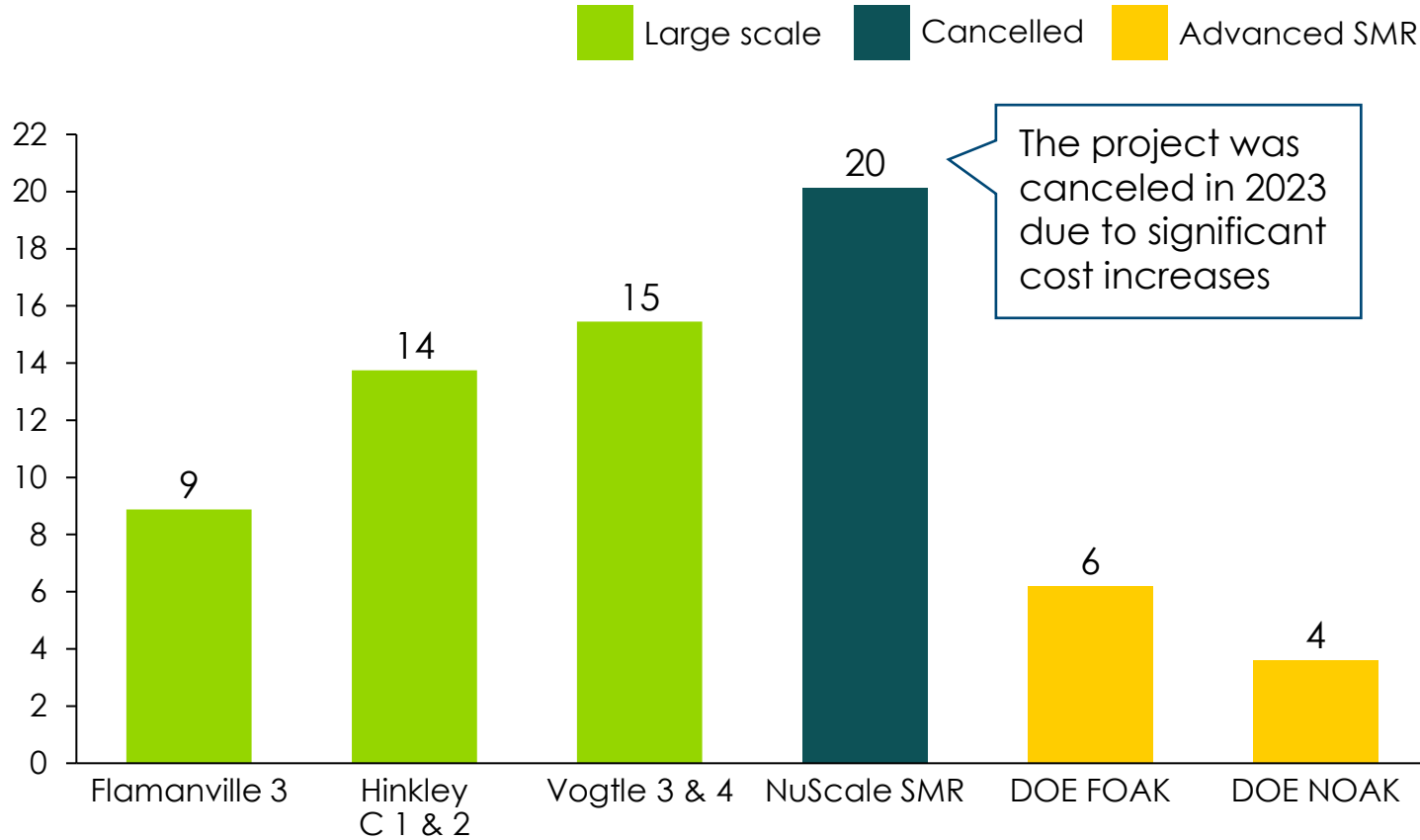




SMR/NMRs face substantial obstacles, with some projects already being discontinued

Estimated/promised costs for new nuclear reactor construction

k\$/kW



Considerations

On costs of advanced small, nuclear reactors

Faster deployment: Modular designs reduce construction times, cutting costs and accelerating revenue generation.

Scalable investment: Capacity can be expanded as demand grows, spreading capital costs over time

Lower safety costs: Inherent passive safety reduces the need for complex active systems, cutting expenses.

Simpler regulation: Advanced designs can streamline regulatory processes, reducing compliance costs

Lower fuel costs: Some advanced reactors use alternatives to costly, highly regulated enriched uranium

Notes: NuScale Power Module, a Small Modular Reactor utilized a pressurized water reactor design Department of Energy estimates on First-of-a-kind (DOE FOAK) and Nth-of-a-kind (DOE NOAK) advanced SMR technologies

Source: BloombergNEF (2024) based on U.S. department of Energy Nov, 2024





Nuclear continues to face challenges, even with cautious government support

Headwinds

Examples

Cost Overruns and Delays: NucScale reactor (U.S.) stop –costs jumped 75% from their original price tag

Government withdrawals: Germany's nuclear phase-out after Fukushima due to safety and public opposition

Safety Accidents: Chernobyl (1986) and Fukushima (2011) heightened global fears over nuclear risks.

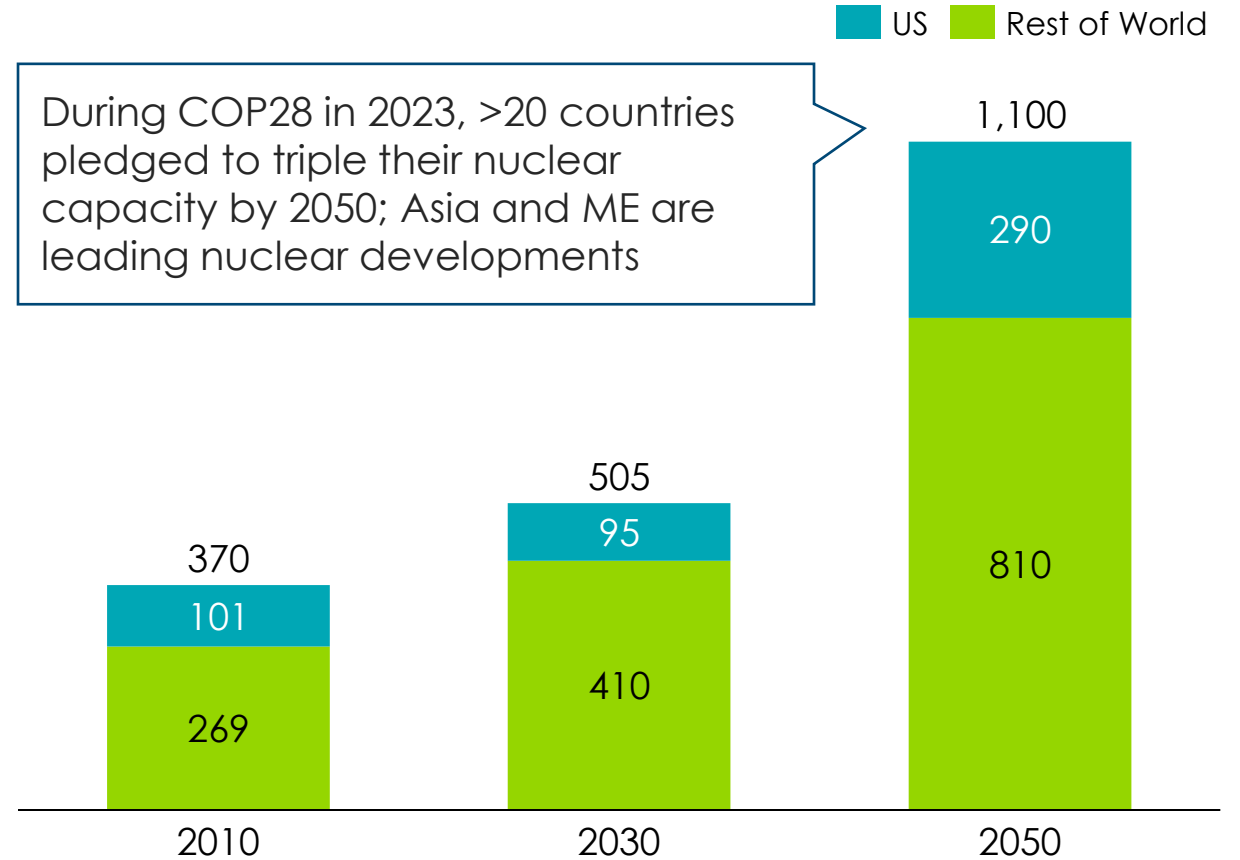
Waste Management Challenges: Long-term disposal of radioactive waste remains unresolved and costly.

Environmental Impact: Some feedstocks, e.g., uranium mining causes land/water damage; high water use for cooling

Security Risks: Ukraine war underscored vulnerabilities of nuclear plants in conflict zones






Global capacity aspirations

GW



Source: Estimated capacity for the U.S. based BloombergNEF (2024) based on U.S. department of Energy Nov, 2024

New nuclear faces commercialization, cost, and regulatory hurdles, limiting its near- to mid-term impact on energy demand

Final energy demand type 	Impact on energy demand by 2050 
Electrification	 <p>Could see an uptick if commercialization of SMR/NMRs occurs in late 2030s, but remains highly uncertain</p>
Final hydrogen use/e-ammonia	 <p>H2 and e-ammonia overall share may not see substantial changes without significant technology breakthroughs (e.g., fusion)</p>
Carbon based fuels (e-SAF, methanol, fossil with and without CCS)	 <p>Nuclear technologies could potentially compete with fossil fuels (+ CCS) for baseload generation</p>

Key questions/considerations

- In the long-term SMRs/NMRs could also face competition not only from renewables and storage but also Nuclear fusion technologies
- SMR/ NMR technologies are in nascent stages, in how far could recent policy support accelerate their development?
- By when is it realistic to assume LCOE of nuclear will come down to costs of renewables + storage?

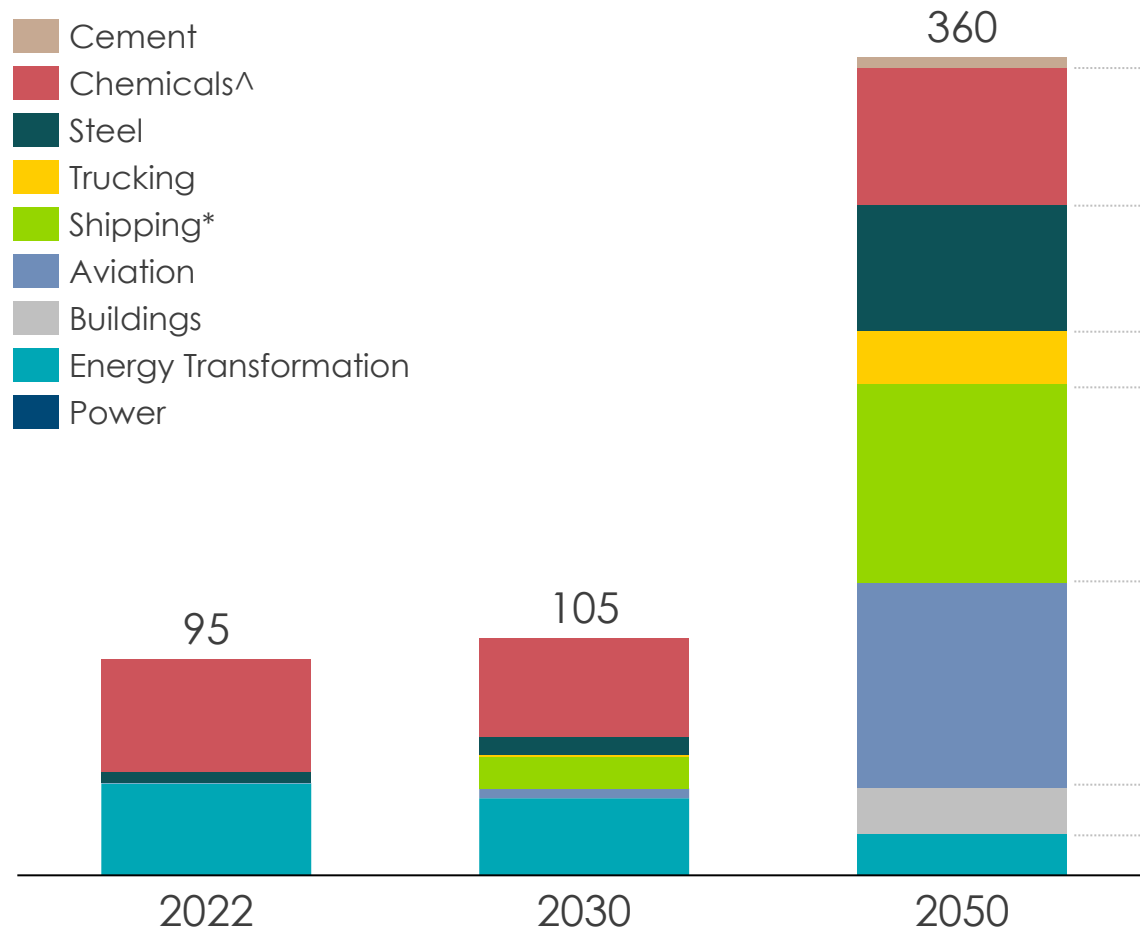


White hydrogen and optimizing electrolyzer costs

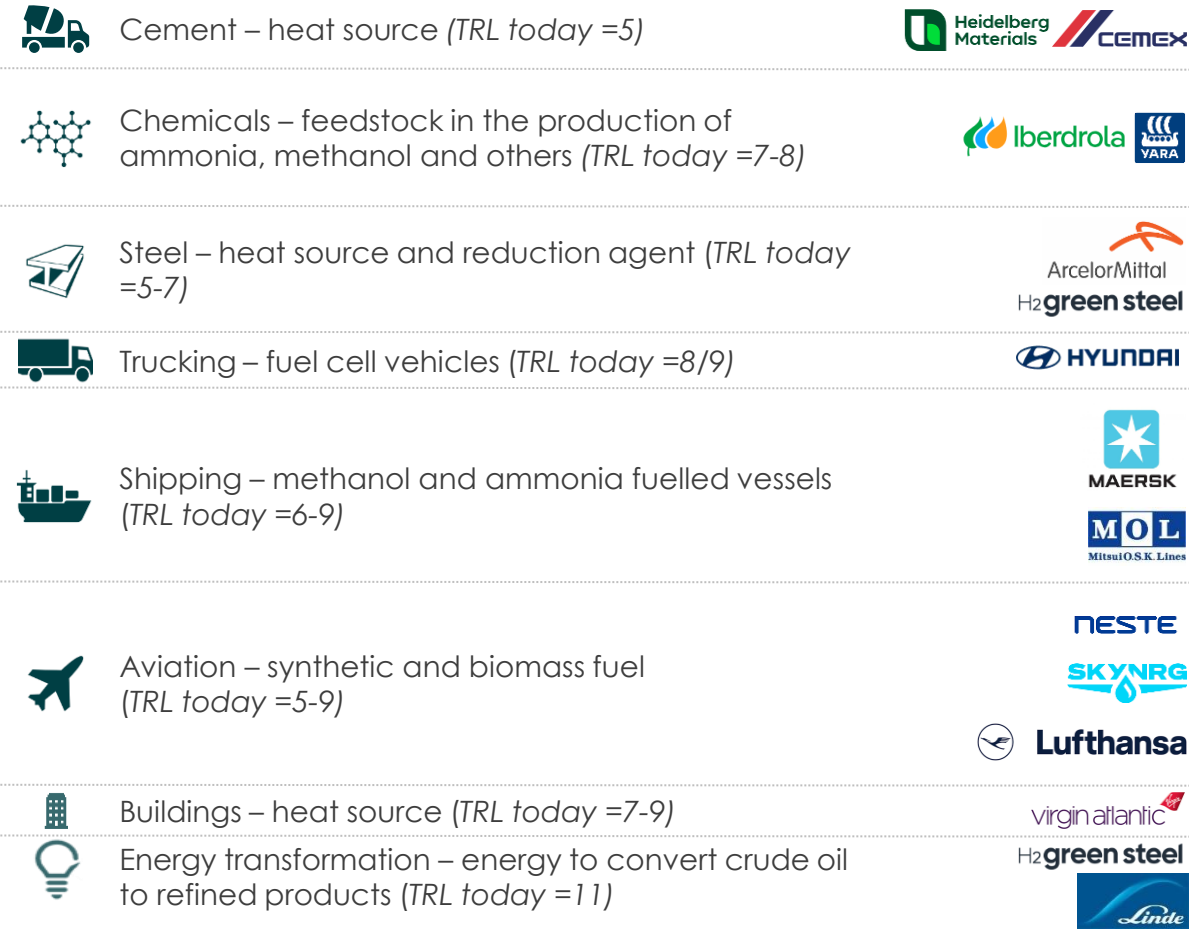


Low-carbon hydrogen demand is expected to grow substantially to 2050, driven by decarbonization particularly of the harder-to-abate sectors

Direct and indirect hydrogen demand¹, per annum Mt H₂



Hydrogen application



1. Includes all hydrogen types. ^Includes petrochemicals, ammonia and methanol, *chemicals sector does not include ammonia/methanol used in shipping, which is accounted for separately under 'shipping'
 Source: Energy Transition Commission (2023) Fossil Fuels in Transition

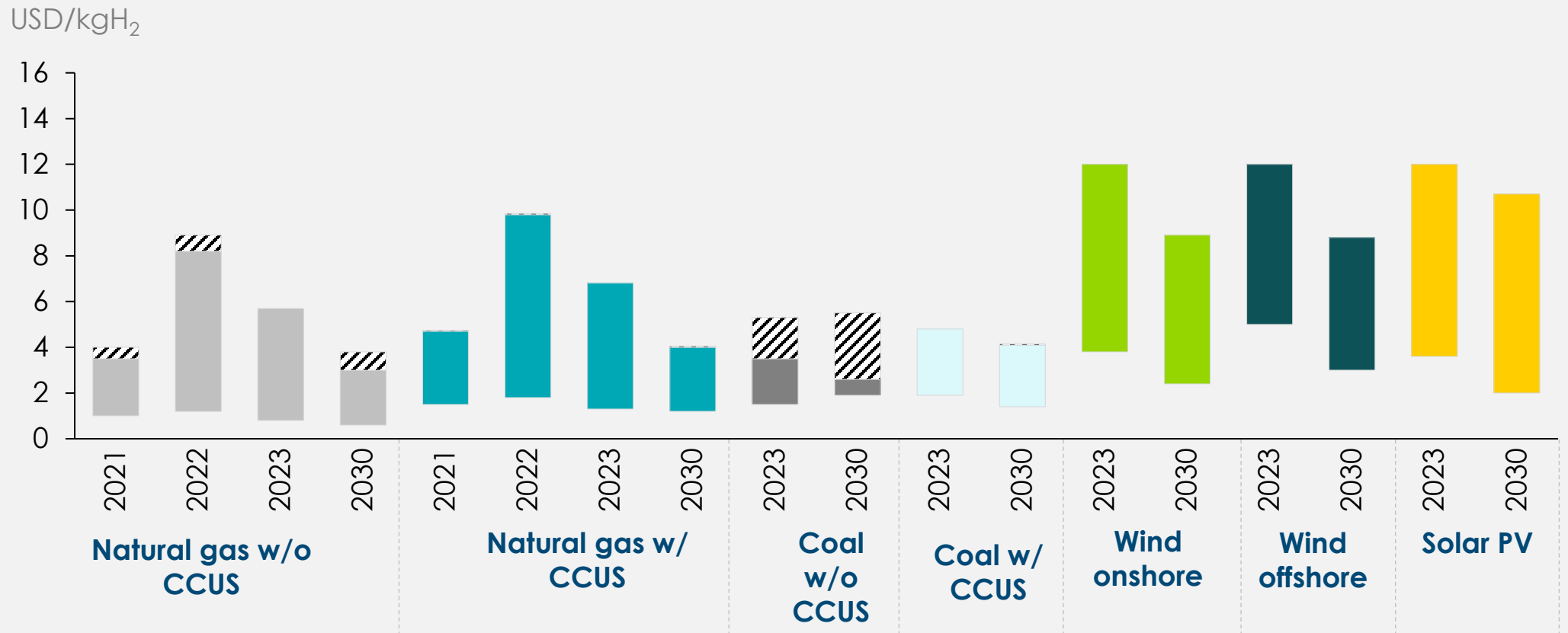
However, the cost of low-carbon hydrogen will need to come down from today's levels, to be competitive and enable demand scale-up

COSTS OUTLOOK








Hydrogen costs, \$ per kg 2023

Hydrogen production cost by pathway, 2023, and in the Net Zero Emissions by 2050 Scenario, 2030



Note: 1. There is limited evidence of the breakdown of current levelized costs and how existing projects will achieve this cost reduction. Dashed area represents the Co₂ price impact, based on USD 15-140 t/Co₂ for the NZE Scenario. Source: IEA (2024) *Global Hydrogen review 2024*

Potential disruptions offering low cost, low-carbon hydrogen could include white hydrogen and cost optimization of electrolyzer systems

Technology	Process	TRL	Companies
White hydrogen	White hydrogen involves drilling through geological layers and injecting a mixture of water, sand and chemicals under high pressure to release the gas from rocks	3-4	 
Cost optimization of electrolyzer systems	Advances in electrolyzer technology and manufacturing , along with improvements in the balance of plant and design optimization, are expected to materially reduce the cost of electrolyzers.	8 (SOEC)	  TOPSOE
	Besides established Alkaline and PEM electrolyzer tech, advancements continue to be made in higher efficiency electrolyzers (such as SOEC) , and the trade offs explored between costs and other dimensions (e.g. efficiency, stack lifetimes) to develop electrolyzers with less reliance on expensive materials such as Anion Exchange Membrane (AEM) technology.	7 (AEM)	 Enapter

Several key technological and economical challenges need to be overcome to realise developments in low-cost, low-carbon hydrogen

Key barriers



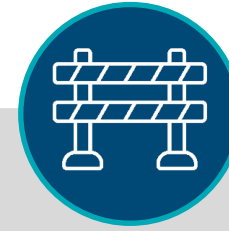
ECONOMICAL

- **White hydrogen** costs are relatively unknown, but there could be challenges with high exploration, capital and transport costs
- **Electrolyzer stack** degradation and replacement, and materials costs for scarce materials.
- Risk of lock-in of other fossil based and 'blue' hydrogen technologies



TECHNICAL

- **White hydrogen** challenges in drilling for the resource, i.e. which depth and how best to drill, measurement of hydrogen concentrations
- For developing electrolyzer types such as **SOEC** - moderate technical challenges in trying to extend stack lifetimes



ORGANISATIONAL

- **White hydrogen** faces long lead times for project development
- Scaling of H2 generally faces the same challenges as existing hydrogen production routes for infrastructure requirements, but some could be addressed before disruptions scale



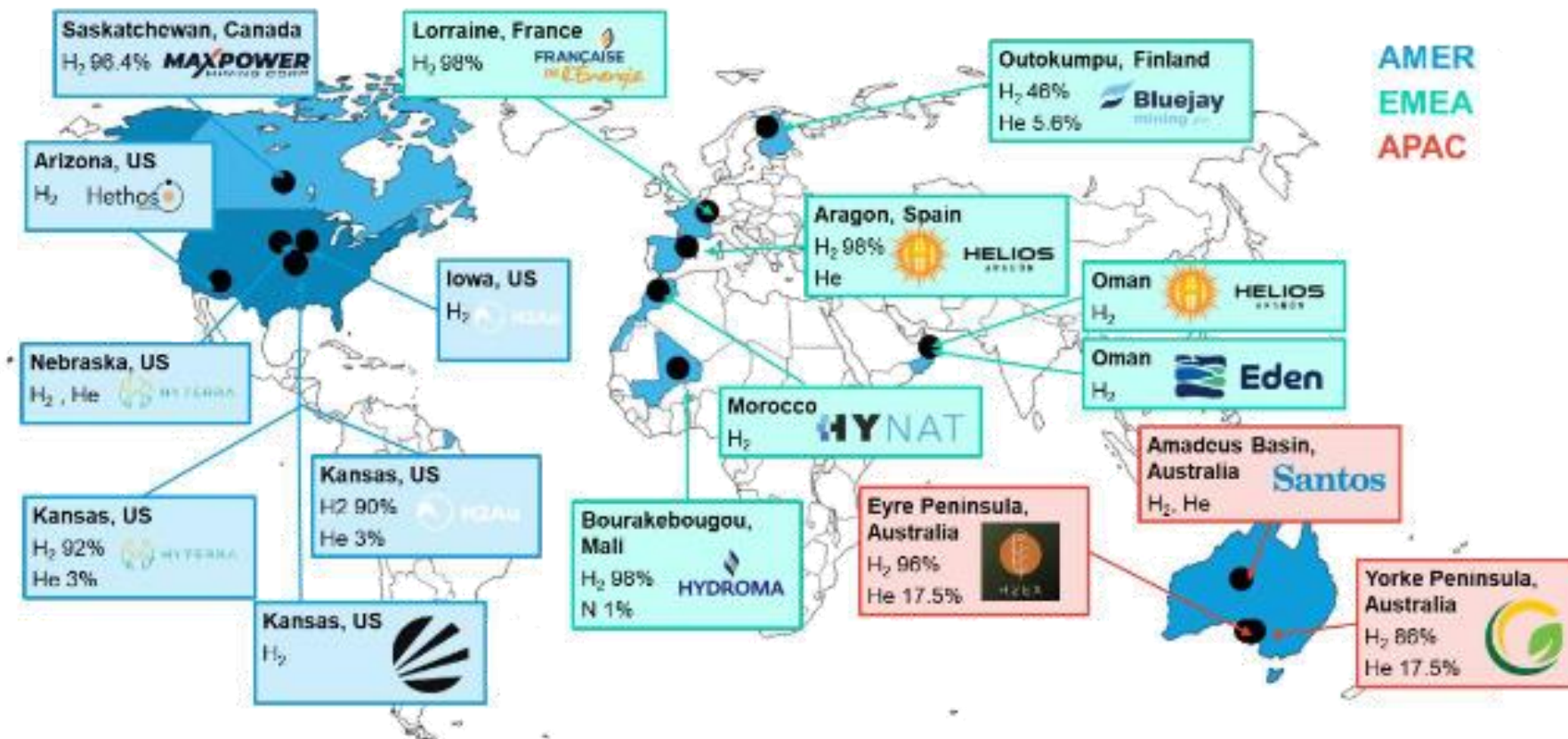
Project pipelines for disruptive Hydrogen technology – early exploration for white hydrogen

MARKET POTENTIAL



Helium co-product can help project economics

White hydrogen and helium: Projects and exploration activity



- 17 exploration projects ongoing for white hydrogen
- \$0.5-\$2.4 kg/H₂ targeted costs, with commercial production unlikely until 2030
- Exploration undertaken by **pure-play explorers** (e.g. Helios, Gold Hydrogen) and **existing oil, gas and mining companies** (e.g. Santos, Engie, EcoPetrol)
- Only **one white hydrogen** resource has been developed to date – in Mali 2012
 - 50 t/H₂ per year
 - Combusted to power a nearby village

Source: Bloomberg NEF (2023) Tech Radar: Geologic Hydrogen

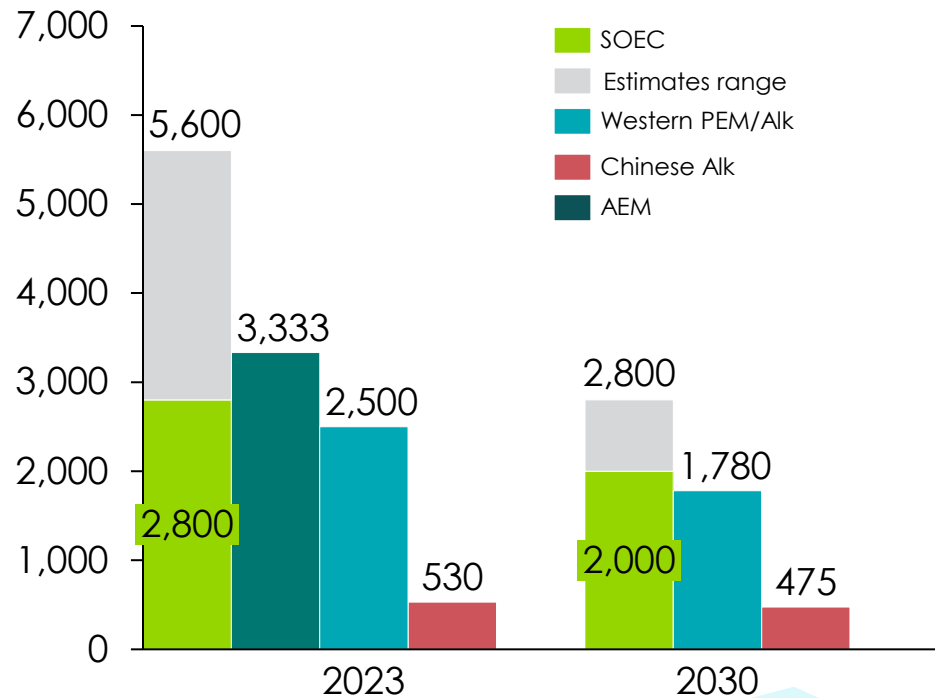
There are four main types of electrolysis technology in the market today

Electrolysis technology>	PEM – Polymer Electrolyte Membrane	AEM – Anion Exchange Membrane	Alkaline	HT – High temperature (SOEC)
Electrolyte	Acidic Solid (polymer)	Alkaline Solid (polymer)	Alkaline Liquid	O ₂ or H ⁺ conducting Solid (ceramic)
Description	Uses a proton conducting solid polymer electrolyte (SPE) for the assembly of the electrolysis cell and separation of H ₂ and O ₂ evolution reactions separately on cathode and anode sides	Anion-exchange membrane in combination with nickel-based electrodes. In contrast to alkaline electrolysis the use of the anion-exchange membrane enables the use of a dilute alkaline electrolyte or even pure water.	Uses nickel-based electrodes and a concentrated alkaline solution (25-35 wt% KOH) to enable the splitting of water	Electrochemical systems operating at high operating temperatures (600°C-900°C), allowing the splitting of steam into hydrogen (H ₂) and oxygen (O ₂), by use of a ceramic solid oxide membrane
TRL	9	7	9	8
Stack lifetime (hrs)	50,000-90,000	5,000 – 40,000	60,000 – 100,000	20,000 – 50,000
Advantages	<ul style="list-style-type: none"> • Relatively mature tech • High power densities • Fast startup and fast load changing capabilities 	<ul style="list-style-type: none"> • Does not use expensive minerals • Compact design • Potential to be low capex 	<ul style="list-style-type: none"> • Mature technology • Large capacity possible today • Does not use expensive minerals 	<ul style="list-style-type: none"> • High efficiency • Can co-electrolyze steam and carbon dioxide for syngas production, which can be used to synthesize fuels/chemicals
Disadvantages	<ul style="list-style-type: none"> • Use of expensive and potentially scarce PGM metals • Long term stability to be proven at MW scale 	<ul style="list-style-type: none"> • Shorter stack lifetimes relative to PEM and Alkaline • Low kW stack sizes driving up balance of plant costs 	<ul style="list-style-type: none"> • Low power densities • Slow cold start-up time • Inefficiencies created due to alkaline liquid used as electrolyte 	<ul style="list-style-type: none"> • High operating temperatures make for durability and lifetime issues • Stack lifetimes can be 4-8 times shorter than Alkaline and PEM



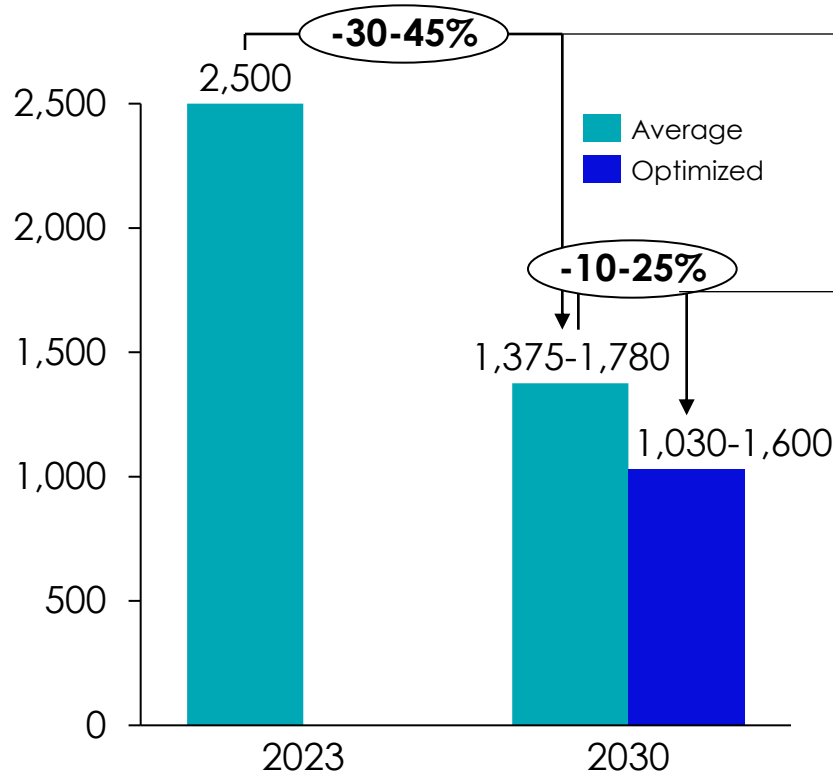
Estimates for highly optimized electrolyzer costs suggest a reduction potential of up to 70% cost reduction from today's levels

System electrolyser cost outlook^{1,2}, \$/kw



AEM relatively new compared to other technologies, so costs projections uncertain

Potential reductions in electrolyzer costs, \$/kw Western PEM/Alk³



On average – 30-45% reduction

- General electrolyzer technology and manufacturing advancements
- Balance of plant improvements
- Learning rate effects

Optimized – 10-25% reduction

- Successive project build to creating maximum learning rates
- Procure at large volumes
- Rigorous design simplification and standardization

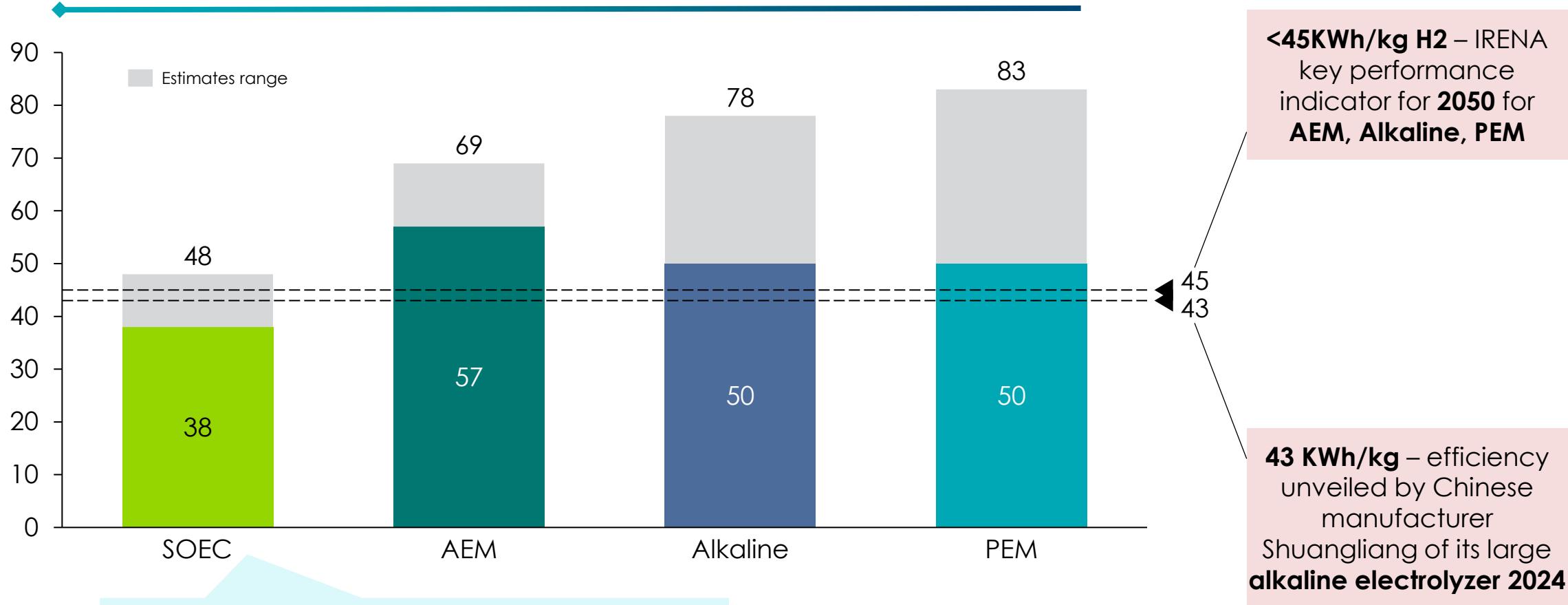


Source: 1. BNEF (2024) BNEF Hydrogen Market Outlook source for Western PEM/Alk and Chinese Alk electrolyzer costs. 2. SOEC ranges based off IEA (2023) Electrolyzers and HydrotechWorld (2023) The role of solid oxide electrolyzers in the green hydrogen landscape. AEM based off of . Clean Air Task Force (2023) Solide Oxide Electrolysis: A Tectomylogy Status Assessment 3. Potential cost reductions in electrolyzers based on Hydrogen Council (2023) Hydrogen Insights December 2023

The different electrolyzer system have efficiencies which can be traded off against their costs

Range of different system electrolyser efficiency 2023

kWh per kg H₂



SOEC can reach 38 kWh/kg of H₂ by utilizing external sources of process heat to generate steam.

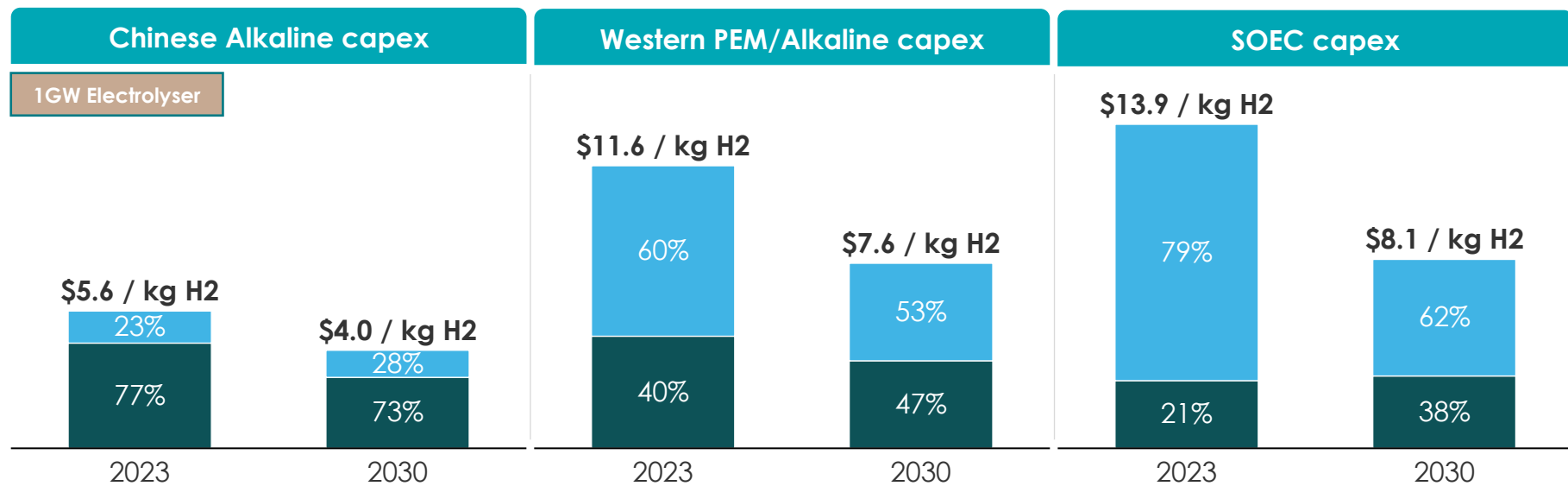
Source: BNEF (2024) BNEF Hydrogen Market Outlook for Western PEM/Alk and Chinese Alk electrolyzer costs. SOEC ranges based off IEA (2023) Electrolyzers and HydrotechWorld (2023) The role of solid oxide electrolyzers in the green hydrogen landscape. Clean Air Task Force (2023) Solide Oxide Electrolysis: A Tecyhology Status Assessment

Electrolyzer costs are a large share of LCOH currently, but energy costs become more important as capex drops

Electrolyser Cost of energy



Utility scale production with Solar PV dedicated renewable¹



Variable	2023	2030	2023	2030	2023	2030
Electrolyzer capex (\$/kw)	530	475	2500	1780	4200	2400
WACC (%)	10%					
Load Factor	35%					
Energy Cost (\$/MWh)	2023: \$70/MWh, 2030: \$52/MWh					
Efficiency (KWh/kg H2)	64	55	64	55	48	45

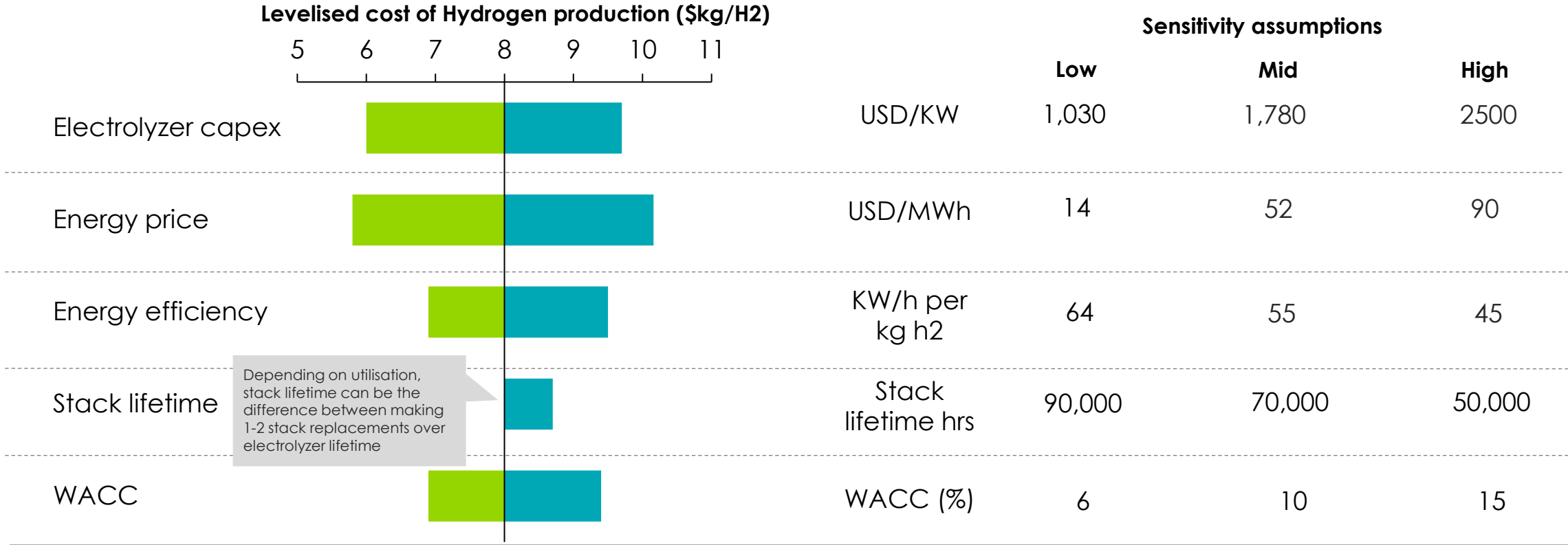


Main assumptions

Notes: 1. Mid LCOE prices used, no transport, storage, tax or margins. Electrolyzer costs based on BNEF (2024) BNEF Hydrogen Market Outlook source for Western PEM/Alk and Chinese Alk electrolyzer costs. SOEC ranges based off IEA (2023) Electrolyzers and HydrotechWorld (2023) The role of solid oxide electrolyzers in the green hydrogen landscape. Load factors, energy cost and discount rate based off of IEA (2024) Hydrogen Review 2024

Hydrogen and capex are sensitive to electrolyzer capex and energy prices, but other variables can be optimized

Illustrative trade-offs of hydrogen production costs, Western Alkaline example using Solar PV in 2030



Notes: 1. Mid LCOE prices used, no transport, storage, tax or margins. Electrolyzer costs based on BNEF (2024) BNEF Hydrogen Market Outlook source for Western PEM/Alk and Chinese Alk electrolyzer costs. SOEC ranges based off IEA (2023) Electrolyzers and HydrotechWorld (2023) The role of solid oxide electrolyzers in the green hydrogen landscape. Load factors, energy cost and discount rate based off of IEA (2024) Hydrogen Review 2024

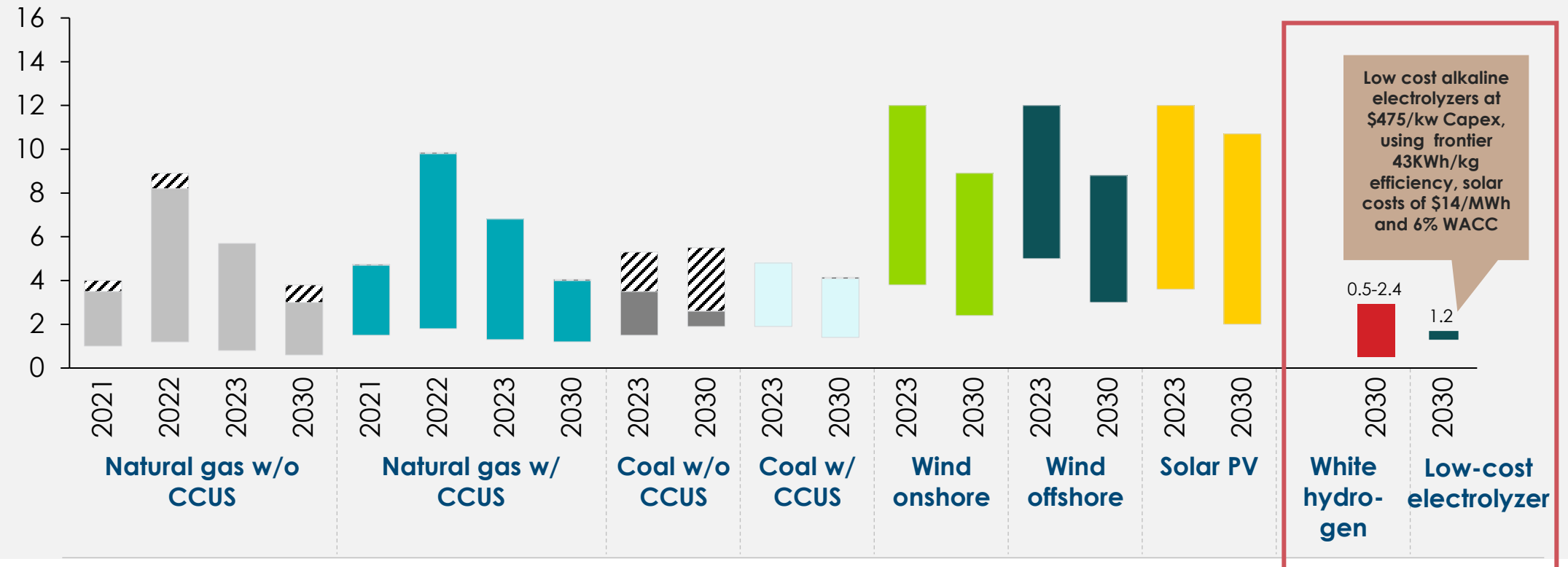


Hydrogen disruptions could see lower cost by 2030, enabling faster low-carbon H2 adoption

Hydrogen costs¹, \$ per kg 2023

Hydrogen production cost by pathway, 2023, and in the Net Zero Emissions by 2050 Scenario, 2030

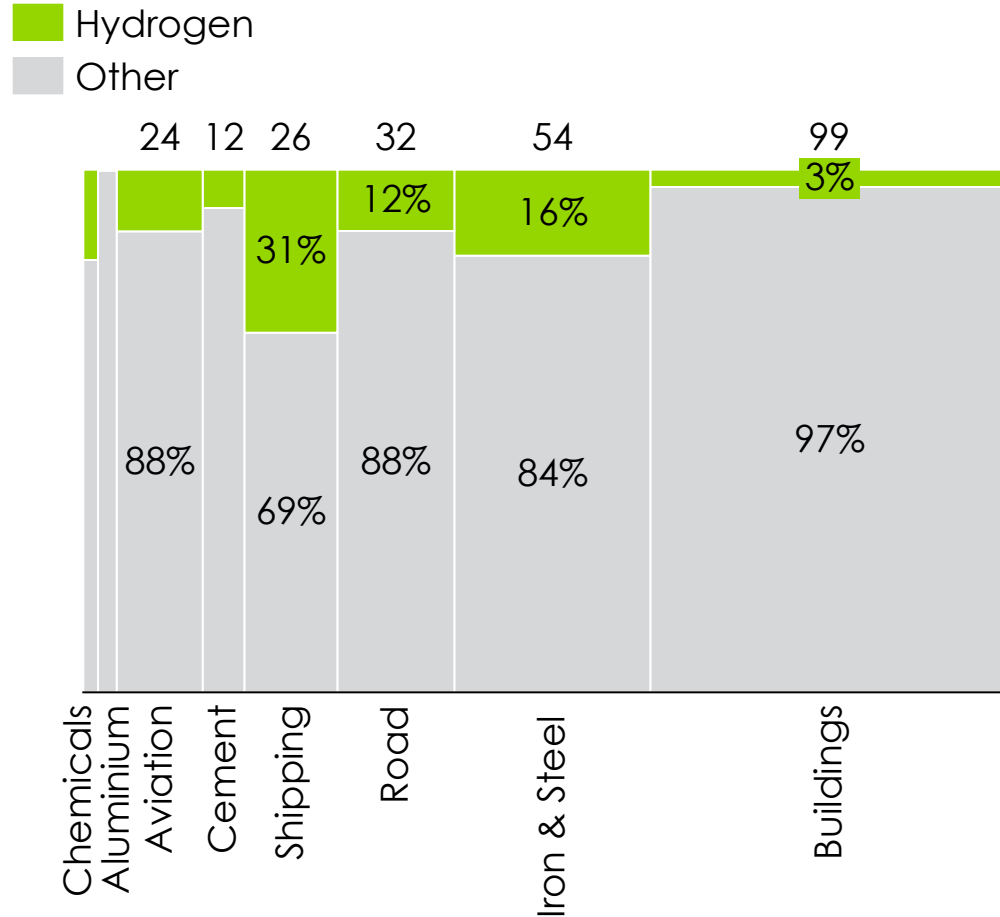
USD/kgH₂



Note: 1. There is limited evidence of the breakdown of current levelized costs and how existing projects will achieve this cost reduction for white hydrogen. Dashed area represents the Co2 price impact, based on USD 15-140 t/Co2 for the NZE Scenario. Source: BNEF (2024) Tech Radar: Geologic Hydrogen. IEA (2024) Global Hydrogen review 2024

If cheaper hydrogen can be made available, which sectors are mostly likely to scale their usage?

Direct use of hydrogen and e-ammonia ETC AFC 2050 view, EJ



Proposed approach for constrained and unconstrained H2

Constrained

1. Evaluate priority sectors business case (shown left) and their sensitivity to higher H2 price
2. Reduce or eliminate H2 share if business case is not strong under higher H2 prices

Unconstrained


1. Find where business case of H2 for priority sectors reaches tipping point under progressive H2 prices
2. Evaluate against 'unconstrained' innovative disruptions from electrification – do H2 alternatives still compete?
3. Depending on 2 – replace with electrification or increase H2 share



Conclusions and next steps



Emerging conclusions

Technology disruption conclusion 	Sectoral implications
<p>1 Industrial heat electrification (>600°C) – High-temp technologies are advancing. Could be less capital intensive than other decarbonization tech</p>	<p>Has potential to displace potential to displace H2 and other carbon-based alternatives in heavy industry such as cement, steel and chemicals.</p>
<p>2 Electrical steam cracking – Cost-competitive electricity and technological advances could see electric crackers scale</p>	<p>Cracking in the chemical sector could be shifted to electric, displacing H2 and fossil alternatives</p>
<p>3 Molten Oxide Electrolysis and Electrowinning MOE/electrowinning technologies are advancing, bringing them closer to commercial readiness. They may be less capital-intensive than other decarbonization options</p>	<p>Cost-competitive electricity and technological advances could increase demand for electrons to produce iron in the iron and steel sector</p>
<p>4 Li-ion solid state batteries – Solid-state batteries have the potential to further accelerate electrification in mobility by significantly enhancing energy density.</p>	<p>Steady advancements in battery technology could increase demand for electrons across all road transport and even short-to-medium haul aviation and shipping</p>
<p>5 Advanced Direct Air Capture (DAC) – Technological advancements could significantly reduce the cost of DAC, but there is uncertainty whether these could materials to be any lower than \$100/t Co2 by 2050</p>	<p>Lower cost DAC could provide a more affordable, sustainable carbon source for synthetic fuels and chemicals, while also driving larger adoption of fossil + CCS technologies</p>
<p>6 Sodium-based battery technologies – allows a low cost and safe storage option, which could be commercial by 2030</p>	<p>Sodium further reinforces the scalability and economic viability of battery storage solutions to enable further renewable penetration in power system</p>
<p>7 Small Nuclear Reactors (SMR), Nuclear Micro Reactors (NMR) – Could see commercialization of SMR/NMRs occurs in late 2030s, but remains highly uncertain. Faces competition with decreasing cost of renewables+battery</p>	<p>If new energy demand such as data centres scales and there is not enough existing renewable supply, SMR and NMR could have a roll in meeting that demand by supplying a constant and reliable renewable power source</p>
<p>8 White hydrogen and optimizing electrolyzer costs – Electrolyzers costs are still expected to come down over time, but costs are still higher than previous forecasts. White hydrogen is still nascent</p>	<p>For sectors previously estimated to have H2 demand, potential to switch to an alternate decarb tech under high H2 prices</p>



Next steps....

- Quantification of unconstrained and constrained scenarios
- Further engagement with ETC members and other external experts
- Development of short 5-page publication and innovation briefs
- Begin Sprint 2 in early 2025

