Energy
Transitions
Commission

Carbon Molecules - Disruptions workshop

20/11/2024

Aims of this workshop

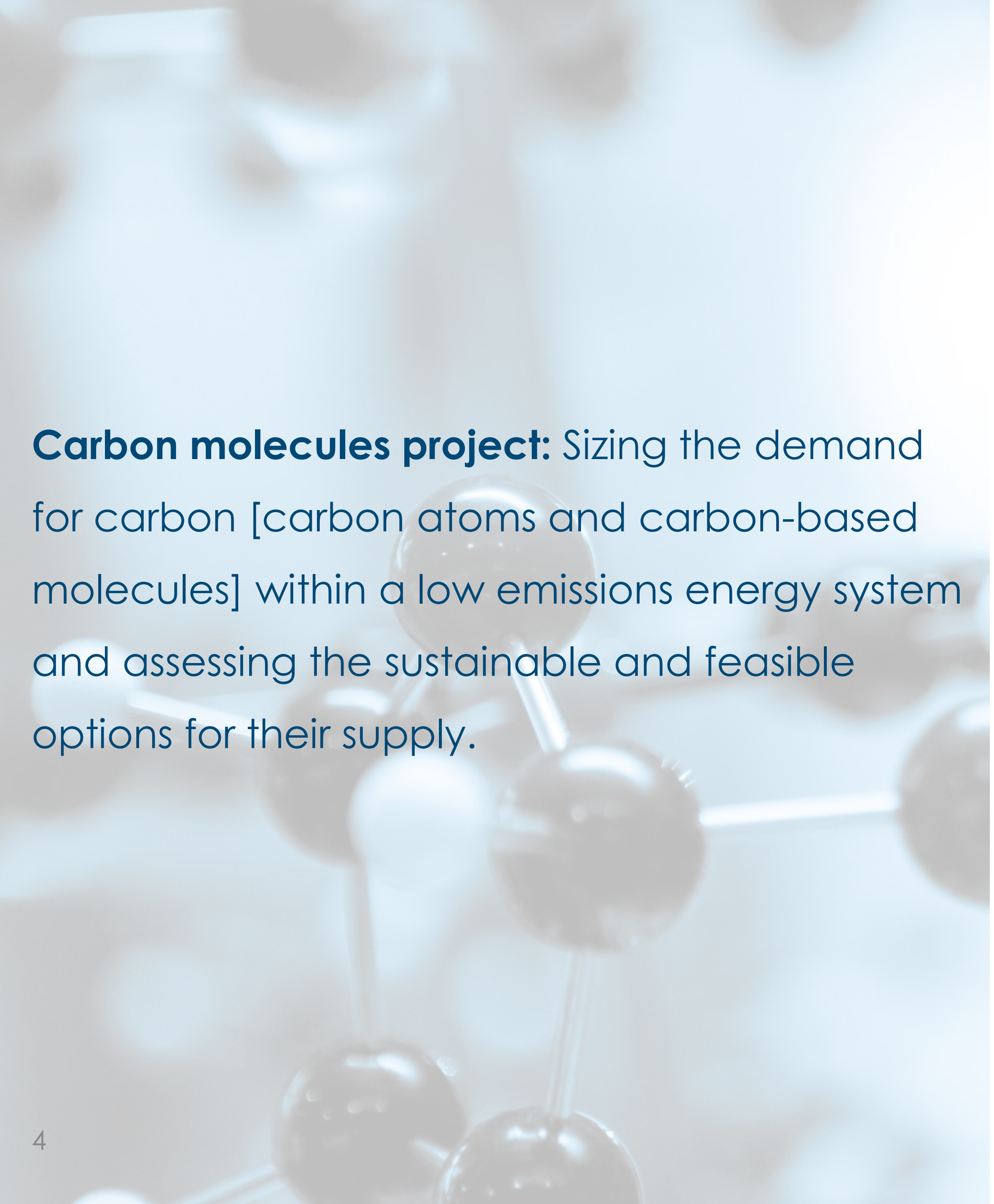
- Introduce the objectives and deliverables of Systemiq/ETC's carbon molecules work
- Understand the incremental trends challenging our views on the size of direct electrification and use of hydrogen
- Deep dive on the major technology innovation disruptions for electrification and hydrogen
- Gain feedback from members on the potential for disruptions to impact final energy demand

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	Deliverables
1. How large a role can and should direct electrification play in a zero-emission economy?	• 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 CO_2 (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	**Sprint 1A** How large can and should the **role of direct electrification** be in a zero-emission economy **Sprint 1B** **The role of hydrogen** and **derivatives (i.e., ammonia)** in a zero-emission economy?	**Sprint 2** The potential to **recycle** and **reuse carbon molecules**	**Sprint 3** Sources of **primary carbon: costs** and **sustainability**	**Sprint 4** **Report production and communication campaign running into COP30**	
Deliverables	• A 5-pager published externally • A series of short innovation briefs for publication	• Publication of the ETC report ahead of COP • A series of short innovation briefs for publication			
Key interactions	• 1-2 workshops with ETC Commissioners	• Workshop • Report reviews • Report launch at COP			

Agenda

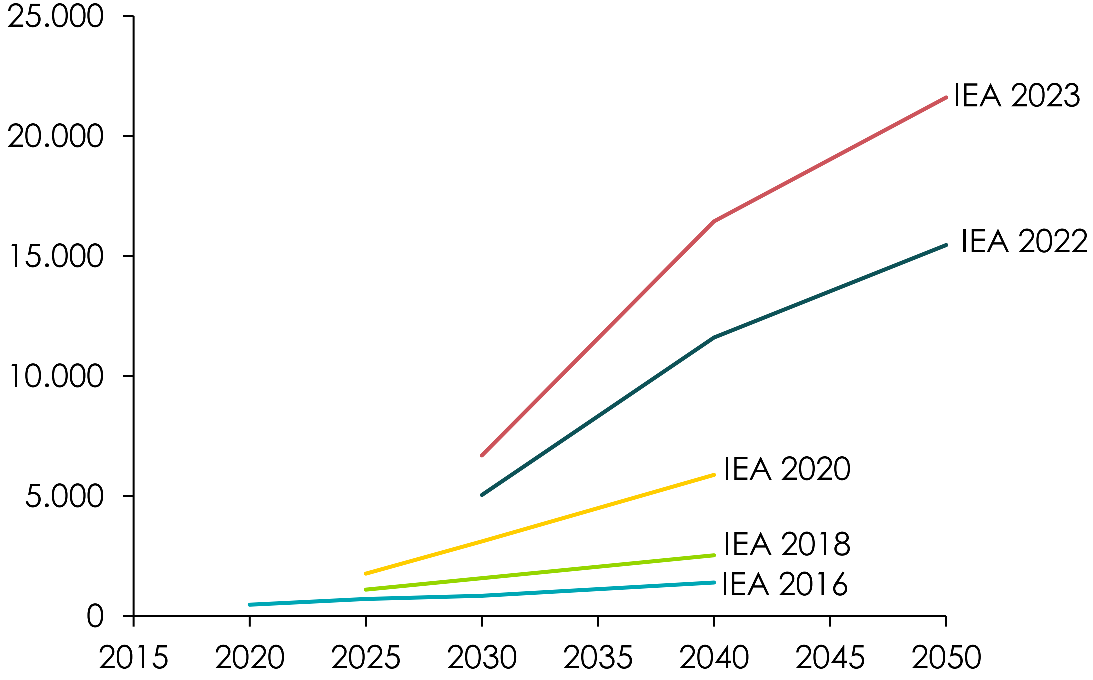
Introduction to the Carbon Molecules Work

Changing trends for electrification and hydrogen

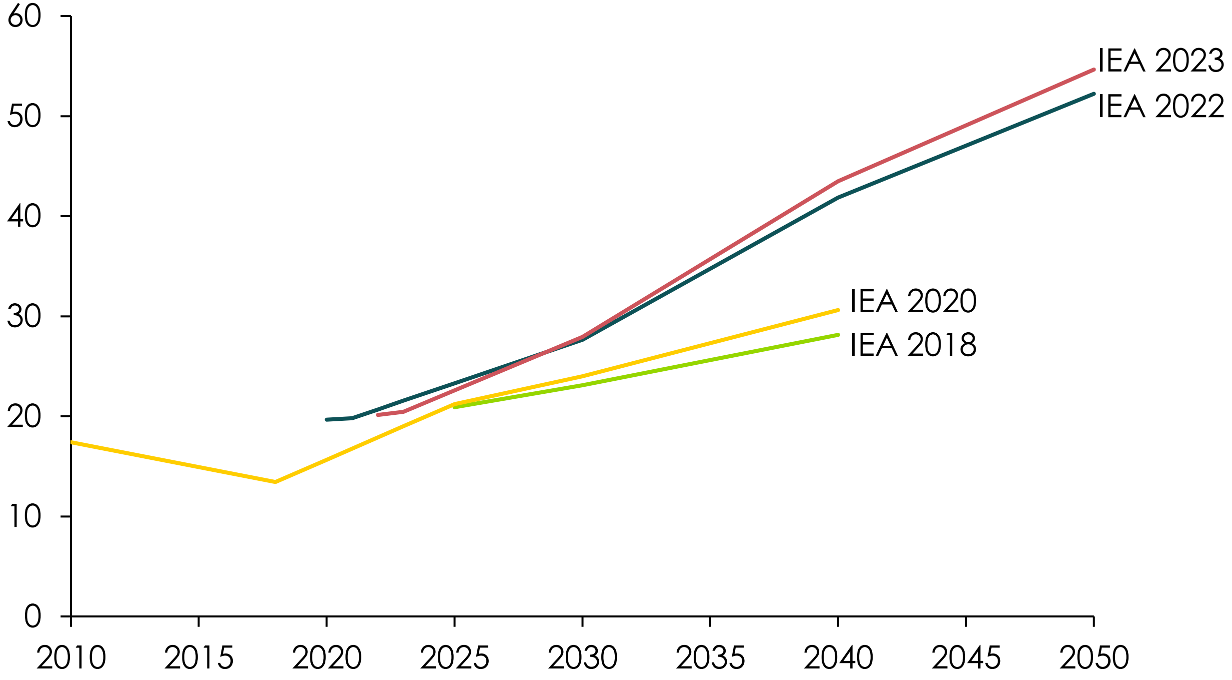
Disruption deep-dives

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, %



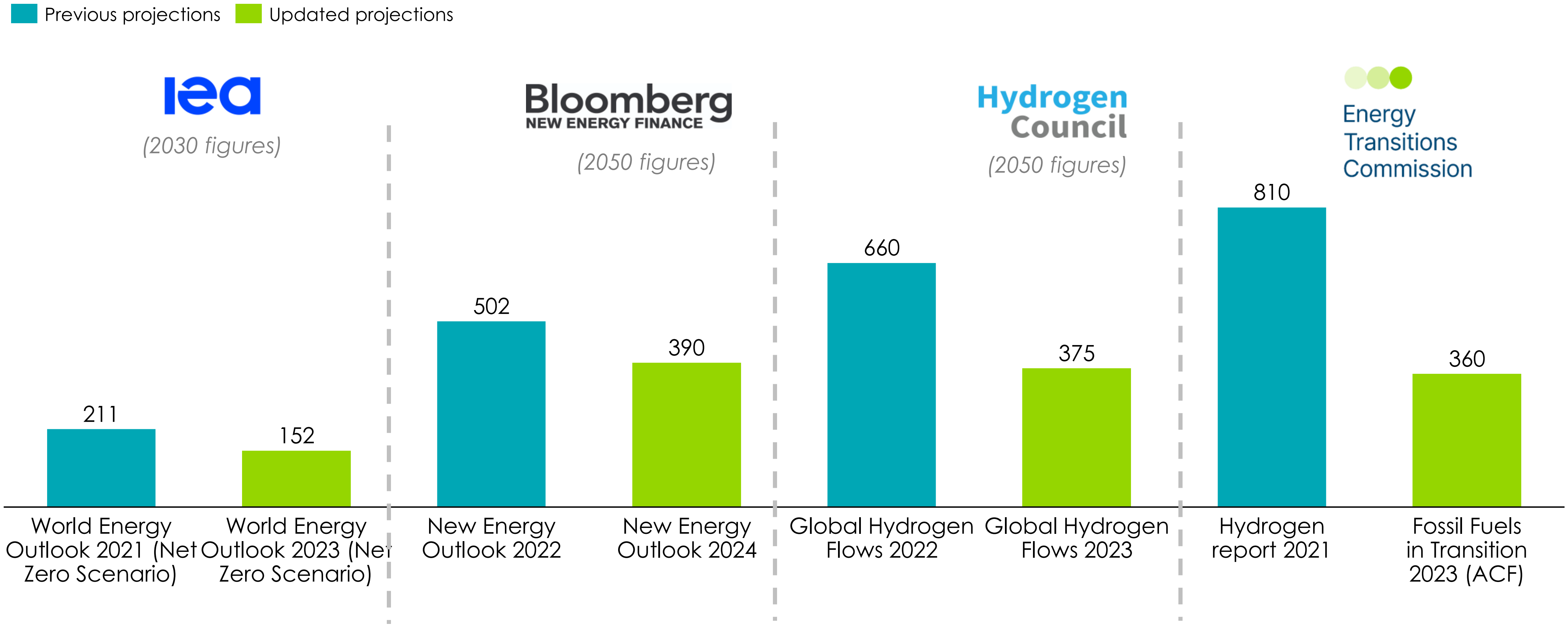
IEA scenarios in World Energy Outlook reports

— 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

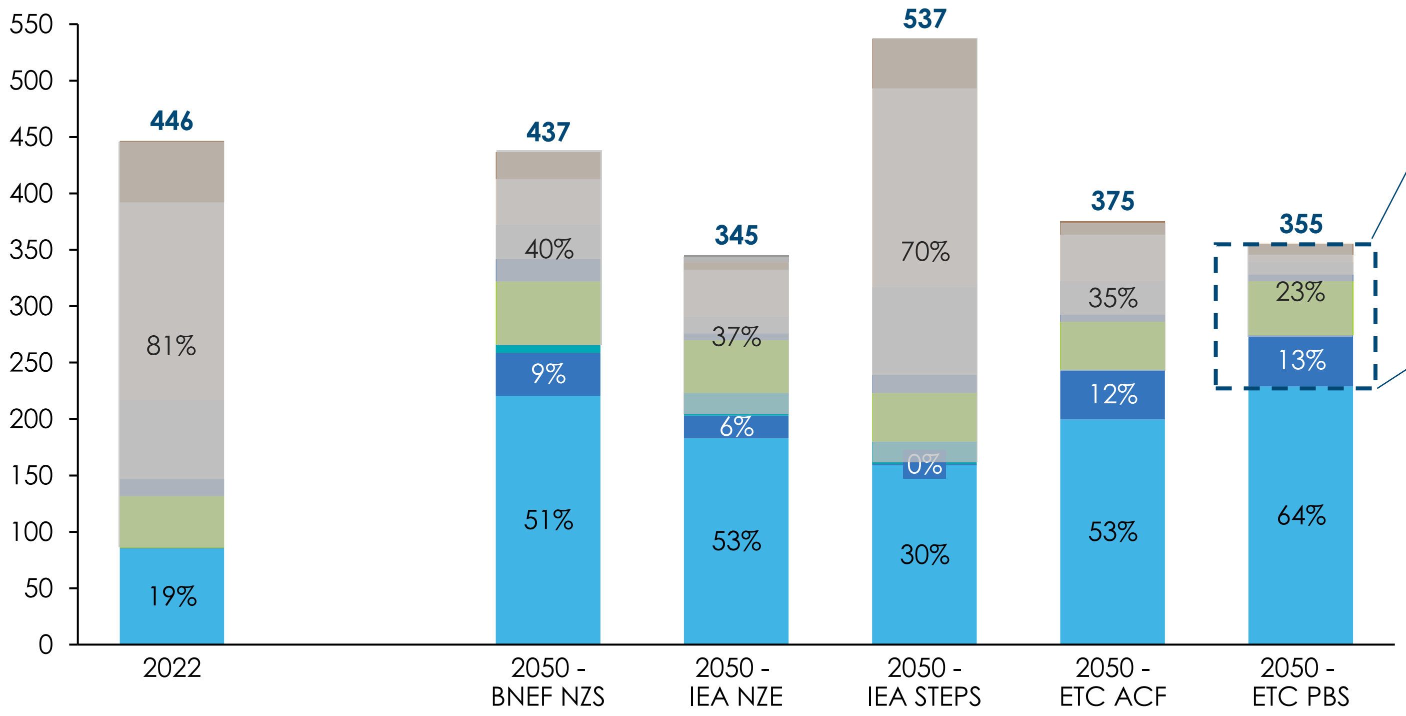
Global hydrogen demand has been revised downwards, Mt H2



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

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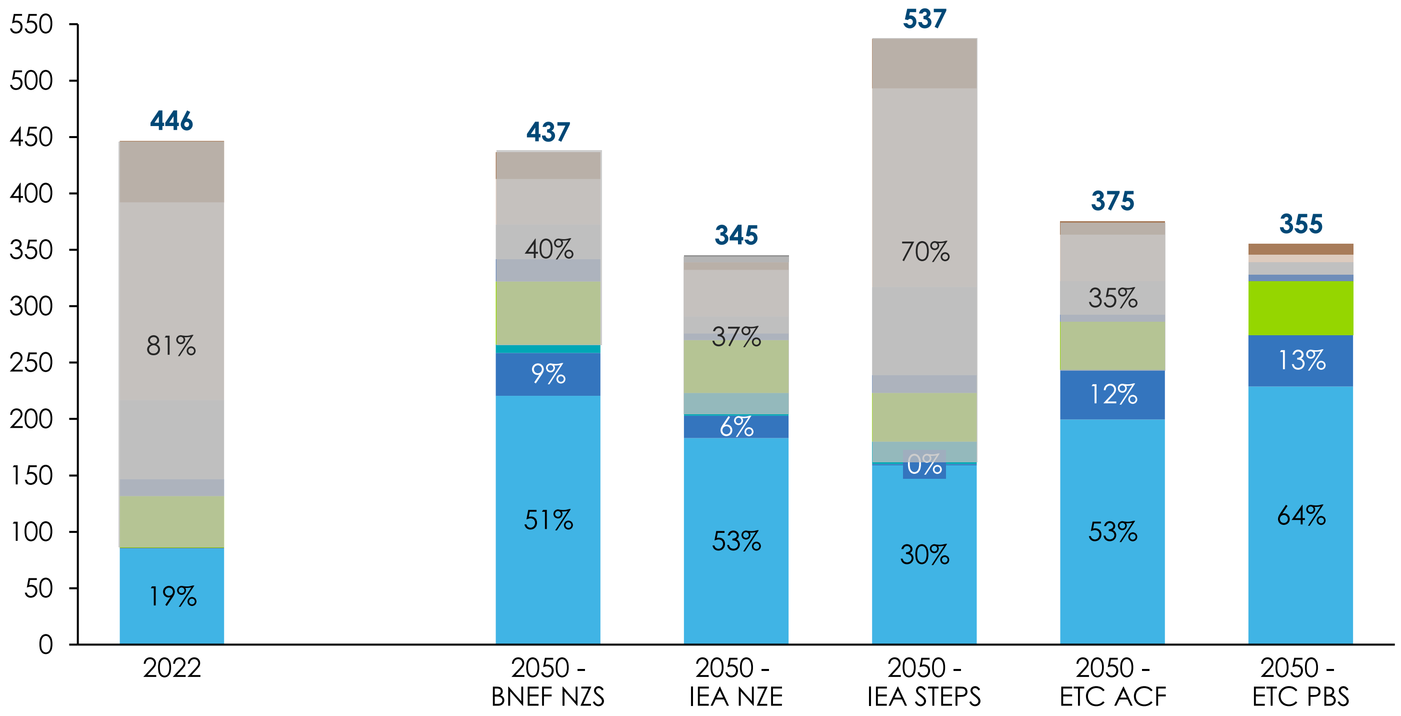

Systemiq/ETC is producing a new updated set of scenarios:

- 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;
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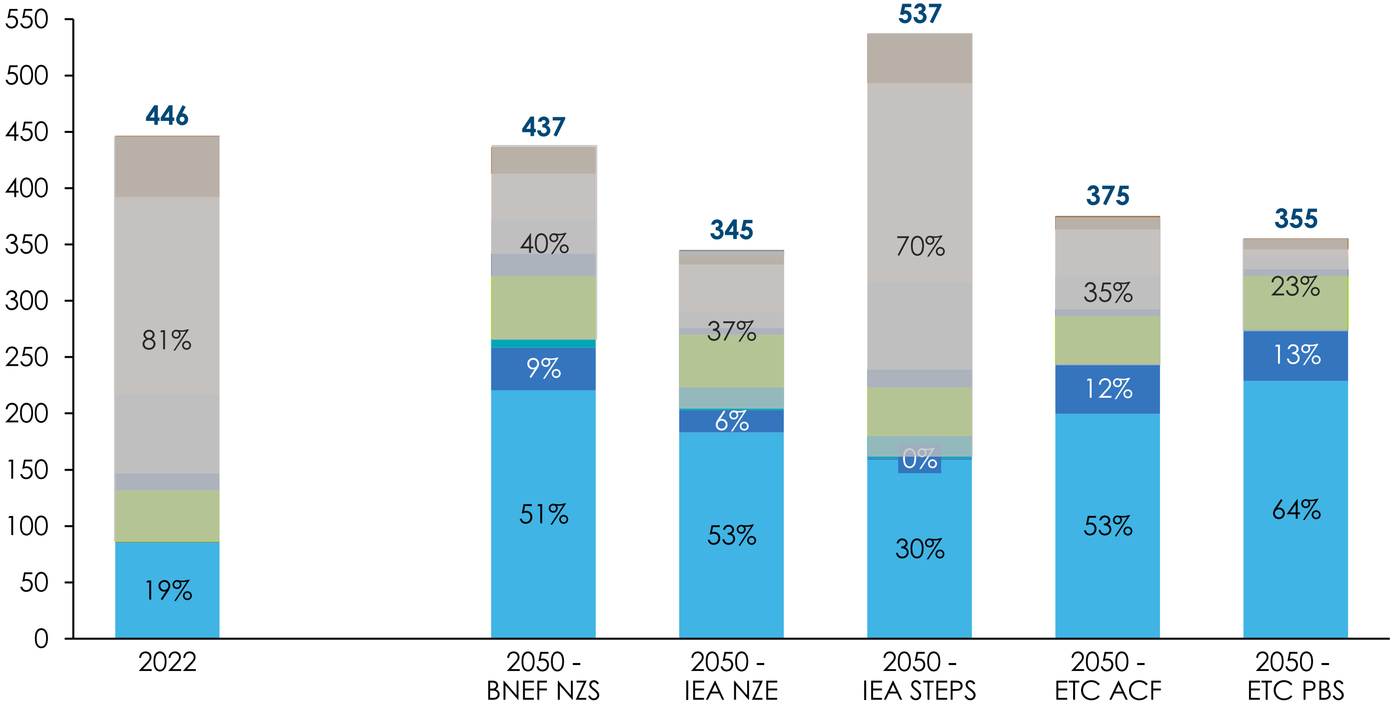
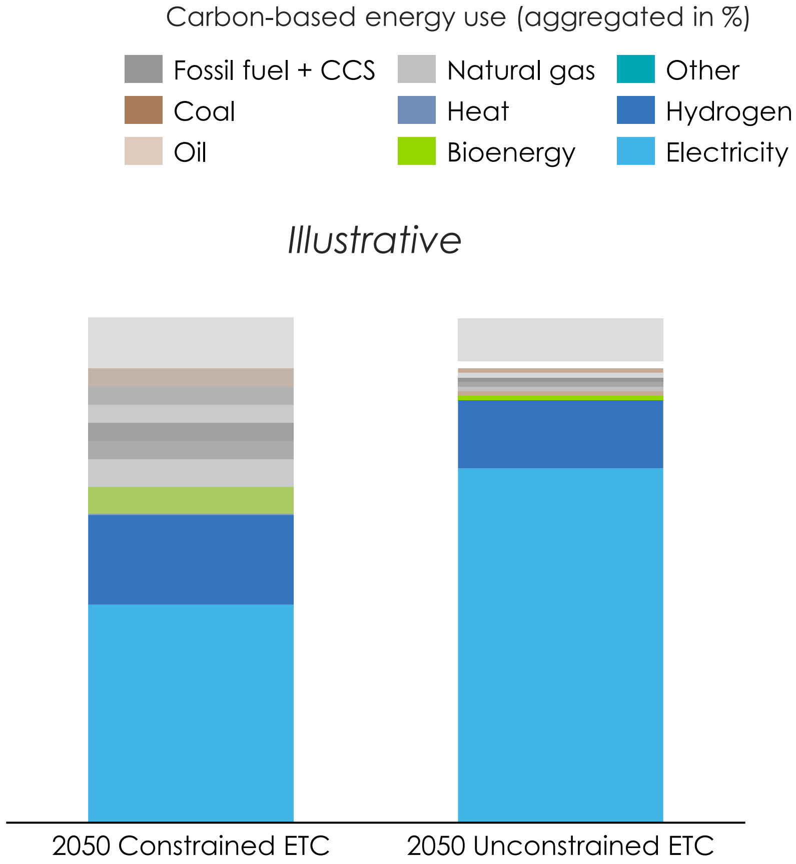


Global Final Energy demand in new ETC scenarios, EJ (%), 2050



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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

New observed trends show the necessity to update and question the relative importance of direct electrification, hydrogen and carbon-based fuels

Trends related to

Direct electrification: ACCELERATING

	TREND	PROOFPOINT
1	**[Cost] Solar PV costs decreasing faster than anticipated**	75% reduction in average estimated Solar PV LCOE and 60% reduction of module cost in the past 3 years
2	**[Cost] Battery costs decreasing faster than anticipated**	85% cost reduction over the last decade EVs in China have reached cost parity with non-EVs
3	**[Use] Expanding energy uses add extra power demand**	short term energy demand from AI and AC (IEA 2024),

Hydrogen and ammonia: STAGNATING

	TREND	PROOFPOINT
4	**[Cost] Much lower price decline due to inflation and system costs**	BNEF electrolyzer cost estimate increasing 90% between 2022 & 2024
5	**[Use] Scale up of green hydrogen production stagnating**	Only 4Mt of 118Mt H_2 production in pipeline at FID/operational
6	**[Use] Use cases are increasingly shifting from H_2 to electrification**	H_2 sefor buildings and trucking projects

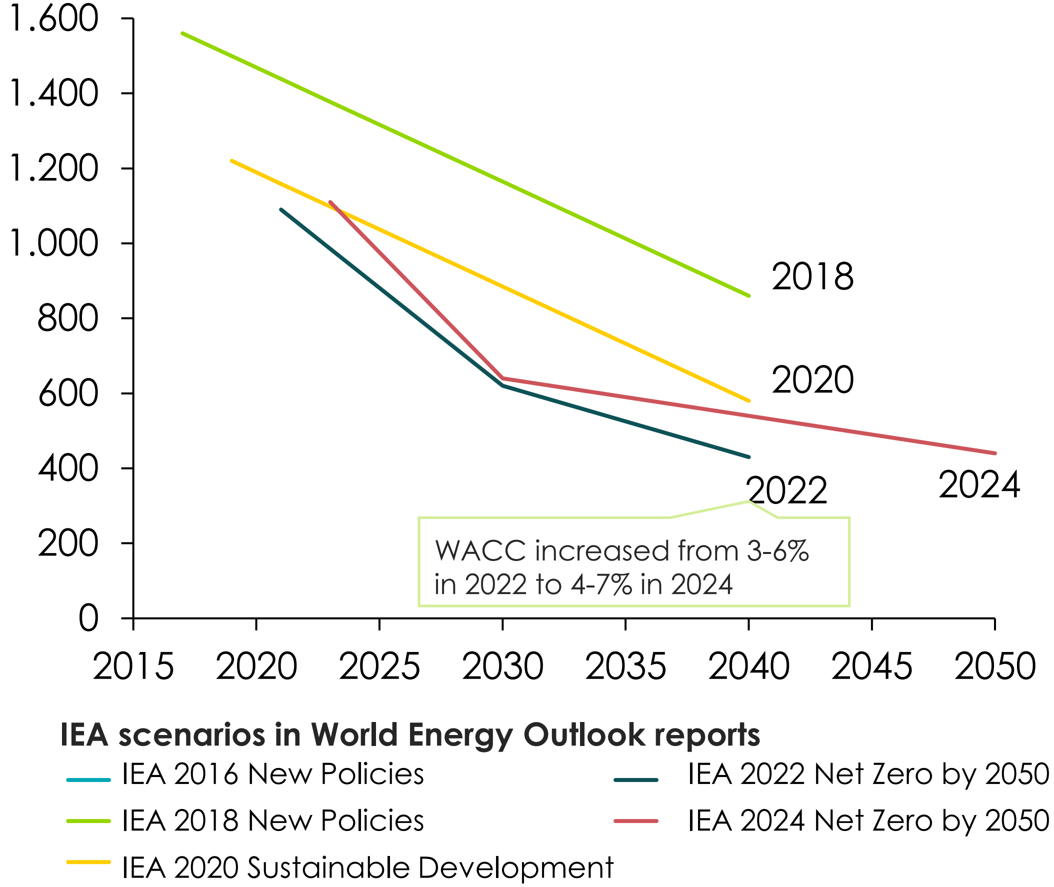
Carbon-based fuels: PLANETARY BOUNDARIES & LOCK-IN TRENDS

	TREND	PROOFPOINT
7	**[Cost] Biofuels and CCS prices expected to remain relatively flat**	Medium to long term projections from MPP, BNEF and OECD
8	**[Use] Methane leakage issue not solved**	Large methane emission events rose by 50% in 2023 compared with 2022
9	**[Use] Increased use of gas and oil in chemicals feedstock**	Chemical industry growing, with over 55% of oil and gas still being used for process energy

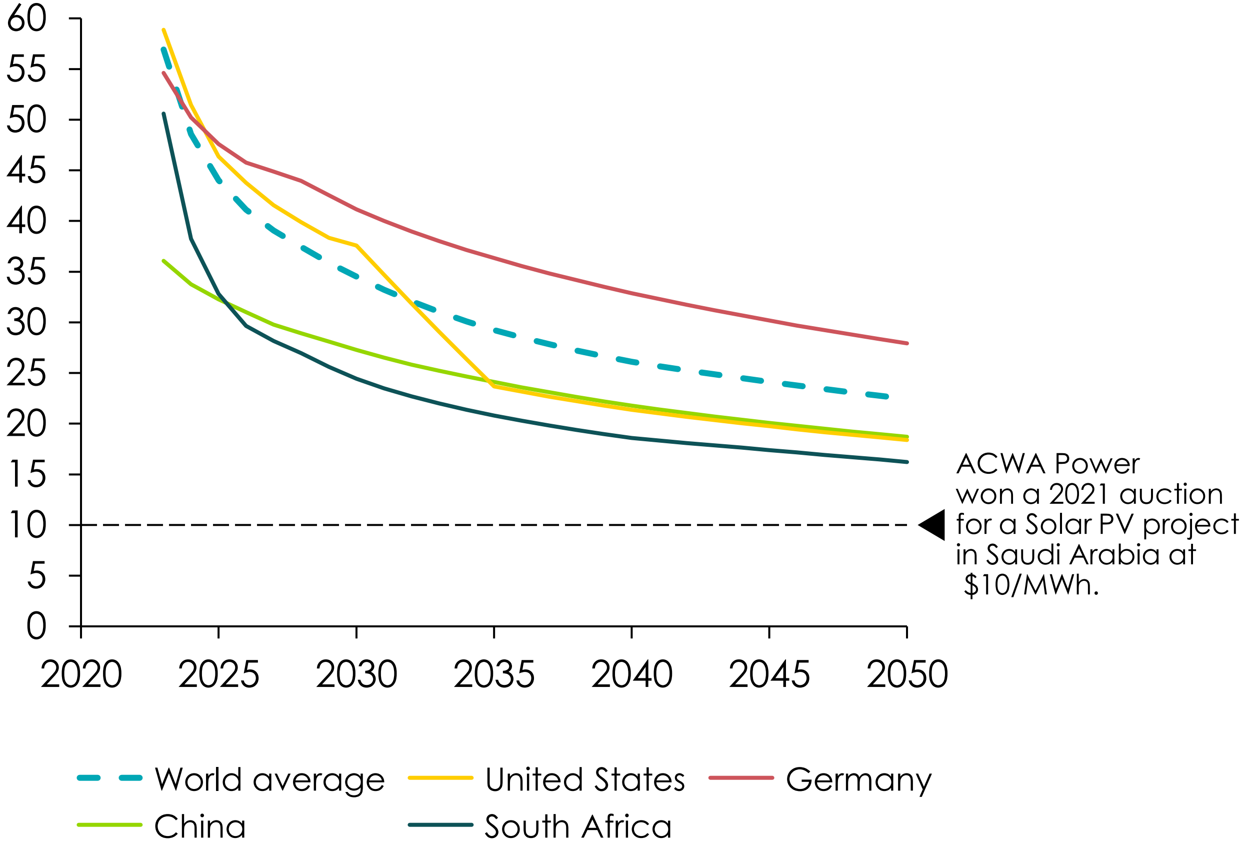
Sources: BNEF (2023), *2H 2023 LCOE: Data Viewer Tool*. BNEF (2023), *4Q 2024 Global PV Market Outlook*. IEA (2024) *Global Methane Tracker 2024, IEA (2023) Chemical*, IEA (2024), Electricity, S&P Global (2024) China ahead in delivering affordable electric mobility

[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 PV[1] globally & select countries
USD/MW (2022 real)

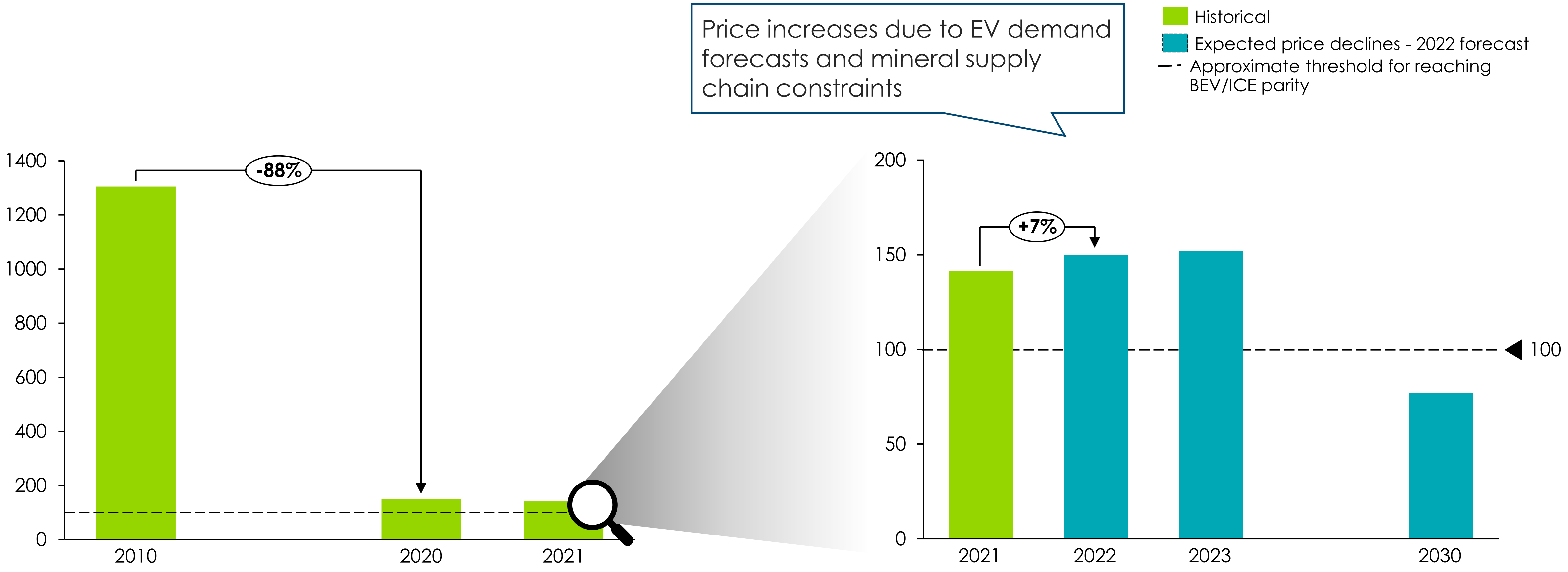


Note: 1. Based on solar PV tracking.
Sources: IEA World Energy Outlook, Bloomberg New Energy Finance 2023, *2H 2023 LCOE: Data Viewer Tool.*

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

Battery costs in EV s – past and projected

$/kWh; 2022 nominal

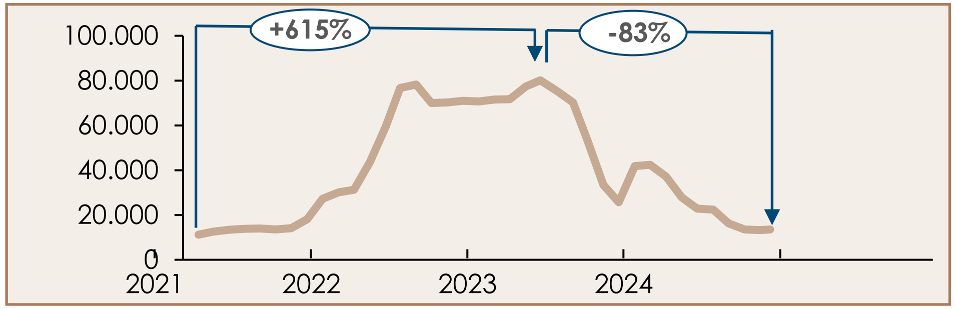


Source: Systemiq analysis for the ETC; BNEF (2023), Long-term electric vehicle outlook; BNEF (2022), Long-term electric vehicle outlook; ETC (2023); Better, faster, cleaner: Securing clean energy technology supply chains; BNEF (2023), Interactive data tool – battery manufacturing

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

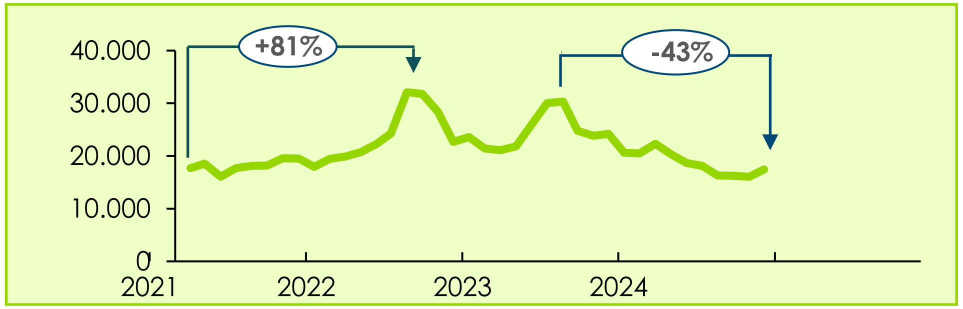
Mineral prices
$/tonne

Lithium



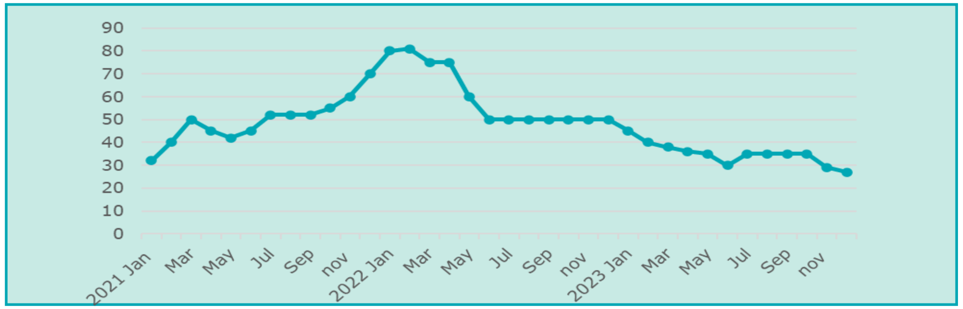
- Slowdown in EV demand relative to very high expectations
- New projects announced in EU , US , Australia, Chile, some subsequently postponed
- New technology Direct Lithium Extraction(DLI) from brine

Nickel



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

Cobalt

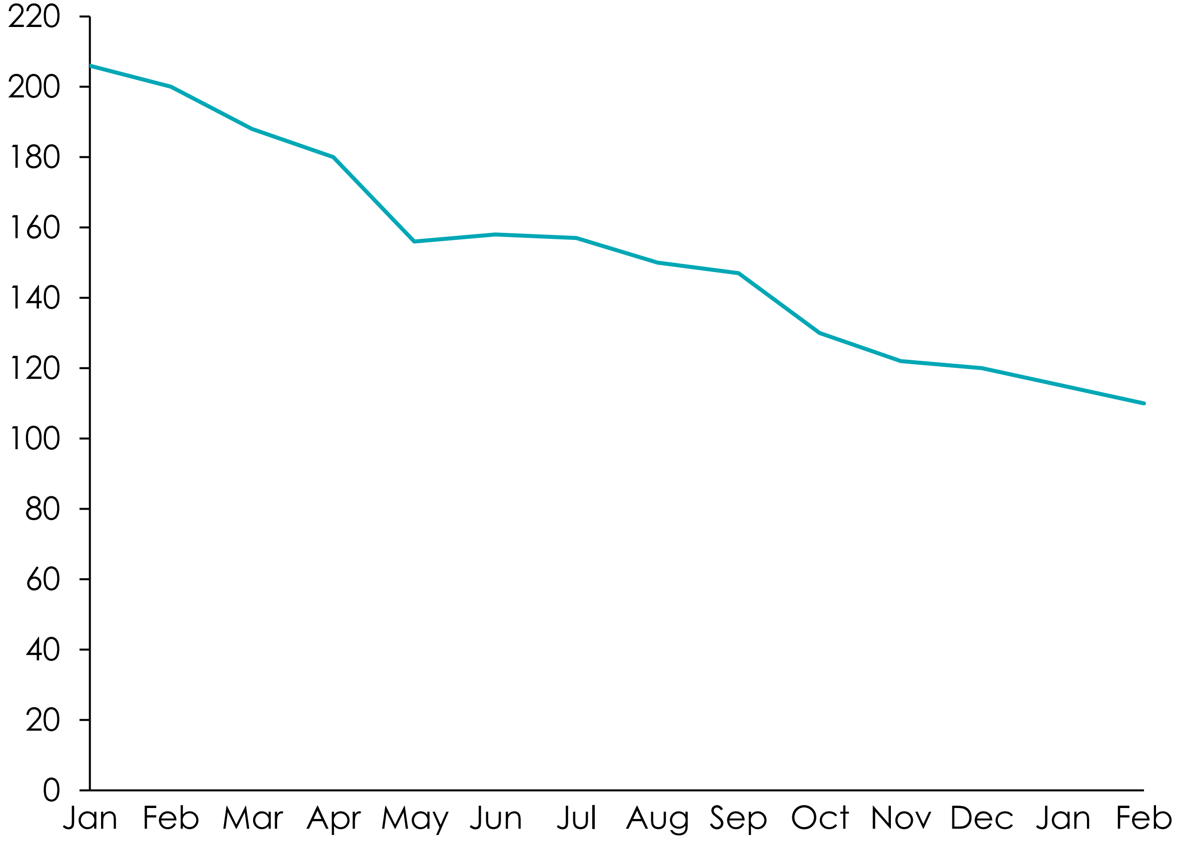


- Reduction of Co-proportion within NMC batteries
- Shift towards nickel and cobalt-free LFP batteries
- By-product of nickel development in Indonesia

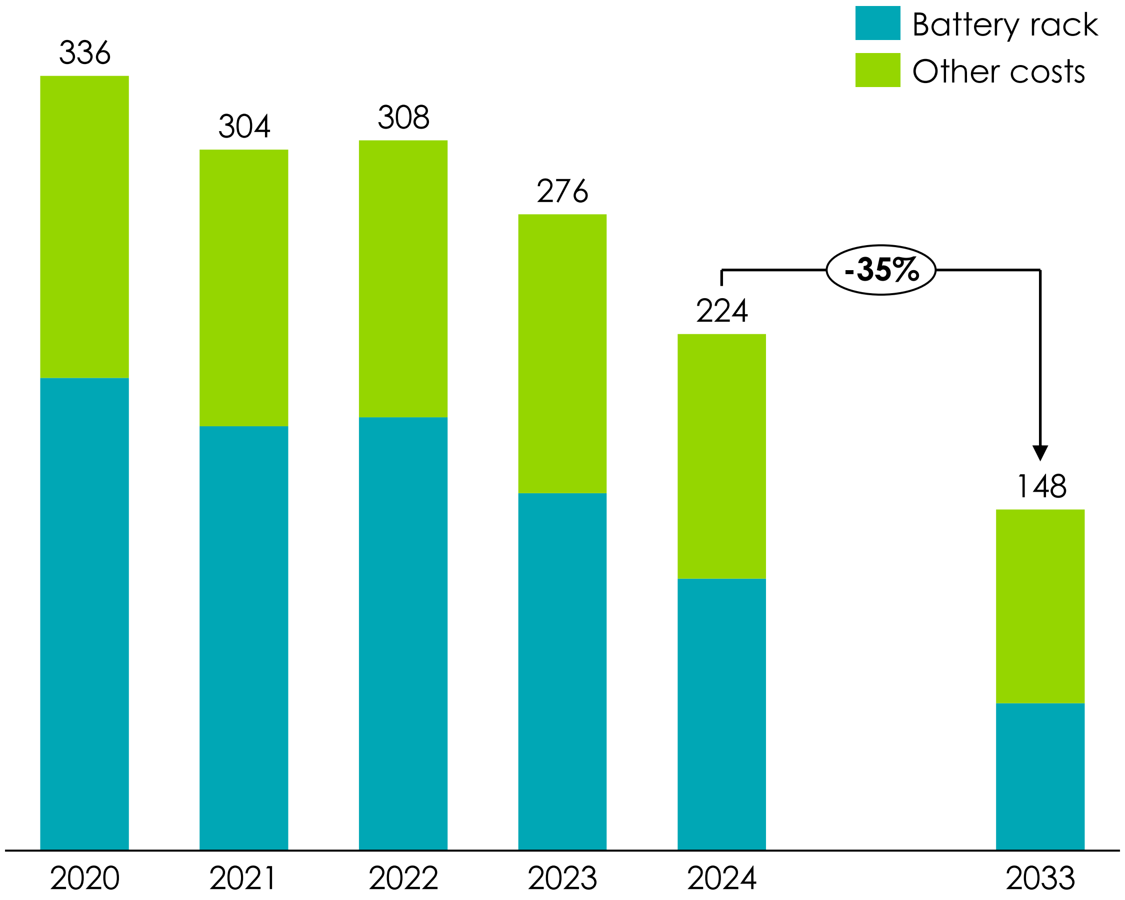
Source: BNEF (November, 2023), Lithium-Ion Battery Price Survey.

[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

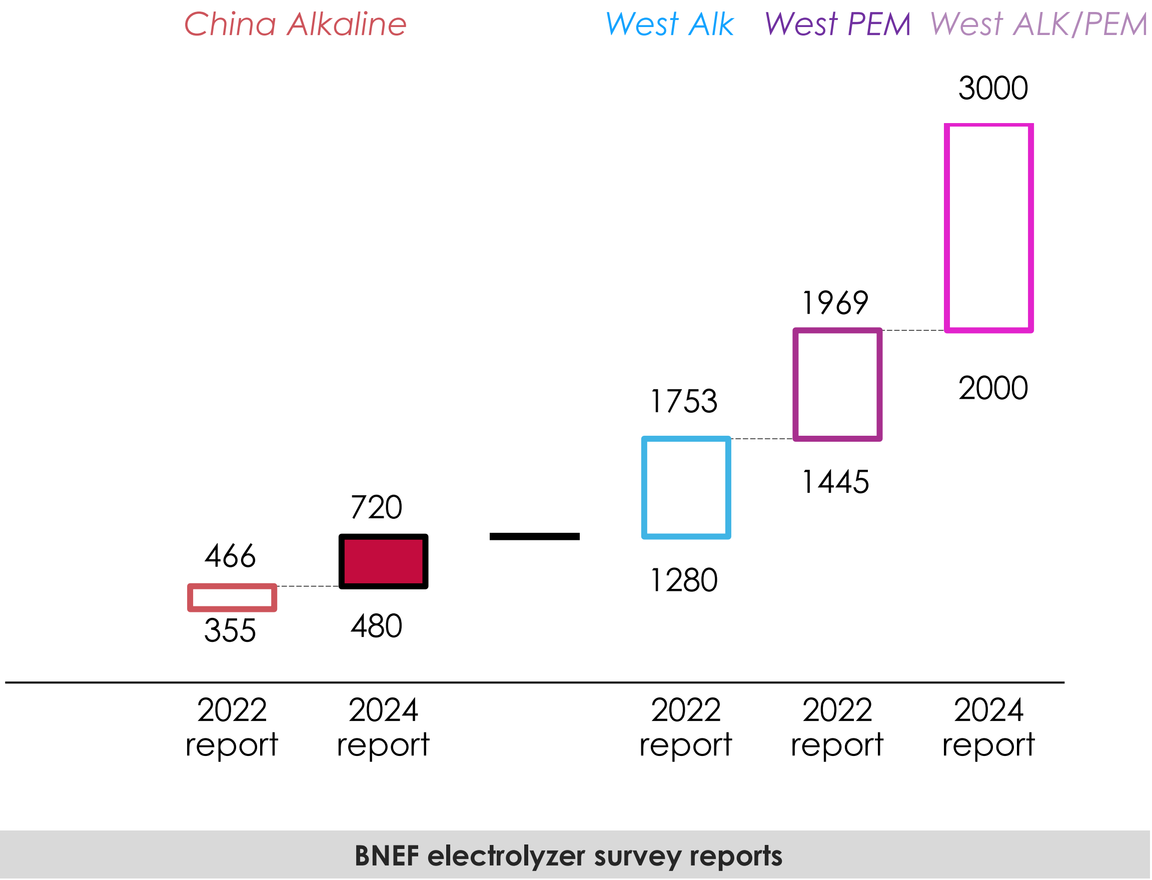


Source: BNEF; IH 2024 Energy Storage Market Outlook, Goldman Sachs (2024) based on Company data, Wood Mackenzie, SNE Research

[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

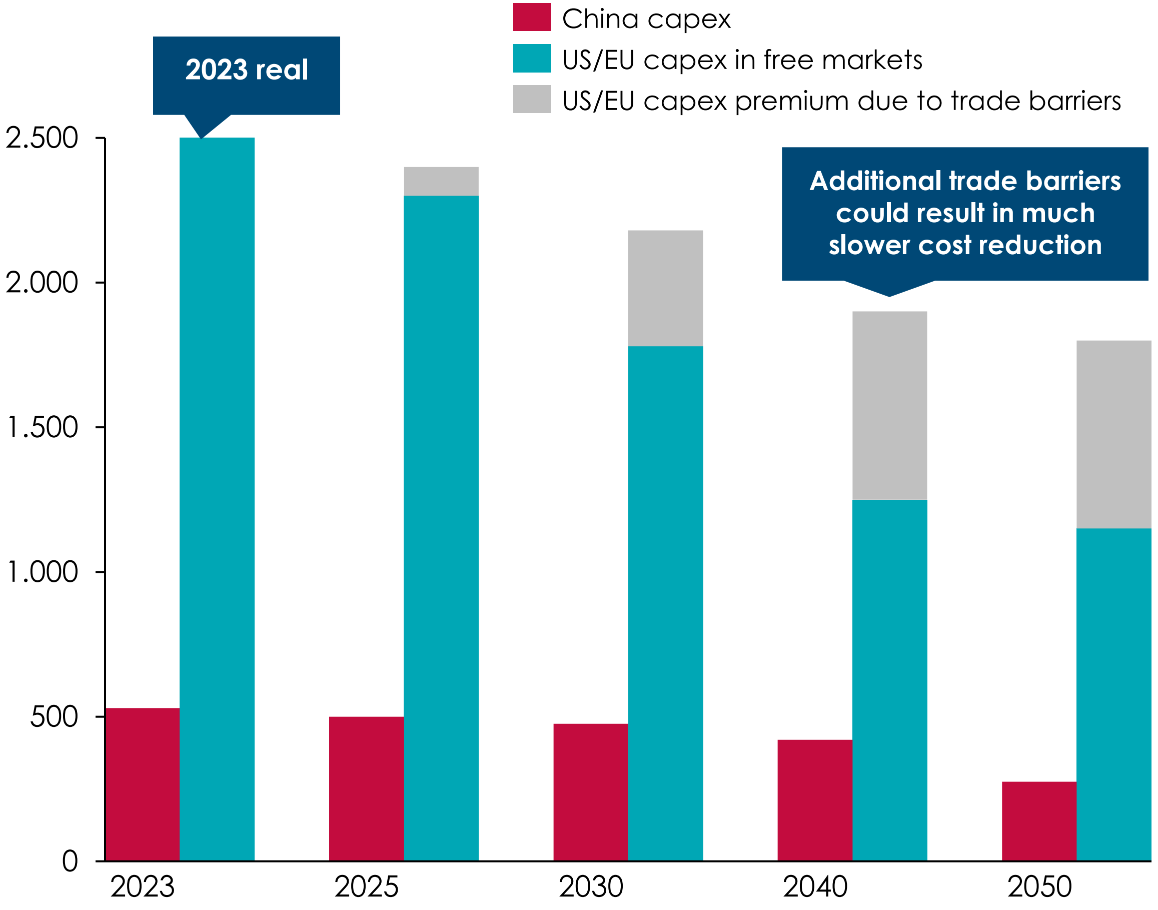
$/kW



BNEF electrolyzer survey reports

Electrolyzer system costs

$ per kw of hourly hydrogen yield

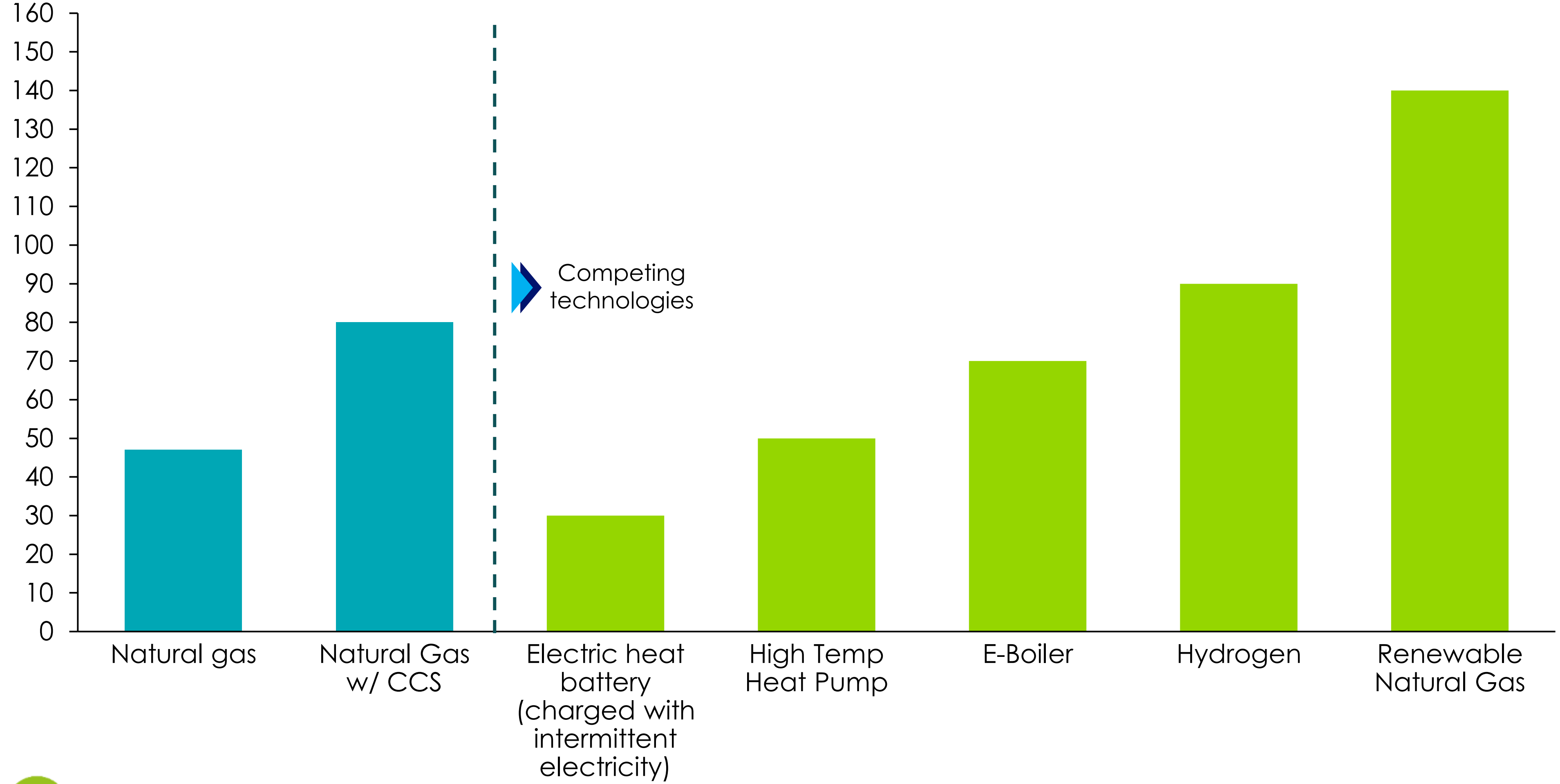


Note: Years refer to time of final investment decision (FID), engineering, procurement and construction bidding closure or equipment purchase. There was no trade barrier in 2023, so the 'premium due to trade barriers' was not available then. The unit '0.2Nm^3/h' is equivalent to kw under the current 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?*

Agenda

- Introduction to the Carbon Molecules Work
- 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	Disruption potential with less certainty	Enablers of electrification
1 Industrial heat electrification (>600°C) 2 Electric steam cracking 3 Electrification of iron-making	4 Li-ion solid state batteries 5 Advanced Direct Air Capture	6 Sodium based batteries 7 Nuclear fission (Small and Micro reactors)

8 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 Mobility Buildings
	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

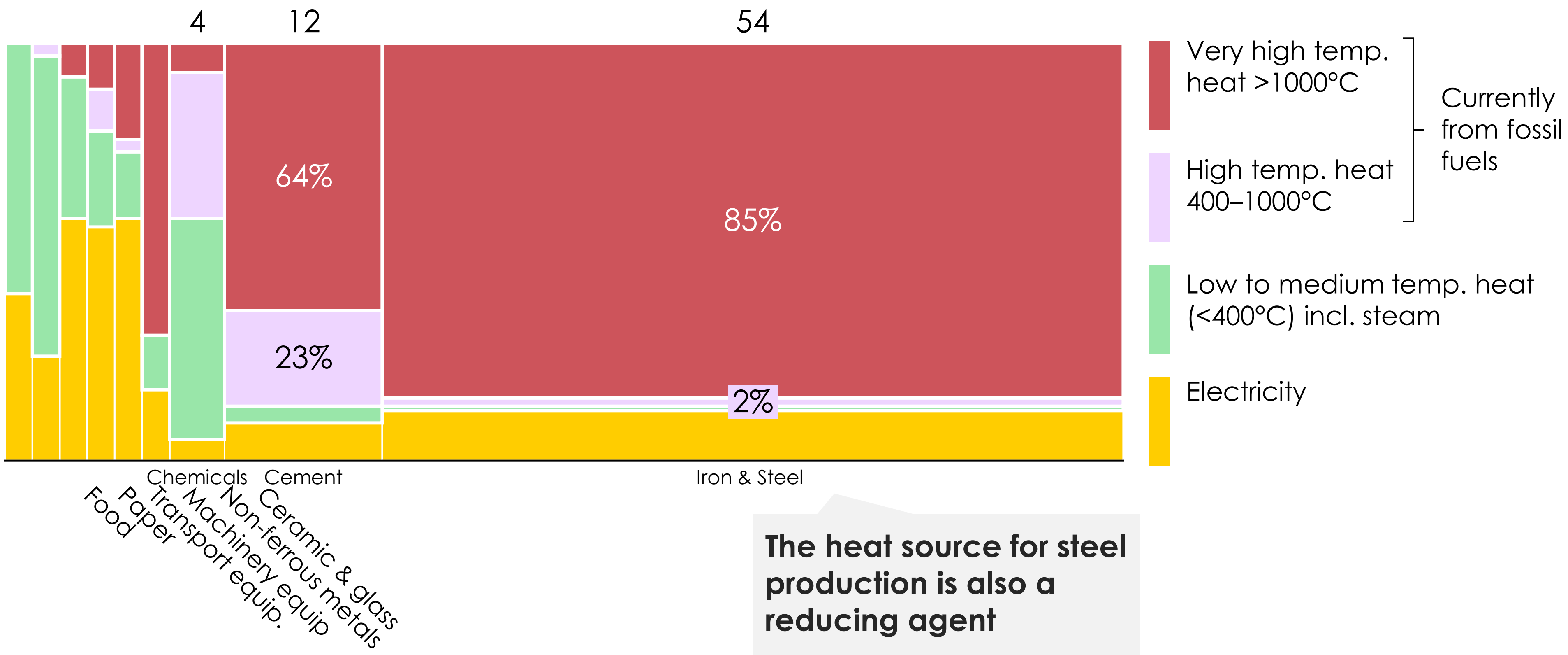
Industrial heat electrification

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 sector[1] in 2050

EJ

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



The heat source for steel production is also a reducing agent

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 adaptions 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 CO_2 reduction potential for the European industry via direct electrification of heat supply. Coolbrook (2024), Electric cracking: RotoDynamic Reactor cuts 100% of CO_2 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 *Non-exhaustive examples*
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%	SIEMENS COOLBROOK T.EN TECHNIP ENERGIES
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%	ALGOMA STEEL INC. SaltX Technology CEMENTA HEIDELBERGCEMENT Group PYROGENESIS
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%	Linde BASF T.EN TECHNIP ENERGIES Chevron سابك sabic
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%	Ferrite Microwave Technologies
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%	GH induction INDUCTOTHERM

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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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.

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

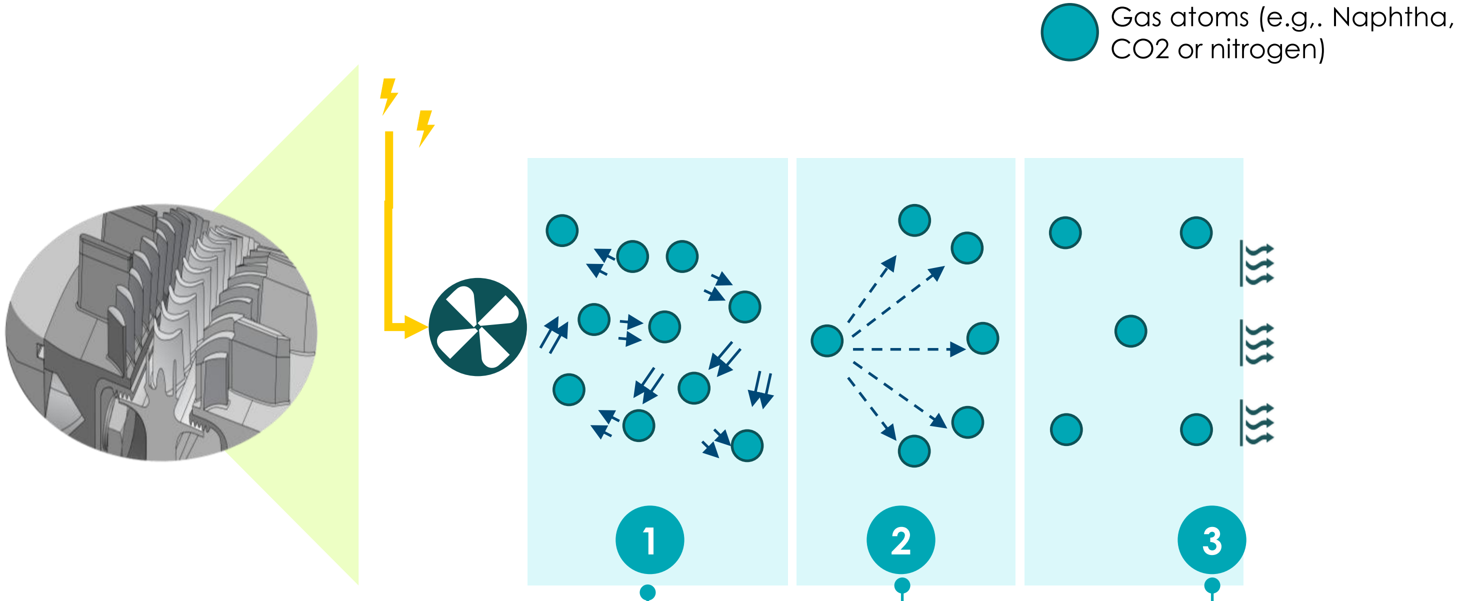
OVERVIEW OF SHOCK WAVE HEATING

Current TRL & steps to get to TRL>7

- **Current TRL**: 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 complex integration with existing plants
- **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



Accelerate gas:
An electric motor spins blades, pushing gas to supersonic speeds (~1250 km/h) in milliseconds, creating heat through atomic collisions.

Decelerate gas:
A diffuser rapidly slows the gas, creating a shockwave and turbulent gasses, rapidly increasing pressure, leading to a high temperature increase

Repeat process:
This process can be repeated in multiple stages, each stage quickly heats the gas even more

Sources: Fraunhofer ISI Agora Industry (2024), Direct electrification of industrial process heat. Denmarks Technical University (2023) Clinker burning electrification. Coolbrook official materials

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

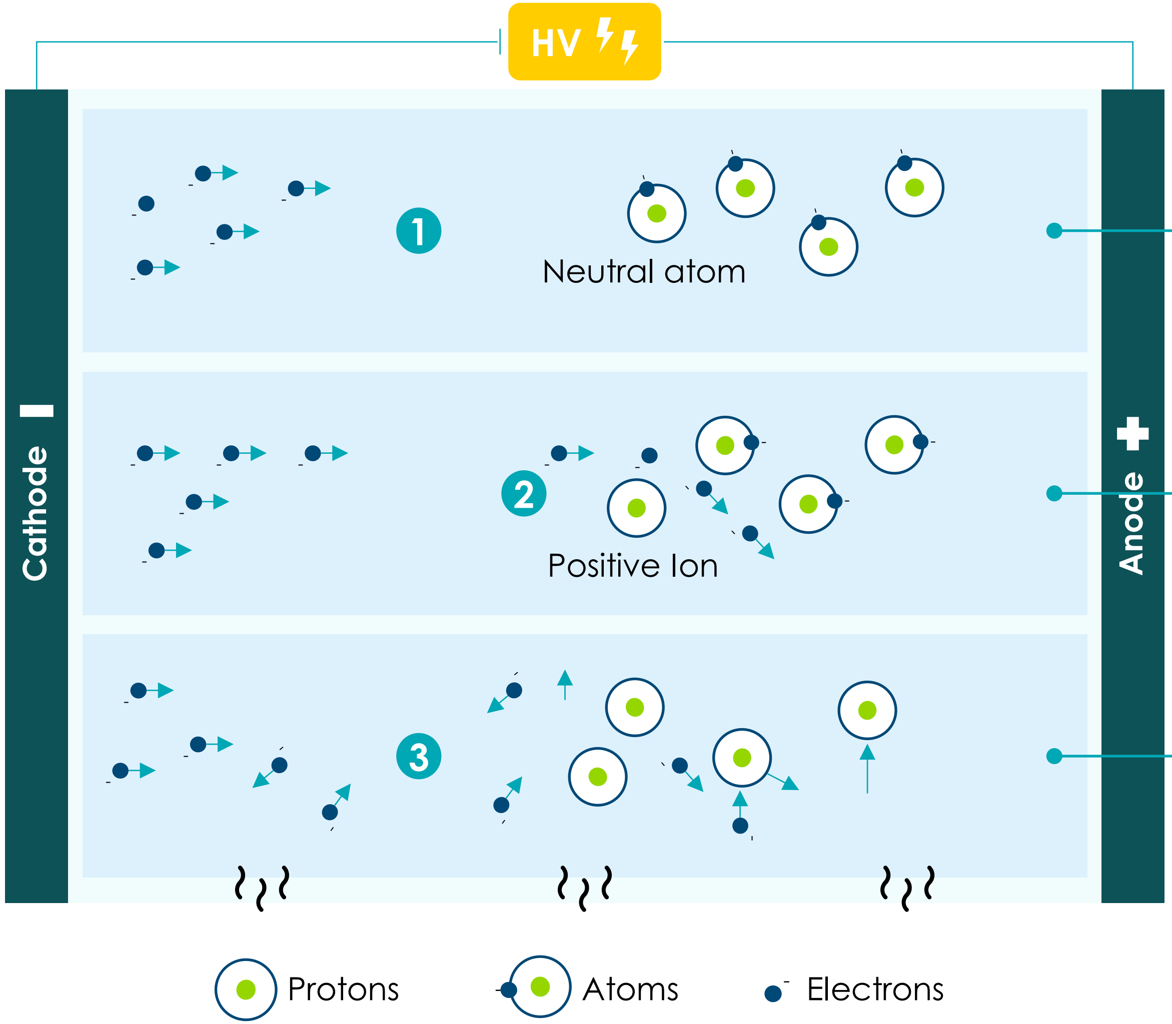
OVERVIEW OF ELECRIC ARC

Current TRL & steps to get to TRL>7

- **Current TRL**: 7, 2MW up to 1500°C test facility commissioned in 2023 and already used for applications with small capacities
- **Challenges:** efficiency for the energy transfer, integration with production plants
- **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

Sources: Silvia Madeddu (2020), *The CO_2 reduction potential for the European industry via direct electrification of heat supply*; Fraunhofer ISI (2024), Direct electrification of industrial process heat. International Cement Review (2024), *SaltX Electrification's promising path*

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

OVERVIEW OF RESISTANCE HEATING

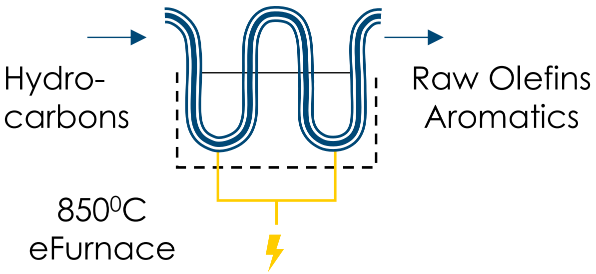
Current TRL & steps to get to TRL>7

- **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

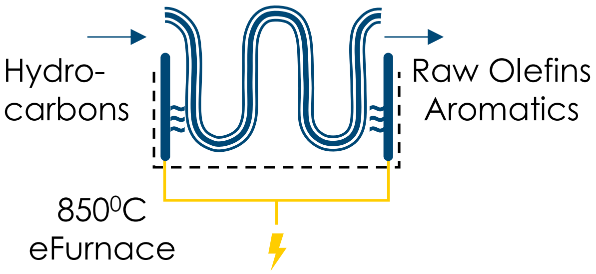


Hydro-carbons

Raw Olefins Aromatics

850^{0}C eFurnace

Indirect Heating



Hydro-carbons

Raw Olefins Aromatics

850^{0}C eFurnace

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.

Sources: Linde Company website. *Strarbridge Academy. discover the electric cracking furnace technology*

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

Key barriers

ECONOMICAL

- **High CAPEX**: The upfront costs or retrofitting existing installation are significantly higher than conventional set-ups
- **Electricity costs**: Electricity price is usually higher than fossil costs, especially for the continuous, high-power demand of high temperature processes

TECHNICAL

- **High temperatures:** Efficiently reaching and maintaining the temperatures required for cracking reactions, typically above 800°C
- **Energy intensity:** Providing sufficient energy for the energy intensive processes
- **Heat resistant materials:** Developing materials that can reliably withstand the extreme temperatures over long operational lifetimes

ORGANISATIONAL

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BloombergNEF (2022), *Decarbonising petrochemicals.* 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?

Estimated cost of heat *$ per tonne of product*	=	1 **CAPEX** *$ annualised per tonne product*	+	2 **Energy input** *MWh/tonne of product*	x	3 **Energy price** *$/MWh*	
Cost of heat using electrification		CAPEX for electrification (shockwave and resistance heating)		Required energy demand per tonne of product		?	
Cost of heat using conventional technologies		CAPEX for conventional heating technology		Required energy demand per tonne of product		Price of gas per MWh	+ cost of capturing CO_2
Cost of heat using hydrogen		CAPEX for hydrogen burner		Required energy demand per tonne of product		Hydrogen price per MWh	

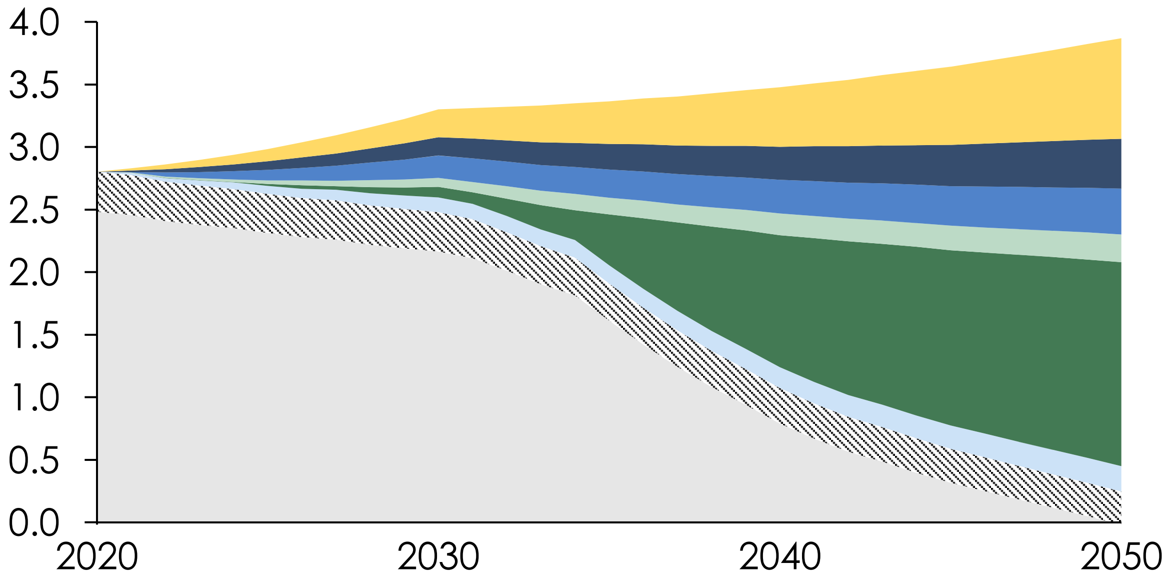
What electricity price do we need to make electrification of high temperature heat cost competitive?

Cement – a use case for industrial heat

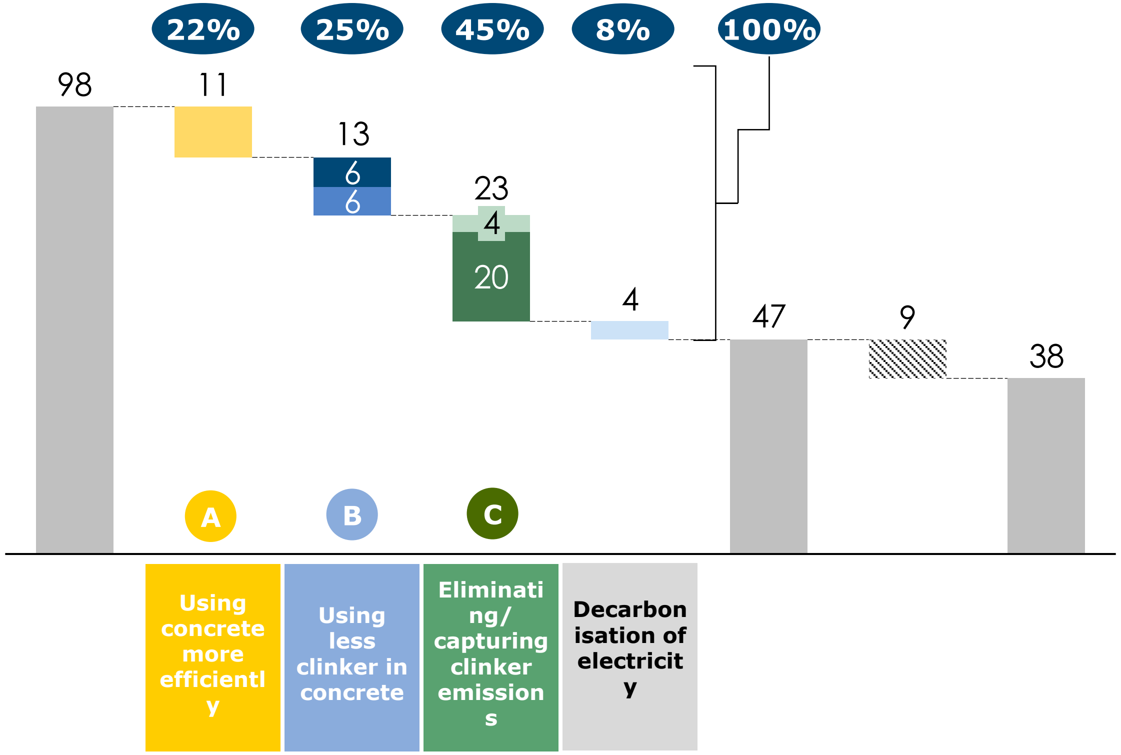
In cement, our FFIT scenarios did not include electrification technologies and but 45% of the emissions reductions were reliant on CCS

🟨 Efficiency in design and construction
🟦 Efficiency in concrete production
🟦 Savings Cement & binders
🟩 Switching to alternative fuels and energy efficiency
🟩 CCUS
🟦 Decarbonisation of electricity
▨ Recarbonation
⬜ Unabated

Annual GHG emissions[1], in Gt CO_2



Cumulative GHG emissions between 2022 and 2050, in Gt CO_2



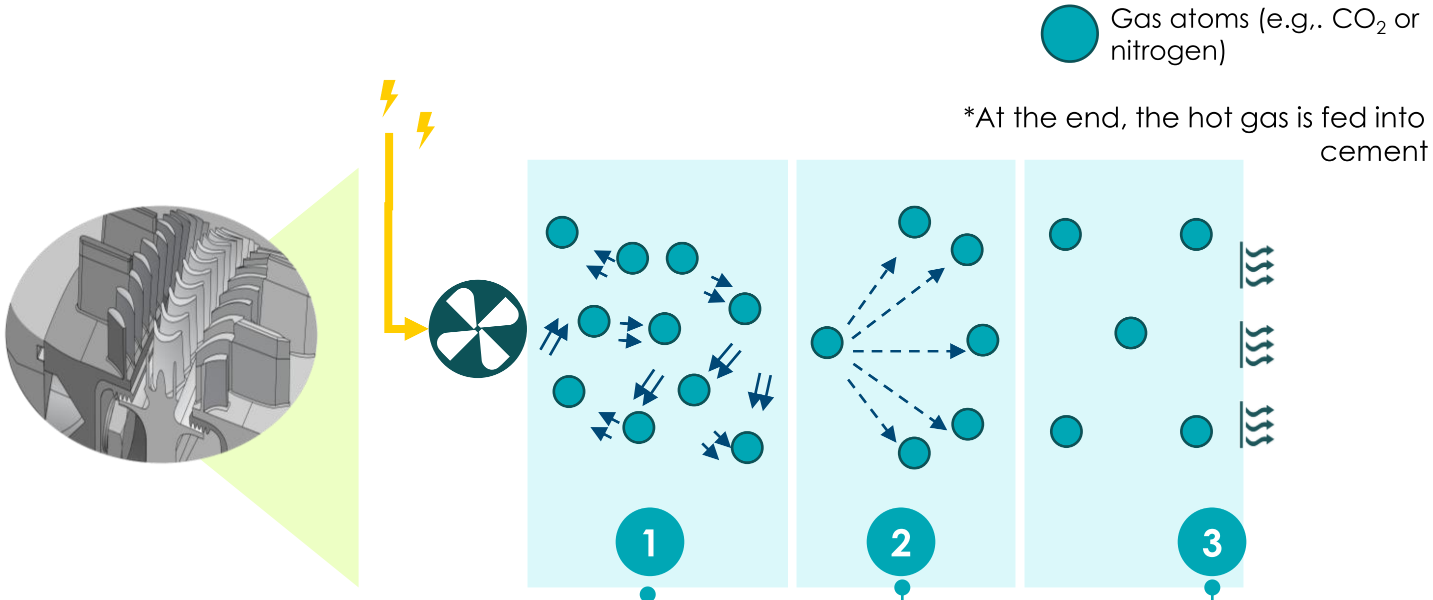
Notes: Includes scope 1 and 2 emissions. Scope 3 upstream would add approximately 3.8 Gt CO_2e of cumulative emissions from 2022 to 2050. “Savings and binders” include switching to new binders. Decarbonisation of electricity involves electricity demand for kilns, grinders and carbon capture.
Source: 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



*At the end, the hot gas is fed into the cement kiln

Accelerate gas:
An electric motor spins blades, pushing gas to supersonic speeds (~1250 km/h) in milliseconds, creating heat through atomic collisions.

Decelerate gas:
A diffuser rapidly slows the gas, creating a shockwave and turbulent gasses that converts kinetic energy into heat

Repeat process:
This process can be repeated in multiple stages, each stage quickly heats the gas even 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

Sources: Fraunhofer ISI Agora Industry (2024), Direct electrification of industrial process heat. Denmarks Technical University (2023) Clinker burning electrification. Coolbrook official materials

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

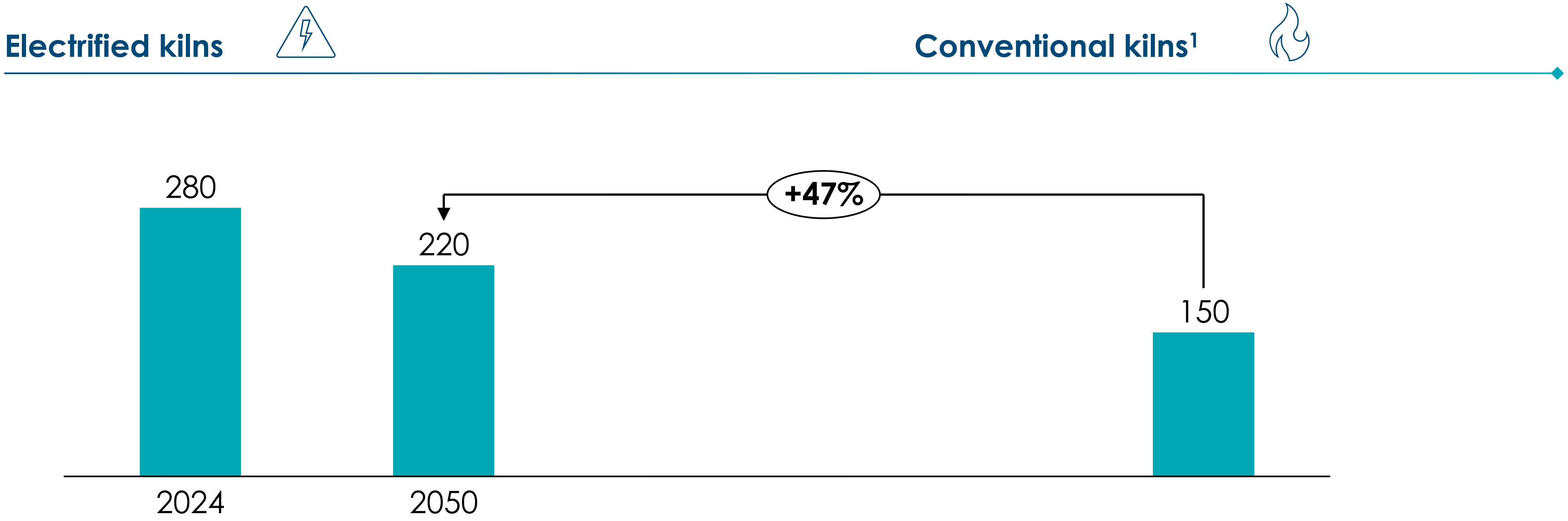
Estimated cost of heat *$ per tonne of product*	=	① **CAPEX** *$ annualised per tonne product*	+	② **Energy input** *MWh/tonne of product*	x	③ **Energy price** *$/MWh*	
Cost of heat using electrification		CAPEX for electrification (shockwave and resistance heating)		Required energy demand per tonne of product		**?**	
Cost of heat using conventional technologies		CAPEX for conventional heating technology		Required energy demand per tonne of product		Price of gas per MWh	+ cost of capturing CO_2
Cost of heat using hydrogen		CAPEX for hydrogen burner		Required energy demand per tonne of product		Hydrogen price per MWh	

What electricity price do we need to make electrification of high temperature heat cost competitive?

Highly preliminary

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

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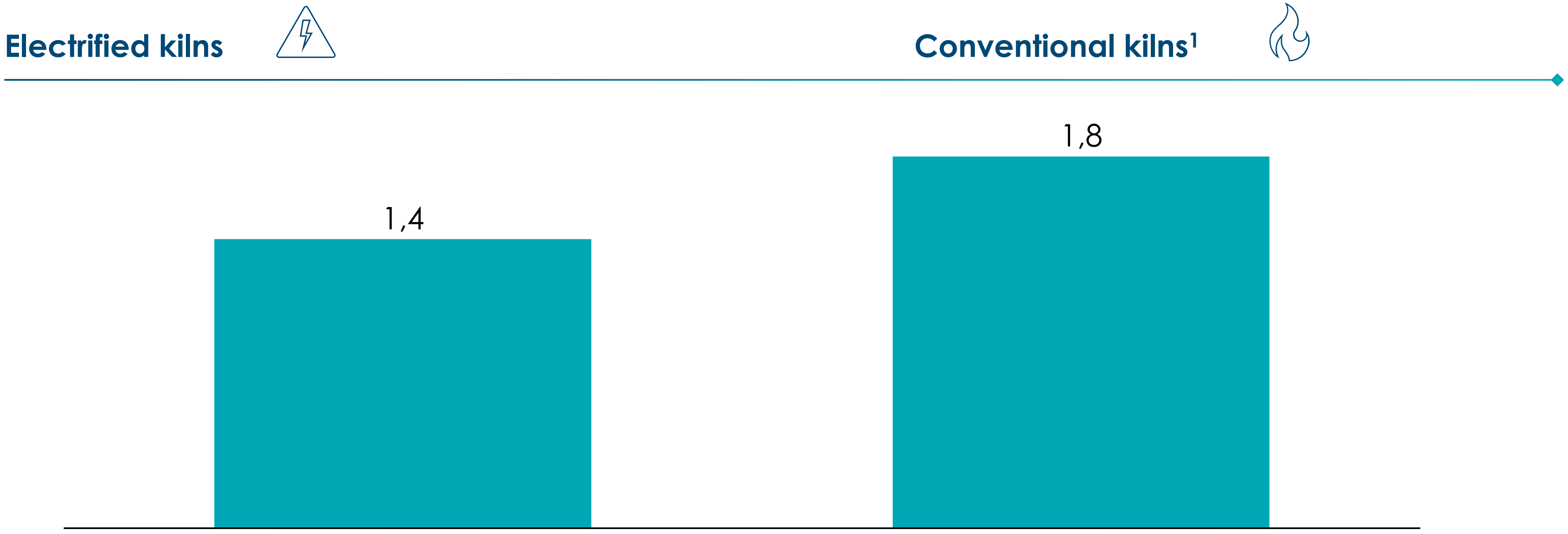
1. CCU/S will be added as variable cost

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

Highly preliminary

② Early estimates suggest that the energy efficiency 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.*

Highly preliminary

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

approximately $60 per ton cement

	Cost of capturing CO_2	=	Coal consumption *MWh / t of product*	x	Emissivity of coal *tCO2 / MWh*	x	Cost of capturing CO_2 *$/tCO2*
Assumption			1.8 MWh/t cement		Approximately 330 kg per MWh		Assumed $100/t$CO_2$
Source			BloombergNEF (2022), *Cement Production Valuation Model*		IPCC (2016). IPCC Guidelines for National Greenhouse Gas inventories		International Institute for Sustainable Development (2023)

Cement's process emissions must be captured regardless of electrification but are excluded here as they impact both sides equally[1]

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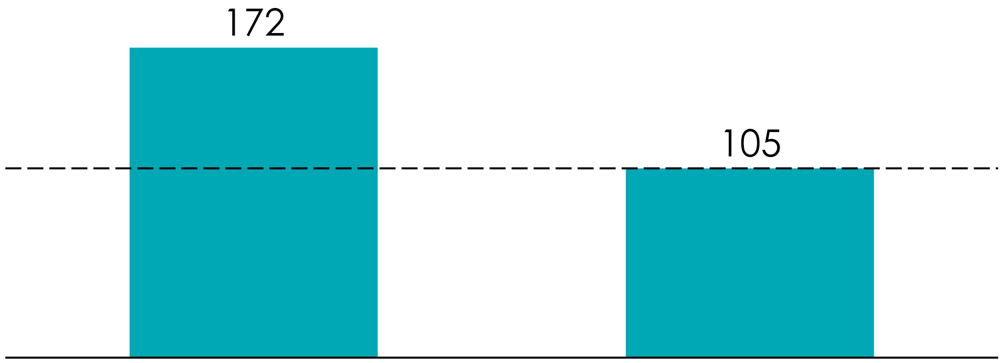
[1] Capturing cement process emissions is cheaper with electrification due to higher CO2 concentration.

Source: BloombergNEF (2024), *Cement Production Valuation Model*; IPCC (2016). *IPCC Guidelines for National Greenhouse Gas inventories*

Highly preliminary

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



Electricity price needed: $60/MWh

Key outputs

	Electrified kiln	Conventional kilns + CCS
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*

Highly preliminary

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 2040)
Electricity price to be competitive in China in 2050 ($/MWh)	110	60

Barriers mitigated

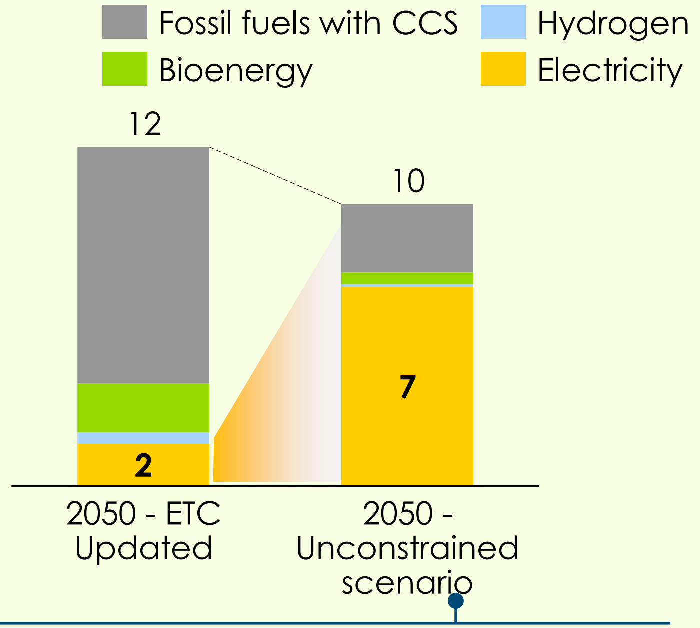
- High temperature requirements
- Pilot testing and scaling up
- Cost-competitive power prices

Latest developments

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

Impact on energy demand,
EJ per year

Preliminary



Key assumption for the unconstraint 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

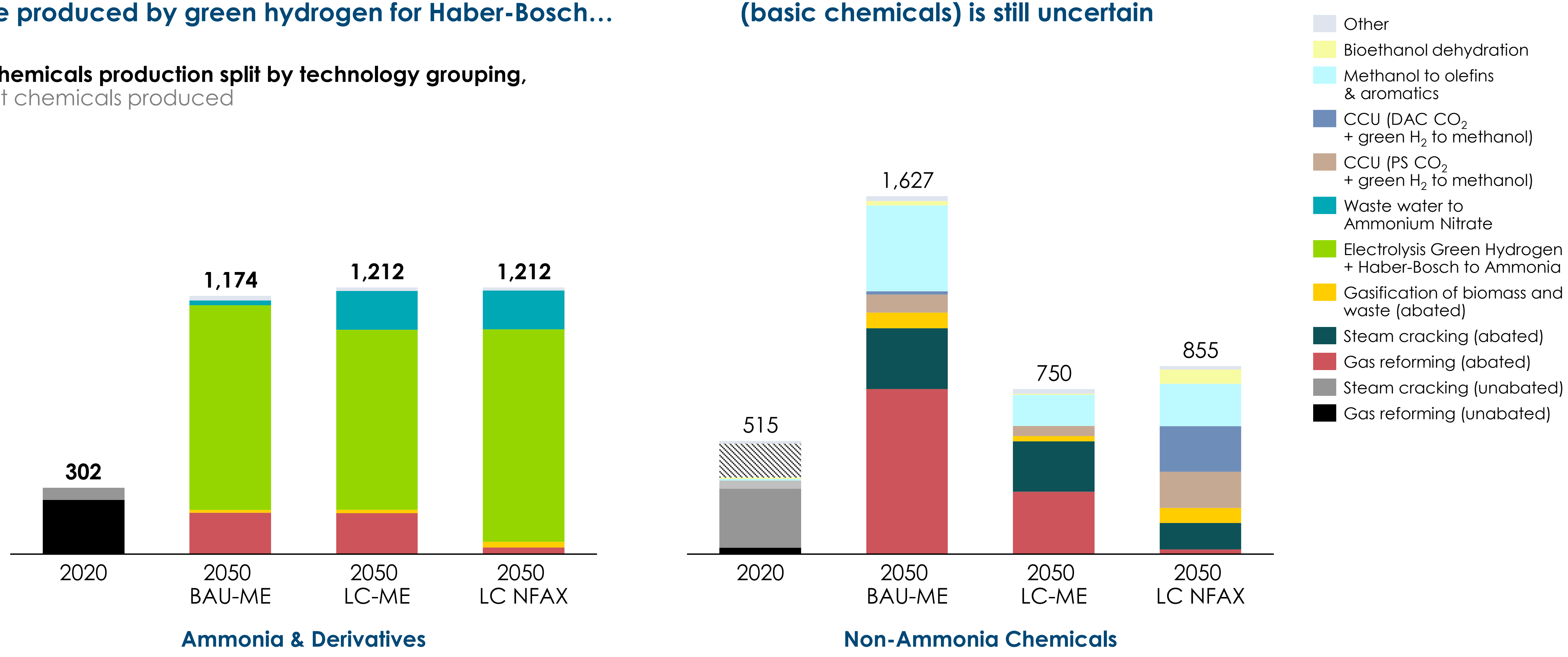
Electrical steam cracking – utilising industrial heat technology

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

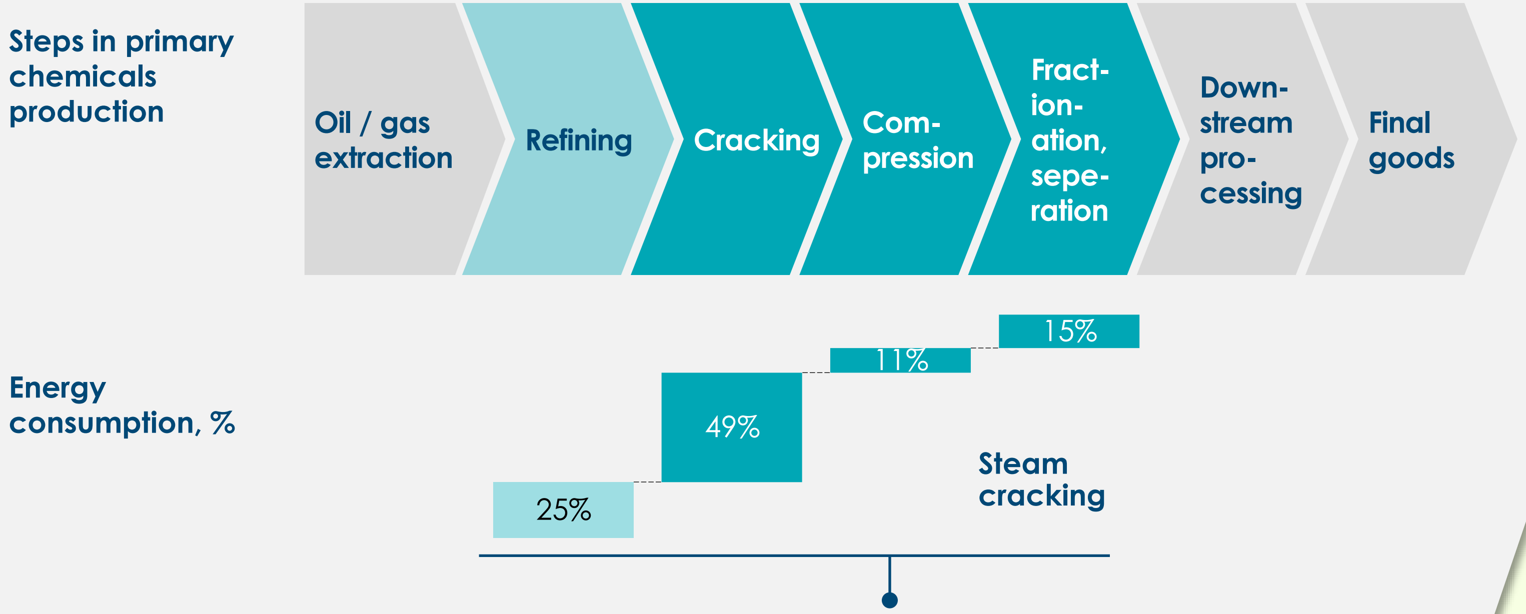
Chemicals production split by technology grouping, Mt chemicals produced



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



75% of the energy demand (and 77% of CO2 emissions) comes from steak cracking

Electrification is one of the solutions to decarbonize the cracking process

Technology	CO_2 reduction potential for steam cracking process
Decarbonizing heating of crackers	
▪ Electrification	97%
▪ Hydrogen firing	97%
▪ CCU/S^2	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*

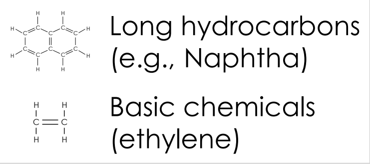
Electric crackers could use shock-wave and resistance heating technologies to electrify basic chemicals

Technology[1]	Process	Sectors[2]	TRL	Energy Efficiency	Company *Non-exhaustive examples*
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%	SIEMENS COOLBROOK T.EN TECHNIP ENERGIES
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%	ALGOMA STEEL INC. SaltX CEMENTA PYROGENESIS
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%	Linde BASF T.EN TECHNIP ENERGIES Chevron سابك sabic
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%	Ferrite Microwave Technologies
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%	CGH induction INDUCTOTHERM

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.

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


Long hydrocarbons (e.g., Naphtha)

Basic chemicals (ethylene)

OVERVIEW OF SHOCK WAVE HEATING

Current TRL & steps to get to TRL>7

- **Current TRL**: 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 complex integration with existing plants
- **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
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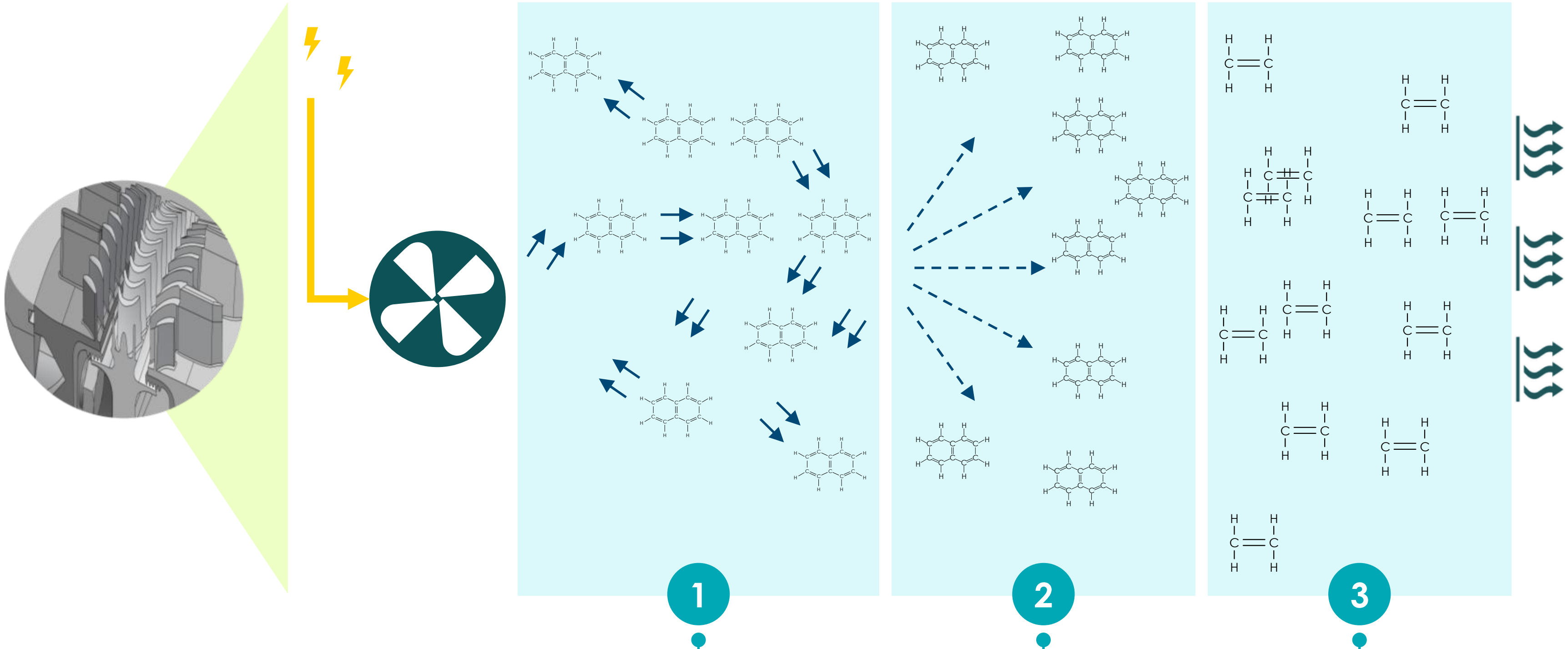
- **Integration into existing production lines** with relative ease enabling retrofit of facilities



Accelerate gas: An electric motor spins blades, pushing gas to supersonic speeds (~1250 km/h) in millisecondes

Decelerate gas: A diffuser rapidly slows the gas, creating a shockwave and turbulent gasses , rapidly increasing pressure, leading to a high temperature increase

Repeat process: This process can be repeated in multiple stages, each stage quickly heats the gas even more

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Advantages

- **Integrated into existing installations** reducing the need for entirely new facility
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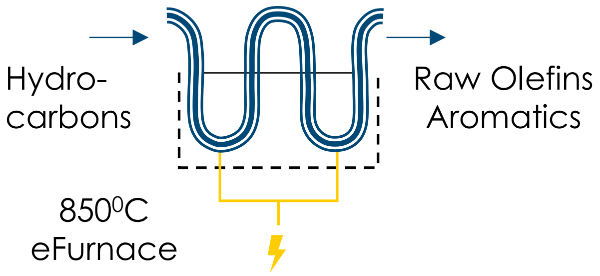
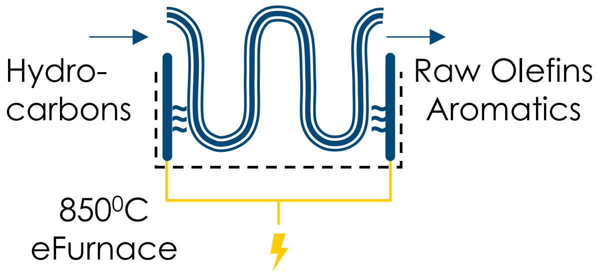
Direct Heating



Indirect Heating



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Sources: Linde Company website. *Strarbridge Academy. discover the electric cracking furnace technology*

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

Key barriers

ECONOMICAL

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- **Electricity costs**: Electricity usually cost more than natural gas, especially for the continuous, high-power demand of e-crackers

TECHNICAL

- **High temperatures:** Efficiently reaching and maintaining the temperatures required for cracking reactions, typically above 800°C
- **Energy intensity:** Providing sufficient energy for the highly endothermic cracking
- **Heat resistant materials:** Developing materials that can reliably withstand the extreme temperatures over long operational lifetimes

ORGANISATIONAL

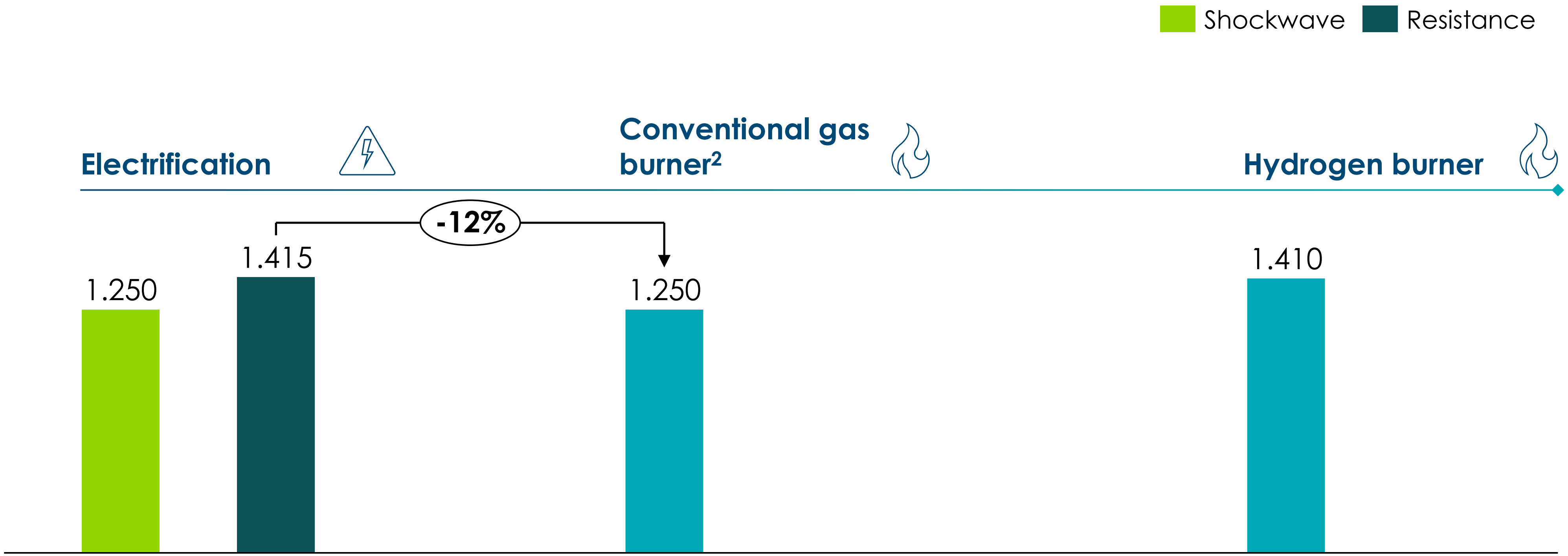
- **Conversion complexity**: steam crackers are highly integrated. It would be technically possible to retrofit but unlikely to be financially viable.
- **Firm 24/7 clean power source**: the energy-intensive cracking process cannot be easily ramped up and down without significant losses

BloombergNEF (2022), *Decarbonising petrochemicals*

Highly preliminary

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

CAPEX/t HVC[1]
(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

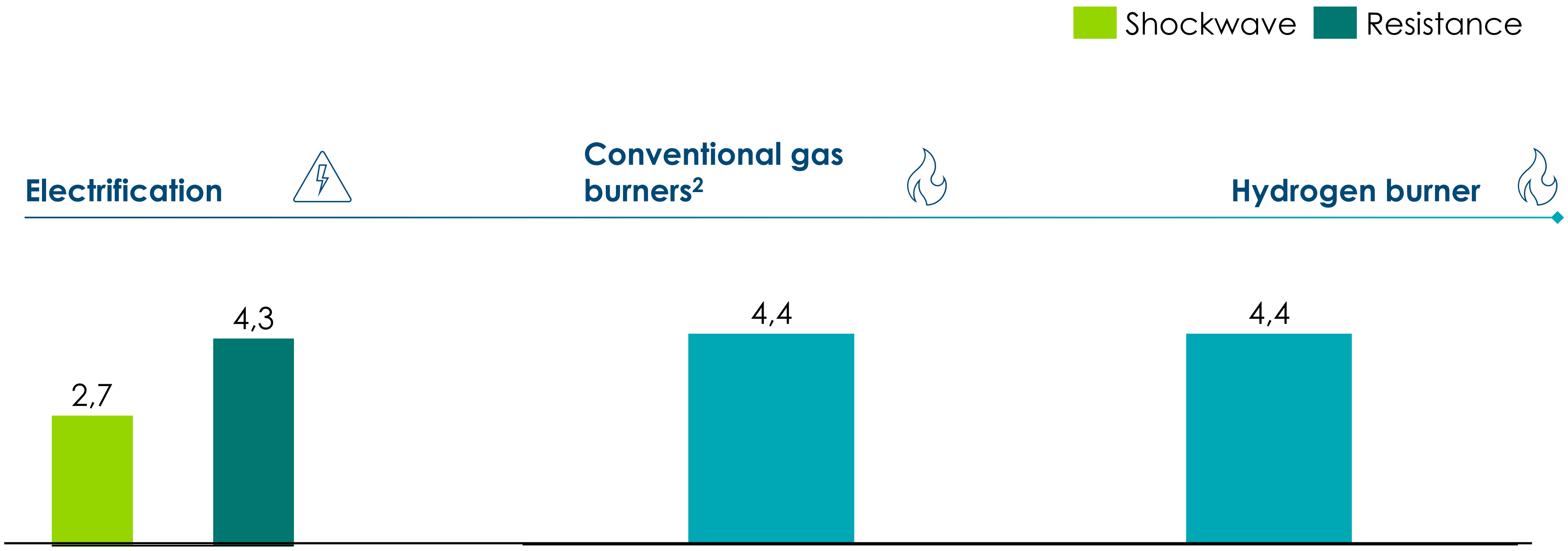
- Capex is higher than conventional gas burners due to added hydrogen pipelines, compressors, furnace adjustments, and NOx abatement equipment.

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.*

Highly preliminary

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

Energy consumption (MWh/t HVC[1])



Rationale	**Electrification**	**Conventional gas burners[2]**	**Hydrogen burner**
	▪ 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

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Sources: BloombergNEF (2022), *Decarbonising petrochemicals.* Center for Global Commons & Systemiq (2022), *Planet Positive Chemicals.*

3 The cost of CCU/S will add around $50 per ton of product to the gas costs

approximately $90 per ton of product

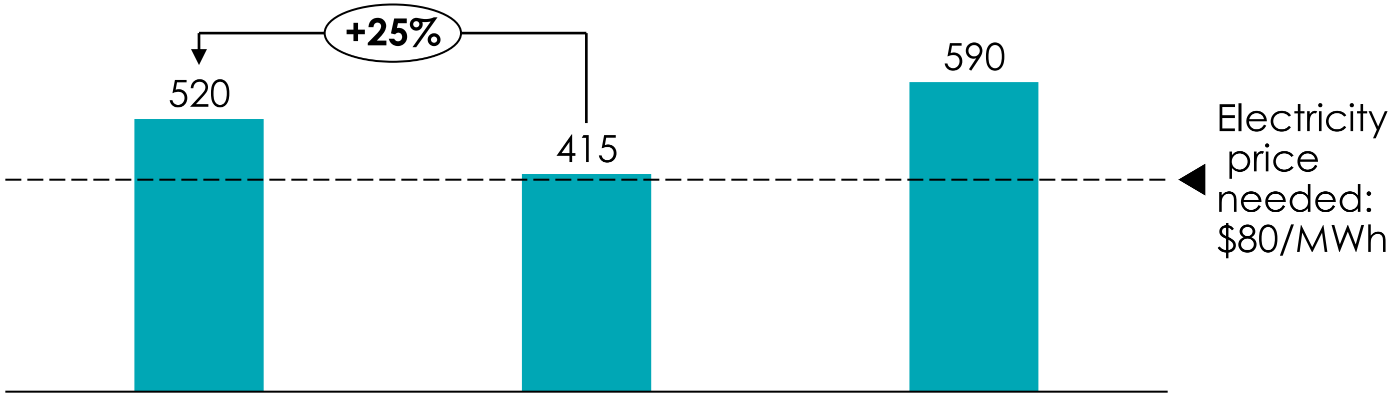
Cost of capturing CO_2	=	Gas consumption *MWh / t of product*	x	Emissivity of gas *tCO2 / MWh*	x	Cost of capturing CO_2 *\$/tCO2*
Assumption		4.4 MWh/t HVC		Approximately 200 kg per MWh		Assumed \$100/tCO_2
Source		BloombergNEF (2022), *Decarbonising petrochemicals*		IPCC (2016). IPCC Guidelines for National Greenhouse Gas inventories		International Institute for Sustainable Development (2023)

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*

Highly preliminary

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



Electricity price needed: $80/MWh

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 H_2

Sources: Center for Global Commons & Systemiq (2022), *Planet Positive Chemicals*. BloombergNEF (2022), *Decarbonising petrochemicals*

Highly preliminary

In Europe, India, and China, the electricity price needed to be cost-competitive compared to gas is reasonable

	Current gas prices			Electricity prices required for alternatives to be competitive ($/MWh)		
Region	Gas price ($/MMBtu)	Gas price ($/MWh)	Gas + CCS[1] ($/MWh)	Shock wave ($/MWh)	Electric arc	Resistive ($/MWh)
China	$ 14	$ 48	$68	$110	n/a	$65
U.S.	$ 2	$ 18	$38	$60	n/a	$35
Europe	$ 13	$ 44	$64	$105	n/a	$60
India	$ 13	$ 44	$64	$105	n/a	$60

Notes: Rounded gas prices based on average 2024 data; 1. CCS price of $100/t CO_2 assumed and an emissivity of 0.2t CO_2/MWh gas
Sources: EIA Natural Gas Henry Hub for U.S. gas price, average values between Jan-Aug 2024, TTF for EU prices, CEIC for CN prices for the public service sector, IGX prices for India, spot price of August taken. ETC Analysis

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?

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)
Carbon price to be competitive in China (EUR/t CO_2)	0	115

Barriers mitigated

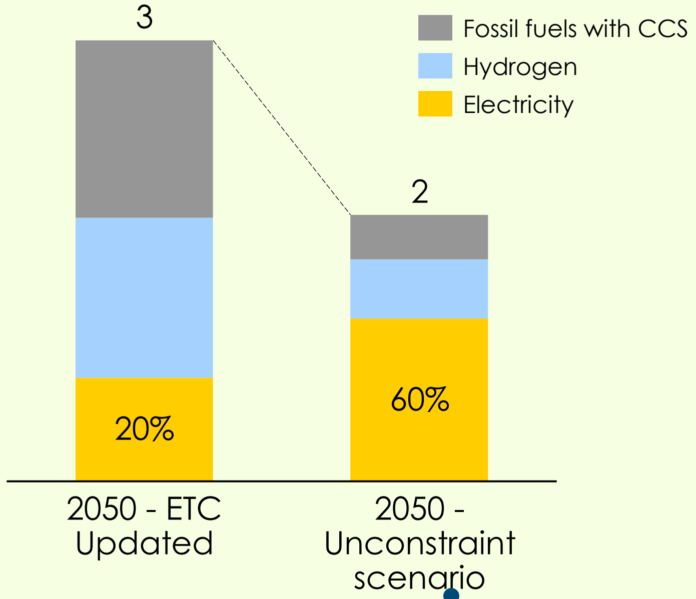
- Proving high temperature heat at 850°C on a commercial scale
- Sufficient cost-competitive power
- Improving the business case (lower CAPEX and competitive power prices)

Latest developments

- 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

Preliminary



Key assumption for the unconstraint scenario: Fossil steam crackers are replaced by electric crackers after 2035

Source: BASF (2022). *BASF, SABIC and Linde start construction of the world's first demonstration plant for large scale electrically heated steam cracker furnaces;* LyondellBasell (2023). *LyondellBasell pursues new e-electric furnace technology;* Shell (2022). Shell and Dow start up e-cracking furnace experimental unit. Systemiq & Center for Global Commons (2022). *Planet Positive Chemicals*

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	⬆ **Cost-competitive electricity (\$60-\$80 MWh) and technological advances** could increase demand for electrons to power **electric applications for the industrial sector**
Final hydrogen use/e-ammonia	⬇ Electrification of high temperature heat may **reduce H_2 demand** for **H_2-based solutions**.
Carbon based fuels (e-SAF, methanol, fossil with and without CCS)	⬇ Could displace reliance on **fossil + CCS** alternatives for decarbonization

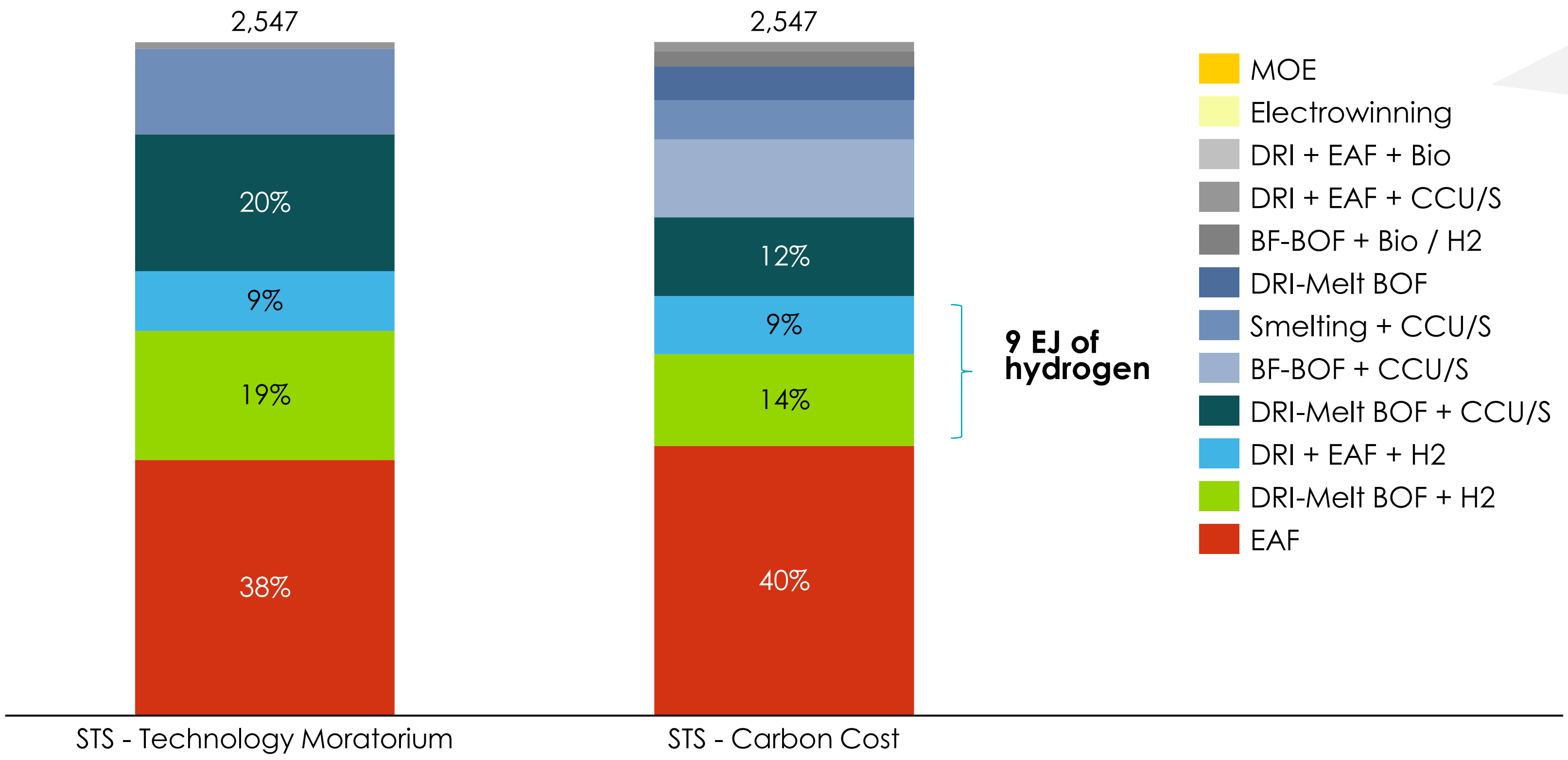
Key questions/considerations

- 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

Electrification of iron-making

Previous iron and steel decarbonisation scenario shows no uptake of MOE and electrowinning before 2050 (and high percentage H_2)

Global technology mix for steel making in 2050, Mt steel



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

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 *Illustrative examples*
Molten Oxide Electrolysis (high temperature electrolysis)	• **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 efficient[1]**	BOSTON METAL ArcelorMittal
Electrowinning (low temperature electrolysis)	• **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 EAF[1] with a small amount of coke to make liquid crude steel.	4-5	**25% more efficient[1]**	John Cockerill ArcelorMittal electra ELEMENTZERO FORTESCUE FUTURE INDUSTRIES

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.* TNO (2020). *Low temperature electrowinning for steelmaking;*

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

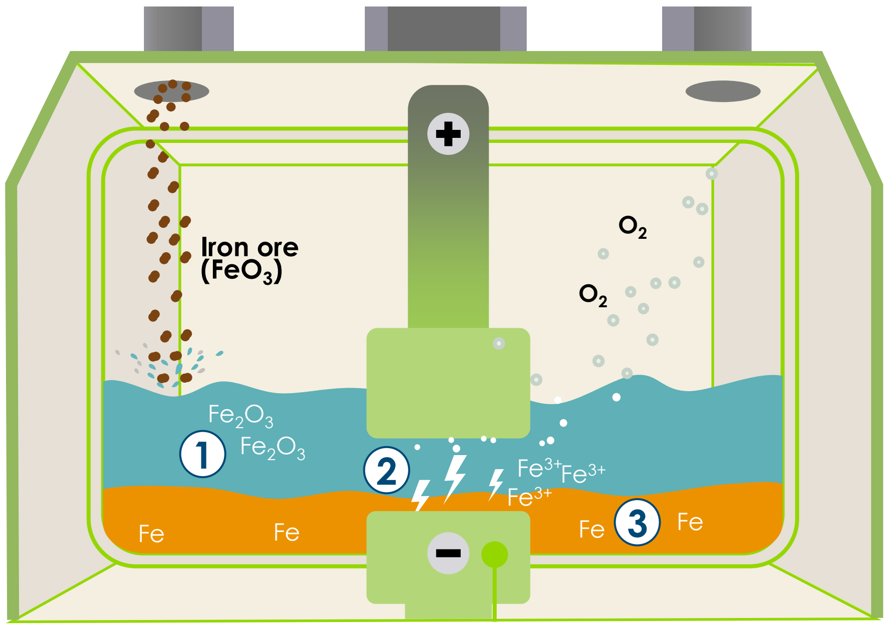
OVERVIEW OF MOLTEN OXIDE ELECTROLYSIS (MOE)

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 procession various grades of iron ore but impact of higher gangue[1] 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 (Fe_2O_3) 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 Fe^{3+} ion, where the Fe^{3+} 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

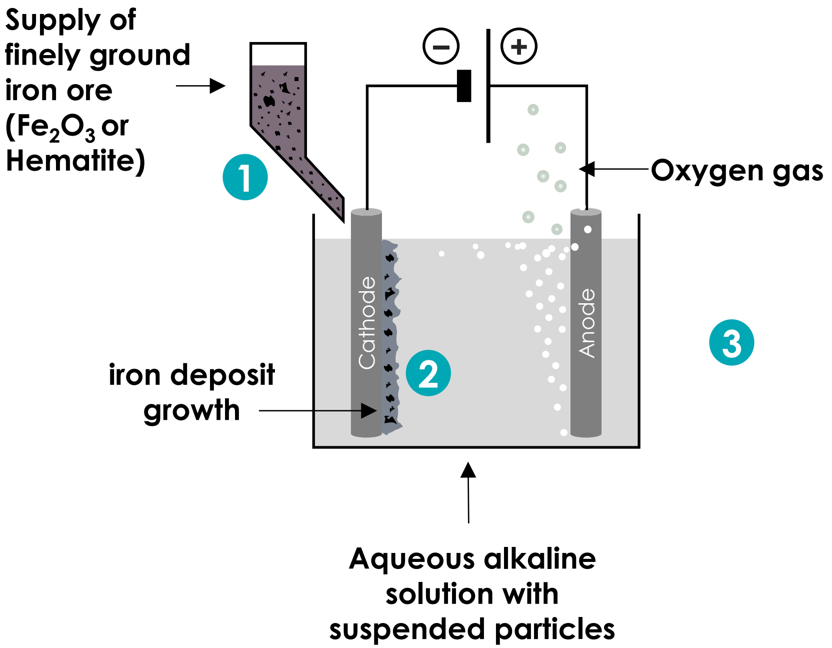
OVERVIEW OF ELECTROWINNING (Alkaline Iron Electrolysis)

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 gangue[1] 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. Afterwards, the iron is fed into the EAF with a small amount of coke to make liquid crude steel.

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

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

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

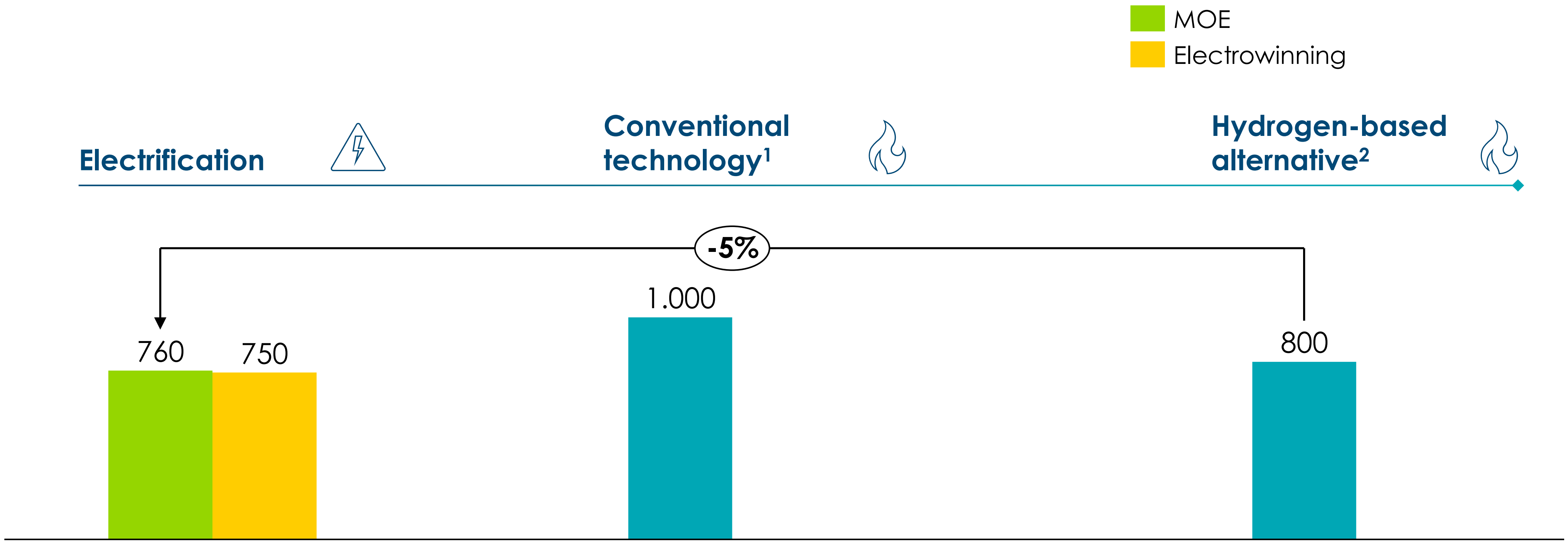
- **Stable power supply:** achieving and maintaining a temperature of 1650°C is challenging and time-consuming for the MOE process. If the feed cools down and solidifies, it may impact the electrolyser modules' performance and stability

Sources: Agora Industry (2024), *Low-carbon technologies for the global steel transformation;* Siderwin website

Highly preliminary

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

Electrification:
- Requires less equipment than conventional technologies
- CAPEX could be further reduced by factoring in learning rates

Conventional technology:
- Requires more equipment compared to electrification technologies and more space

Hydrogen-based alternative:
- Requires less equipment than conventional technologies
- CAPEX could be further reduced by factoring in learning rates

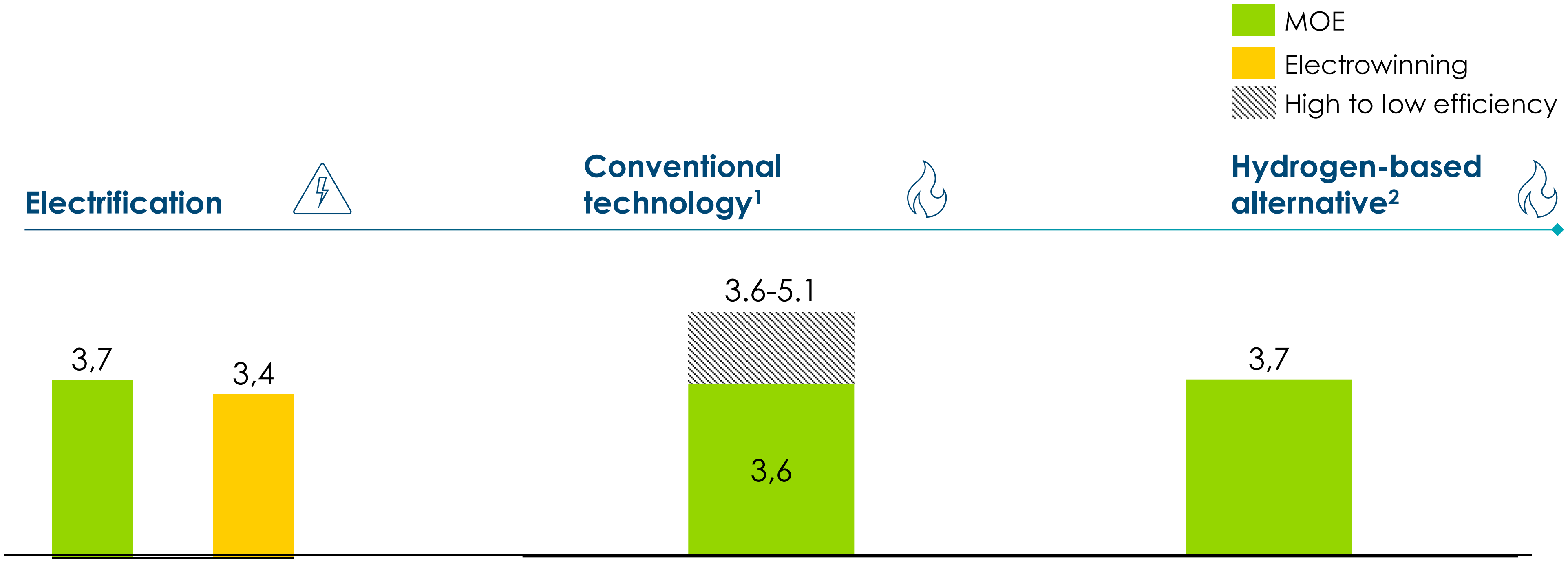
Notes: 1. Blast Furnace – Basic Oxygen Furnace; equipment includes coking plant, sintering plant, pelletizer plant, blast furnace, basic oxygen furnace; 2. Direct Reduced Iron – Electric Arc Furnace.
Sources: Mission Possible Partnership (2022). *Making net-zero steel possible*

Highly preliminary

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

Electrification | **Conventional technology[1]** | **Hydrogen-based alternative[2]**

Energy consumption (MWh/t steel)



Rationale

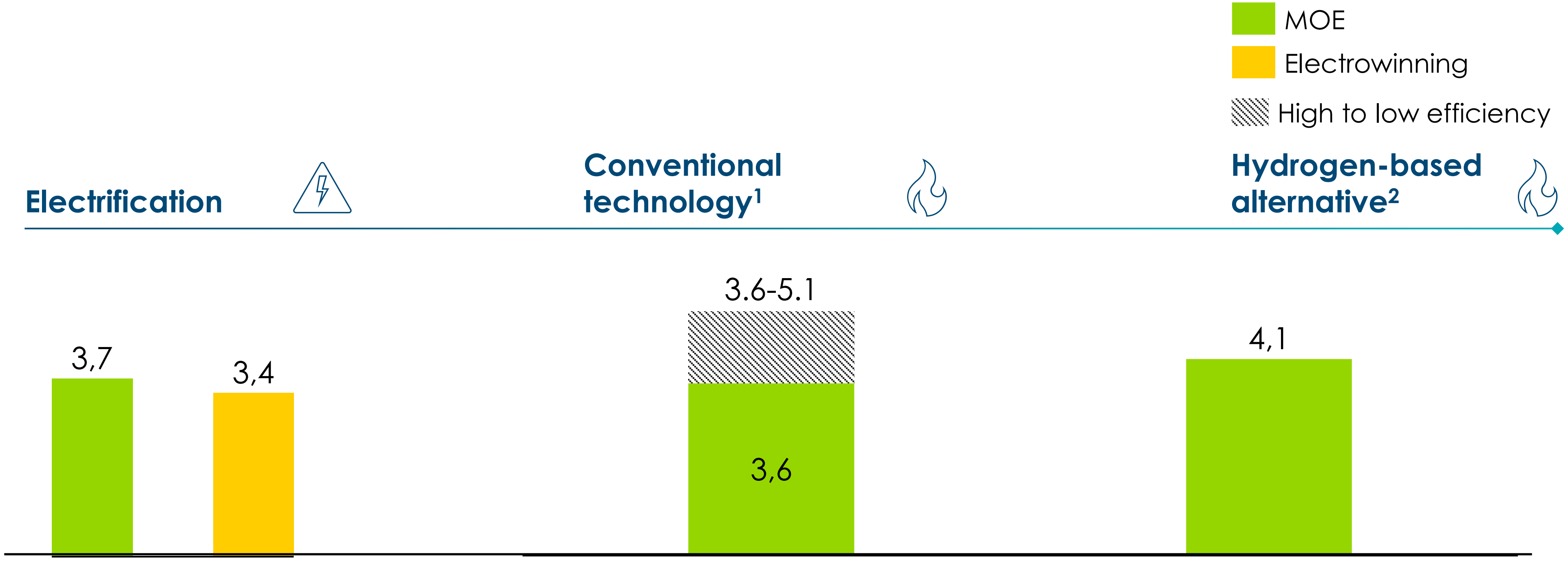
- Electrification: Higher thermal and energy efficiency due to use of electric arc furnaces compared to average conventional technologies
- Conventional technology[1]: Average blast furnace efficiencies are relatively low
- Hydrogen-based alternative[2]: High energy and combustion efficiencies

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

Highly preliminary

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

Energy consumption (MWh/t steel)



Rationale

Electrification	Conventional technology[1]	Hydrogen-based alternative[2]
Higher thermal and energy efficiency due to use of electric arc furnaces compared to avergae contentional technologies	Average blast furnace efficiencies are relatively low	High energy and combustion efficiencies

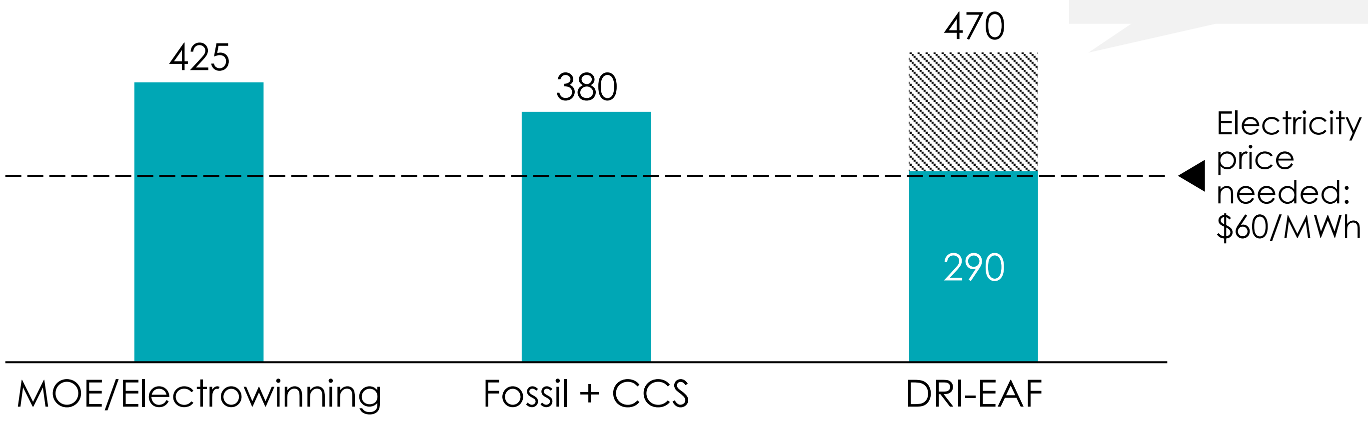
Notes: 1. Blast Furnace – Basic Oxygen Furnace; 2. Direct Reduced Iron – Electric Arc Furnace.
Sources: Mission Possible Partnership (2022). *Making net-zero steel possible*

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

Highly preliminary

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

MPP assumed a low-price of $0.7/kg H_2 but could less competitive with today's estimates- $3/kg H_2



	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. 4. Emissivity for best available technology assumed 1.8 tCO_2/t steel and a capture price of $100/t CO_2. 4. $0.7/kg H_2

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

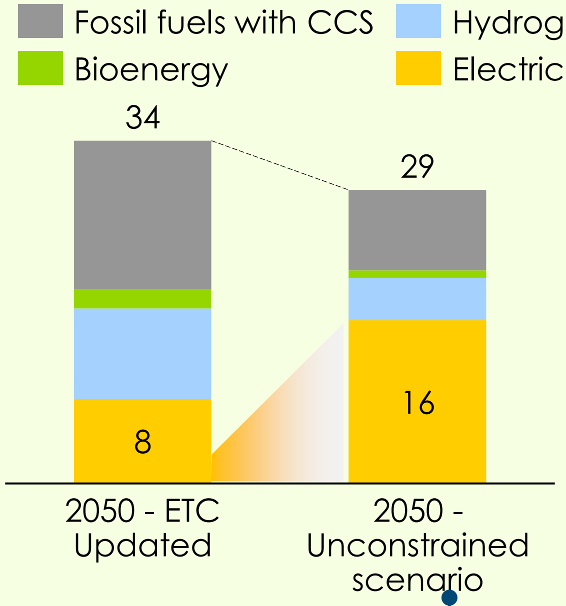
- Accessing a **competitive power supply**
- Proving commercial viability through piloting and demonstrating it can be scaled economically
- Scaling up the technology, improving energy efficiency, ensure long-term anode stability

Latest developments

- **MOE:** BOSTON METAL (backed by ArcelorMittal) 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:** electra commissioned its pilot plant earlier this year in Boulder.
- **Electrowinning:** ArcelorMittal & John Cockerill **'s Volteron plant** will start production in 2027, targeting **40–80 kt/year**
- **Electrowinning:** FORTESCUE FUTURE INDUSTRIES is doing a research funded by the Australian government agency

Impact on energy demand, EJ per year

Highly preliminary



Key assumption for the unconstraint scenario: All fossil-based steel making plant are replaced by MOE/Electrowinning after 2035

Sources: 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.*

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	⬇ Electric crackers may **reduce H_2 demand** for **H_2-based DRI.**
Carbon based fuels (e-SAF, methanol, fossil with and without CCS)	n/a

Key questions/considerations

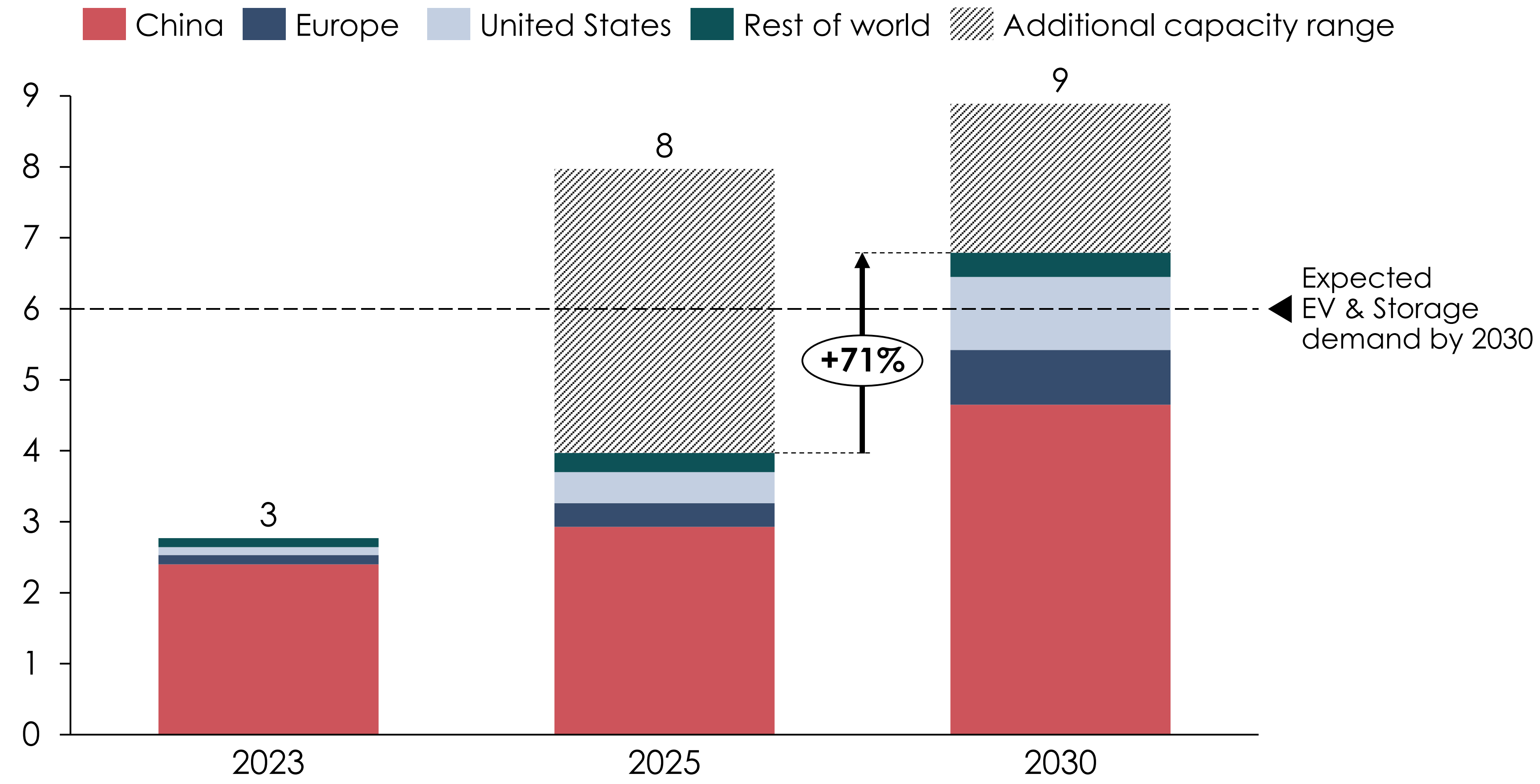
- MOE/electrowinning technologies are advancing, bringing them closer to commercial readiness
- They may be less capital-intensive than other decarbonization options
- Also, MOE and electrowinning could offer better energy efficiency than alternatives
- However, the business case for MOE and electrowinning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

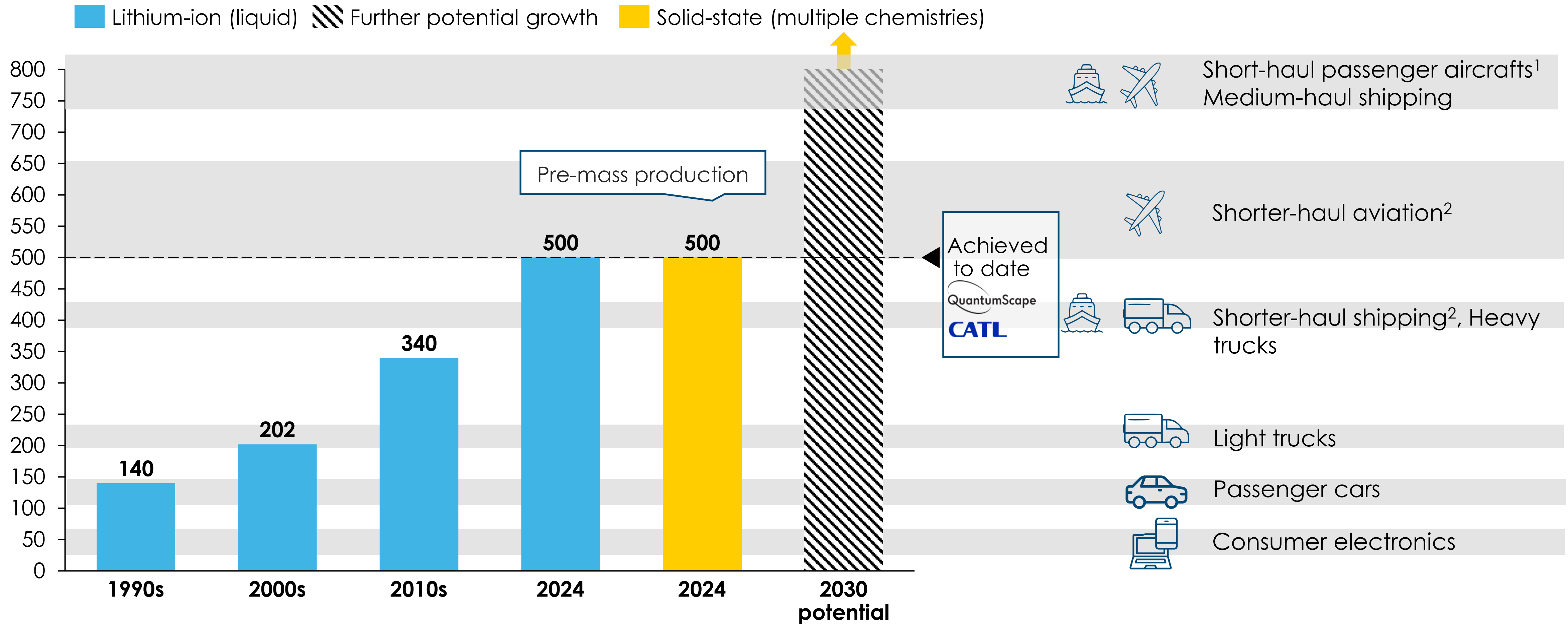
Solid-state batteries have the potential to further accelerate electrification in mobility by significantly enhancing energy density

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-200s, 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 *Ranges*	Life cycles *Before signs of degradation*	Fast charging capability	Companies *Illustrative examples*
Lithium-ion Solid State Battery (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 Solid Power QuantumScape LG Chem
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**	CATL BYD CALB EVE Energy HiTHIUM

Note: 1)For SSB, Li-metal as anode with oxide (+NMC cathode) or polymer (+LPF 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

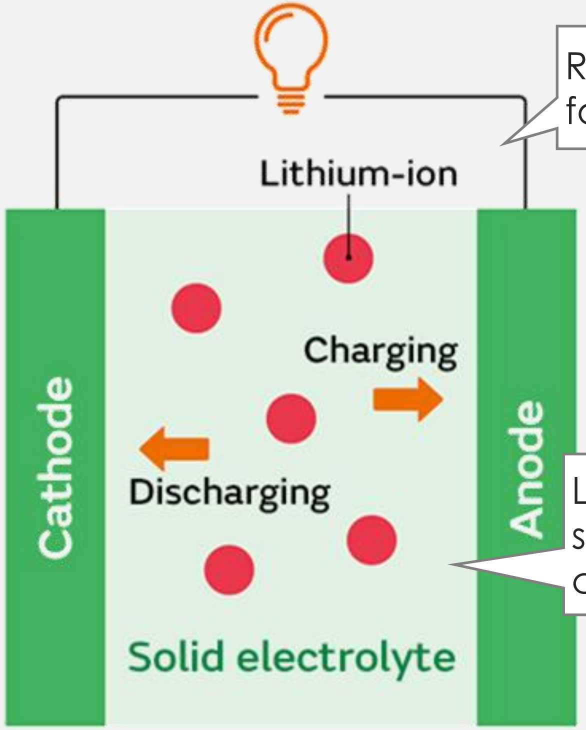
Key performance advantages

- **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



Renewable energy used for charging process

Lithium-ions move in a solid electrolyte (e.g. ceramic separator)

- 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 Isi (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-batteries[1]

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

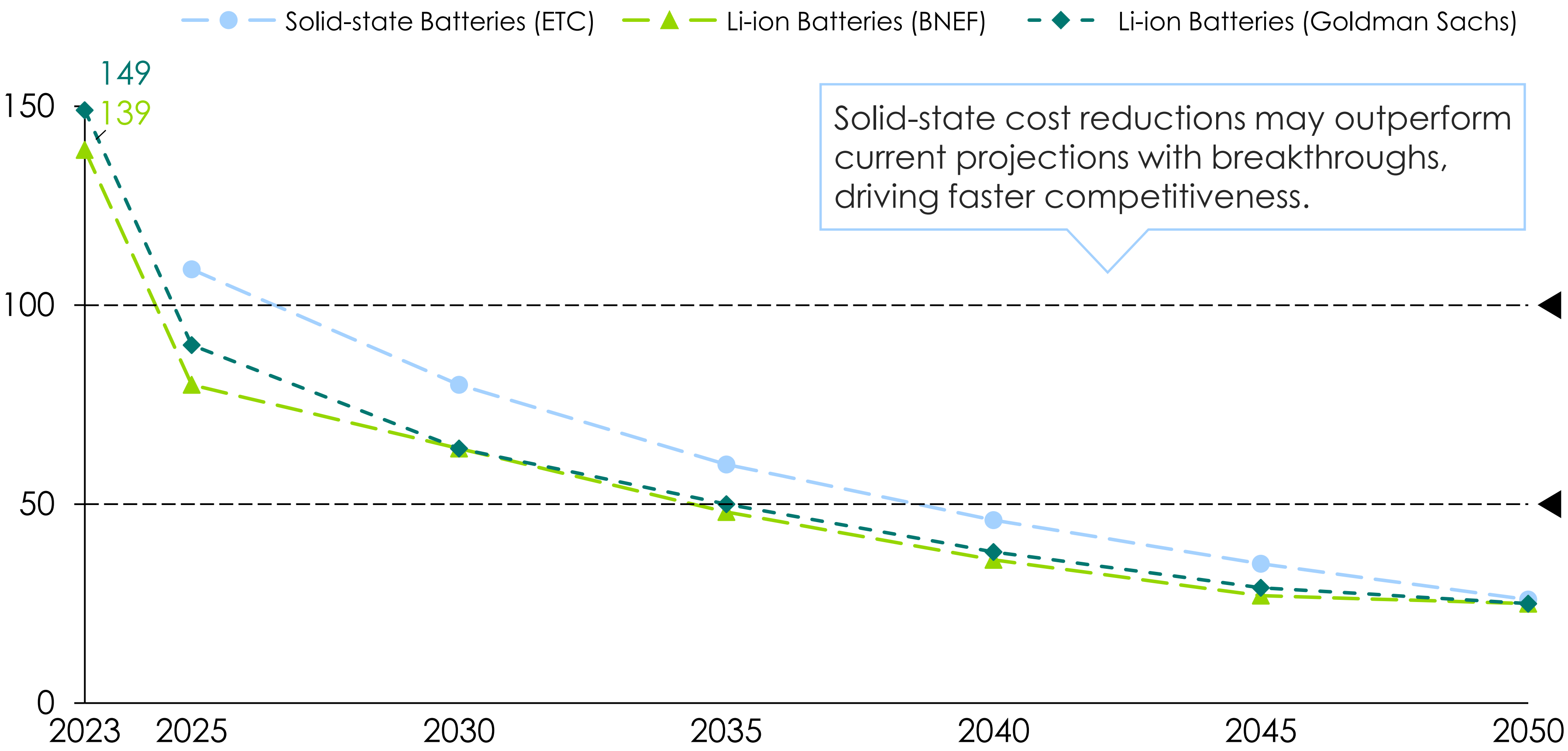
ORGANISATIONAL

Source: Fraunhofer ISI (2024), BloombergNEF (2024) Solid-State Battery Tech Update 2024: Cautious Optimism

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]



Solid-state cost reductions may outperform current projections with breakthroughs, driving faster competitiveness.

Mobility example

Battery pack price, shipping[3]

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)

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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	⬆ **Steady advancements** in **battery technology could increase demand for electrons** across all road transport and **even short-to-medium haul aviation** and **shipping**
Final hydrogen use/e-ammonia	⬇ **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**
Carbon based fuels (e-SAF, methanol, fossil with and without CCS)	⬇ 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**

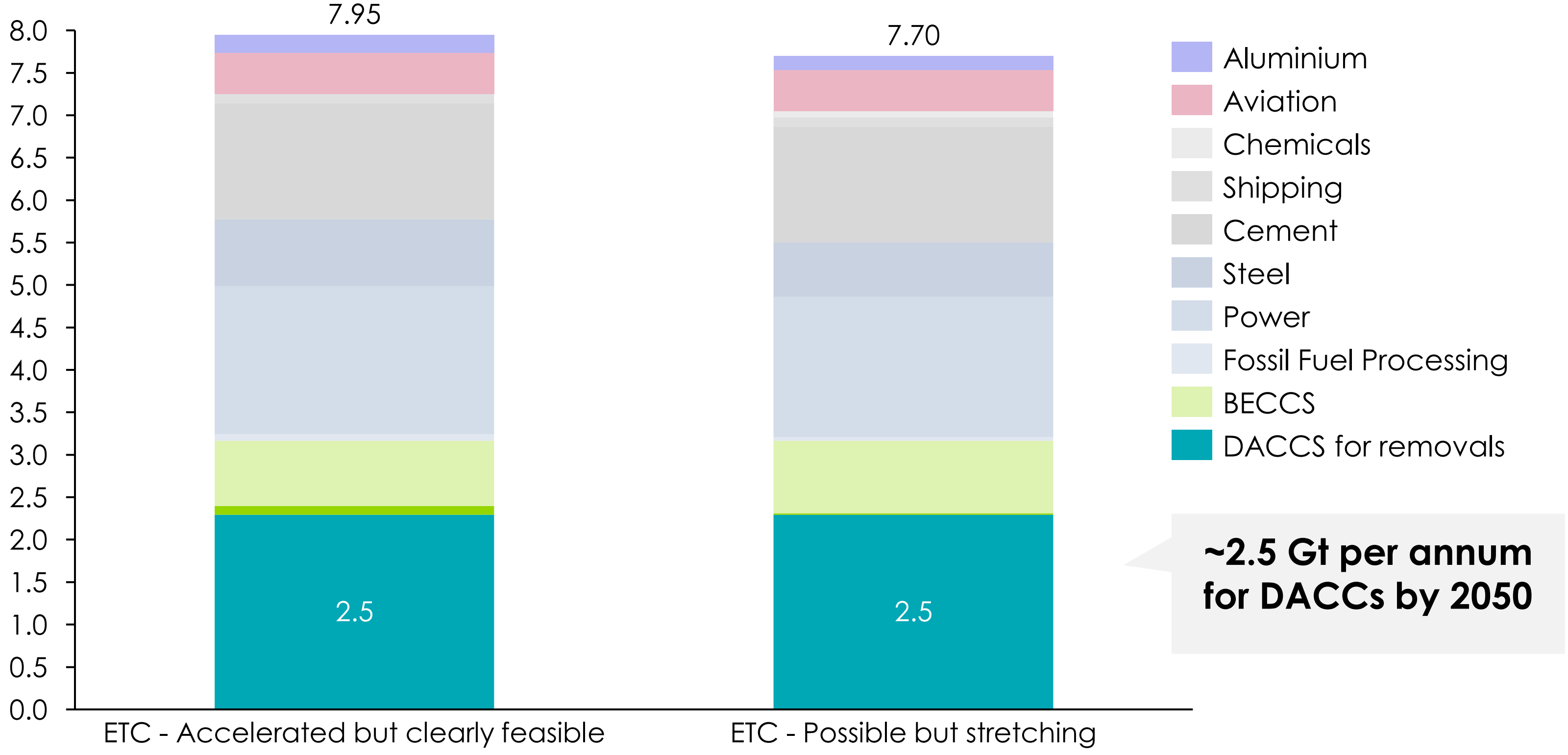
Key questions/considerations

- 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, $GtCO_2$



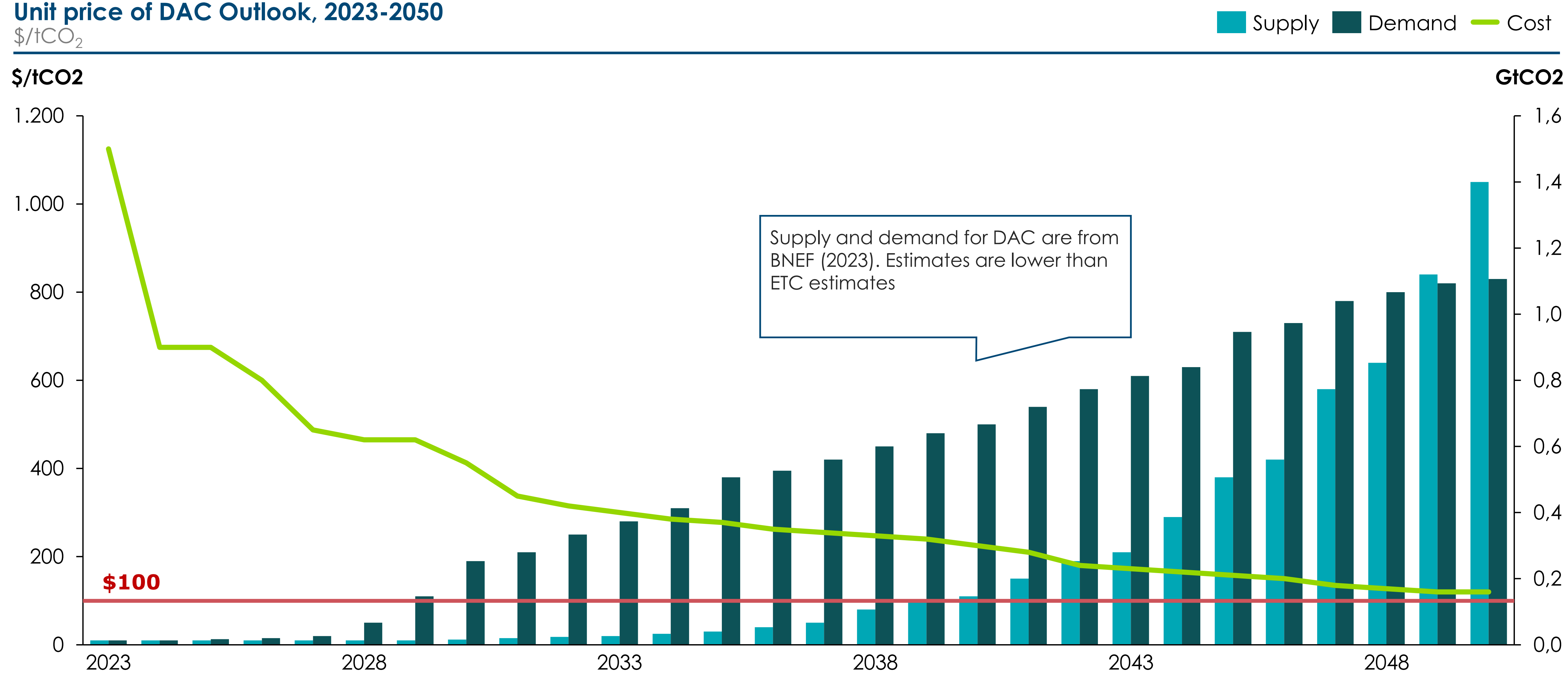
~2.5 Gt per annum for DACCs by 2050

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

$/tCO$_2$



Supply and demand for DAC are from BNEF (2023). Estimates are lower than ETC estimates

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

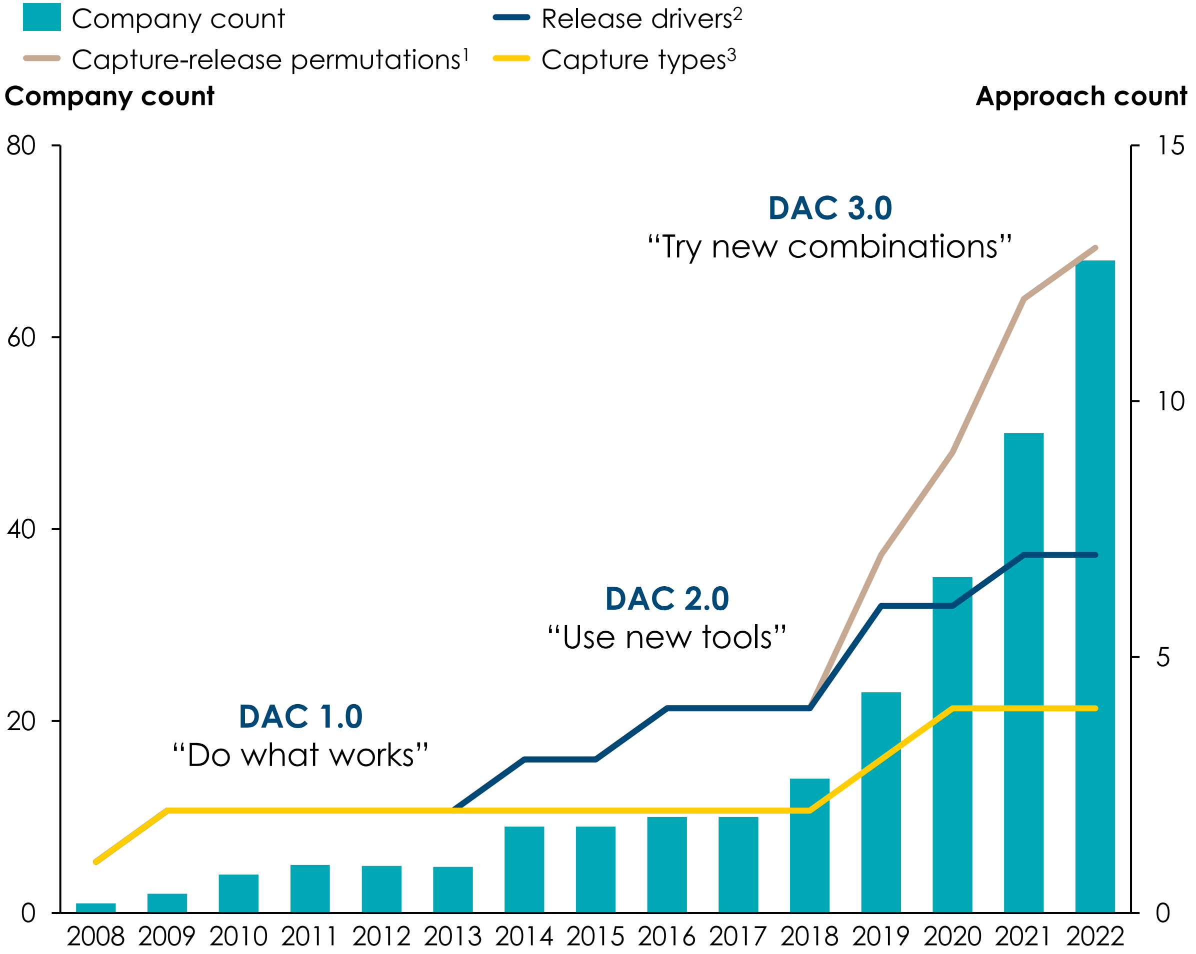
Technology	Process	TRL	Companies
Electrochemical DAC	Uses electrochemical cells to capture and release CO_2. Operates at lower temperatures relative to conventional thermal or pressured-based DAC. Involves adsorption of CO_2 onto a reactive material, which is then desorbed using an electric current. This method could reduce energy consumption and enhances scalability compared to conventional thermal or pressure-based DAC systems.	5-7	VERDOX Greenlyte MissionZero
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	280earth
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 cusp.ai Unlocking the future of materials with AI. Orbital Materials
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 CO_2 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 CO_2 by 2050 could be challenging

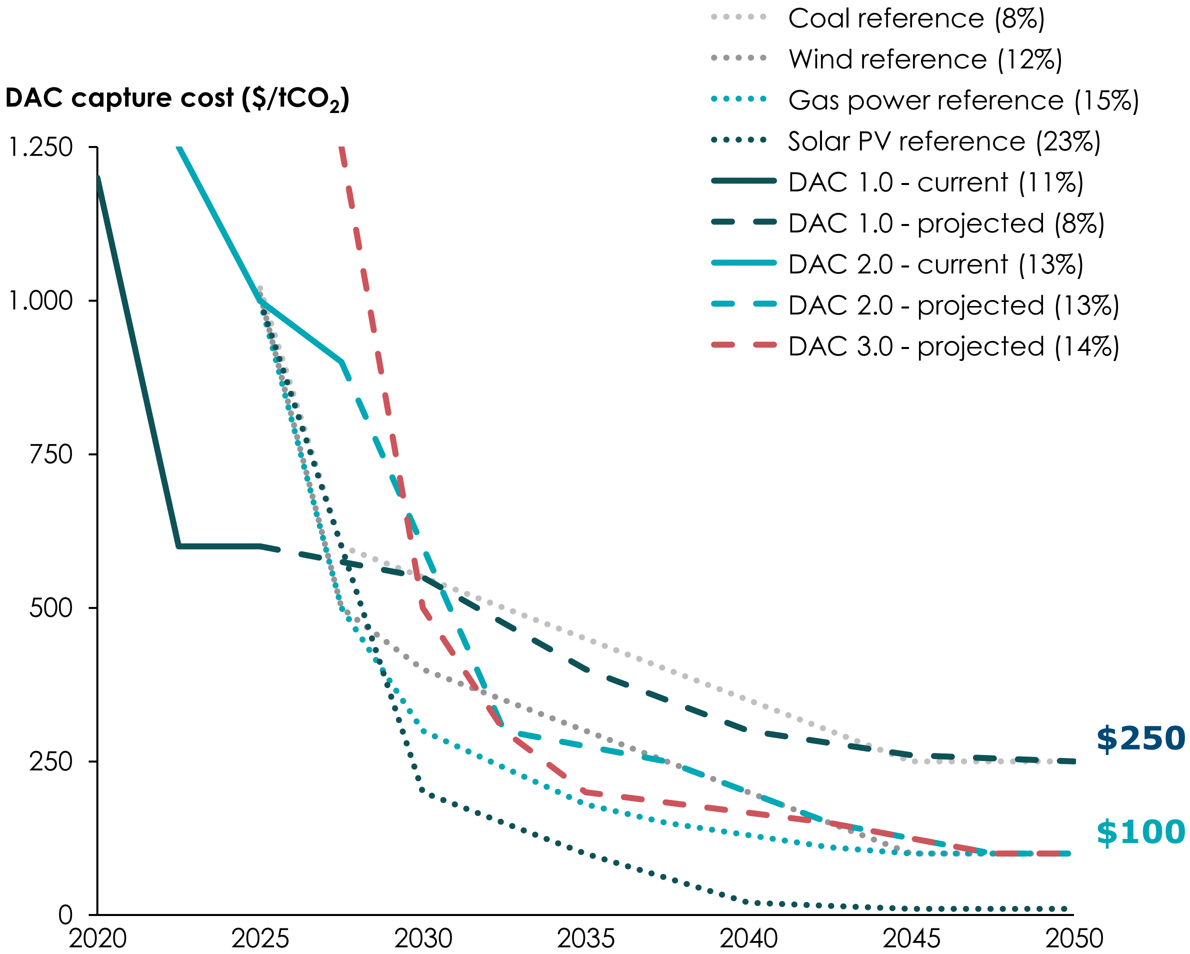
DAC companies and approach combinations over time

Numbers



Potential DAC cost paths by reference learning rates

In 2024 USD



1. Combining various methods for capturing and releasing CO_2, such as replacing thermal techniques with liquid solvent capture and electrochemical release; 2. Applying alternative CO_2 release methods, including pH or voltage control; 3. Developing innovative capture technologies like membranes.

Source: Statista, Extantia 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 CO_2 concentration
- **Electricity costs**: High energy demand for DAC processes and sorbent regeneration
- **Sorbent costs**: Expensive CO_2-capturing materials with significant replacement costs

TECHNICAL

- **Material durability and stability**: Develop efficient, long-lasting sorbents for CO_2 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 CO_2 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** Lower-cost DACCS could **expand the role of blue hydrogen**. In some sectors, increased use of fossil fuels combined with CCS may also **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 reductions impact the cost-competitiveness of fossil fuel solutions with CCS?
  - 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

🟥 Focus

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]		✓	✓	✓	

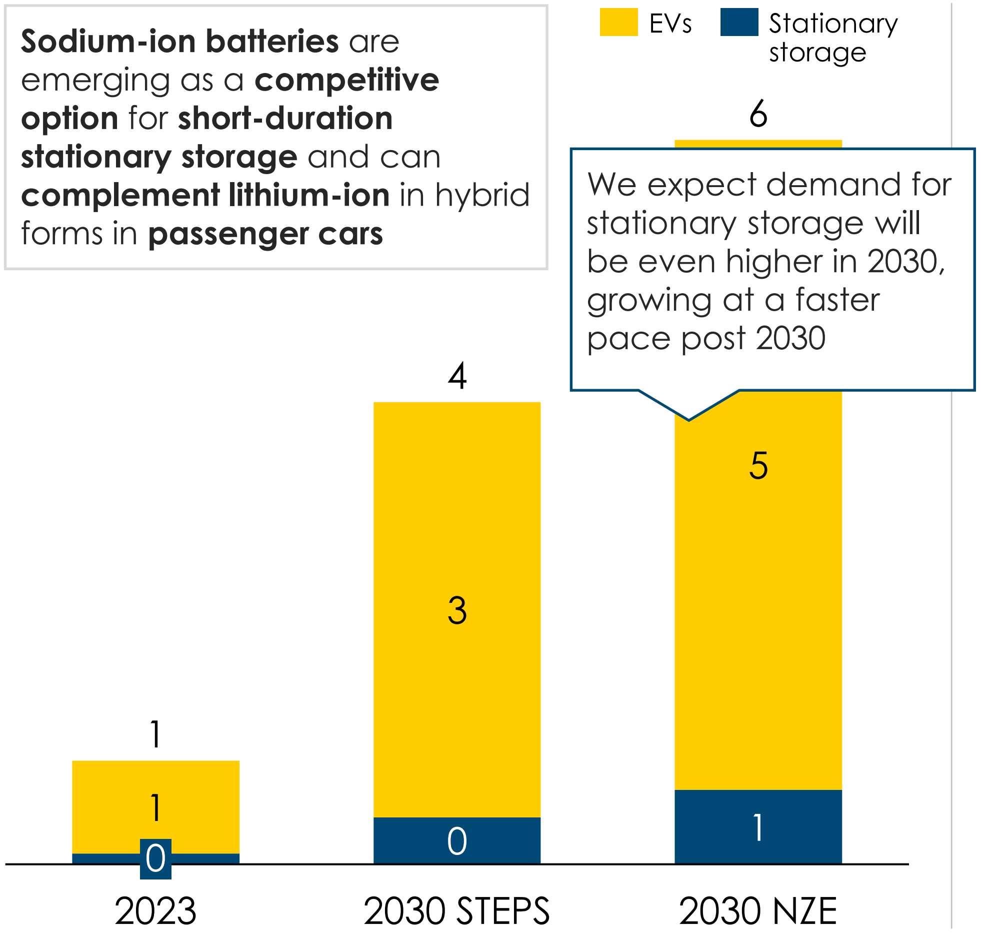
Notes: 1. Limited nuclear capacity for flexible ramping. 2. Battery storage is utility-scale and behind-the-meter. 3. Other technology might include gravitational storage and molten sands storage. 4. Examples of Power-to-X include the production of H2 from electrolysis and re-conversion of hydrogen in power via gas turbines or fuel cells. 5. Residential and commercial standard heating needs6. 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

Sodium-ion batteries are emerging as a **competitive option** for **short-duration stationary storage** and can **complement lithium-ion** in hybrid forms in **passenger cars**



We expect demand for stationary storage will be even higher in 2030, growing at a faster pace post 2030

Stationary storage technologies in a net-zero economy

Mechanical	**Pumped-storage hydropower**	• Most widely used storage technology with significant additional potential in several regions (outside EU)
Electro-chemical	**Batteries**	• 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)**	• Potential for seasonal storage though outpaced in terms of cost and efficiencies by new battery chemistries
Thermal	**Molten salt storage**	• 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 *Before signs of degradation*	Energy Efficiency	Companies *Illustrative examples*
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%	中科海钠 HiNa BATTERY Natron Energy faradion
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%	EVE Energy CATL CALB BYD HiTHIUM

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)

SIBs offer a low-cost and safe storage option due to the abundance of sodium, with improving cycle life and efficiency for stationary applications

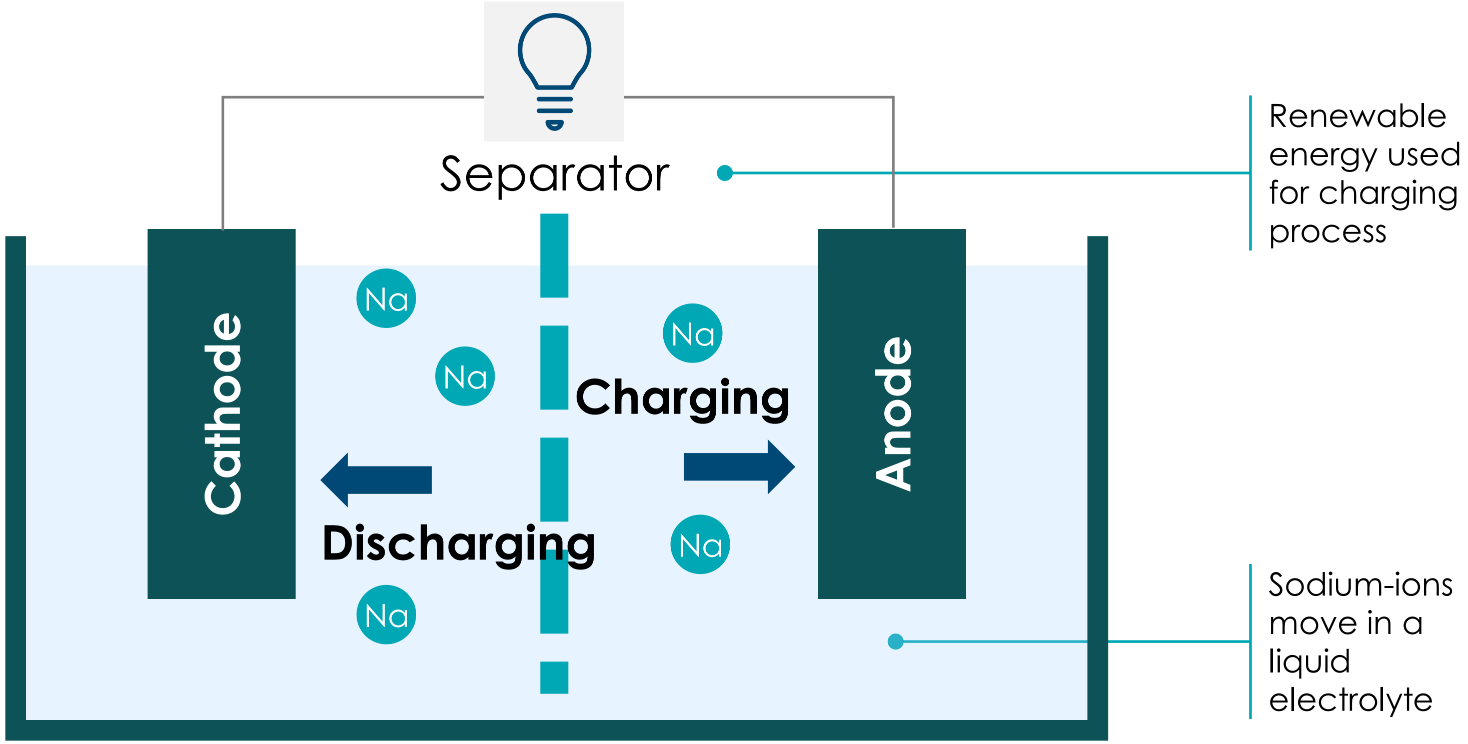
Key advantages

- **Cost-Effective:** Uses abundant, inexpensive sodium[1]
- **Sustainable:** lower material footprint than lithium
- **Safer:** High thermal stability and lower risk of overheating
- **Cold-Resistant:** Performs well in cold climates
- **Durable:** Promises long cycle life for steady, long-term storage

Current status

- **Energy Density**: Higher densities achieved, by Northvolt 160 Wh/kg, CATL 200 Wh/kg
- **Manufacturing Scale**: Natron Energy plans a $1.4B SIB plant in the US by Natron Energy expanding production x40; 50MW/100MWh sodium-ion project online in China since July'24
- **Market Forecast:** SIB could be ~10% of global energy storage additions by 2030

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



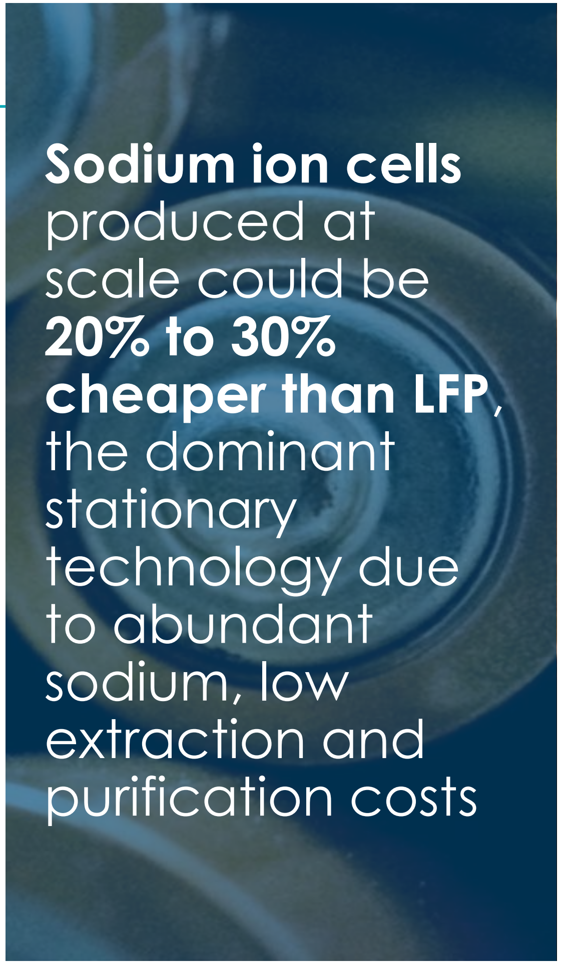
- **Uses abundant materials** like hard carbon and prussian white
- **For utility-scale applications**

Notes: SIB = Sodium-Ion Batteries, 1) Reserves for Lithium estimated at 26Mt globally, compared to abundance of sodium

Sources: Diagram (adjusted) from Murata (2022), What are solid-state batteries?; Fraunhofer Isi (2023) Alternative Battery Technologies Roadmap 2030+; IEA (2024), Batteries and Secure Energy Transitions

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]	• 90-200, with costs btw. 30-80 for the cells
	Lithium-ion battery[2]	• Global: ~210 and ~150 by early 2030s likely • China: well below 200 and falling fast, -40% turnkey cost reduction this year • US: 350 *Note: fully installed system costs, incl. grid connection*
Chemical	**Hydrogen in CCGT**	• $100-200/MWh LCOS
Mechanical	**Pumped Hydro**	• ~260
Mechanical	**A-CAES**	• China ACAES: 280, purpose built 340 • China Tank: 460 • Non-China CAES: 280
Thermal	**Molten Salt**	• 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 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

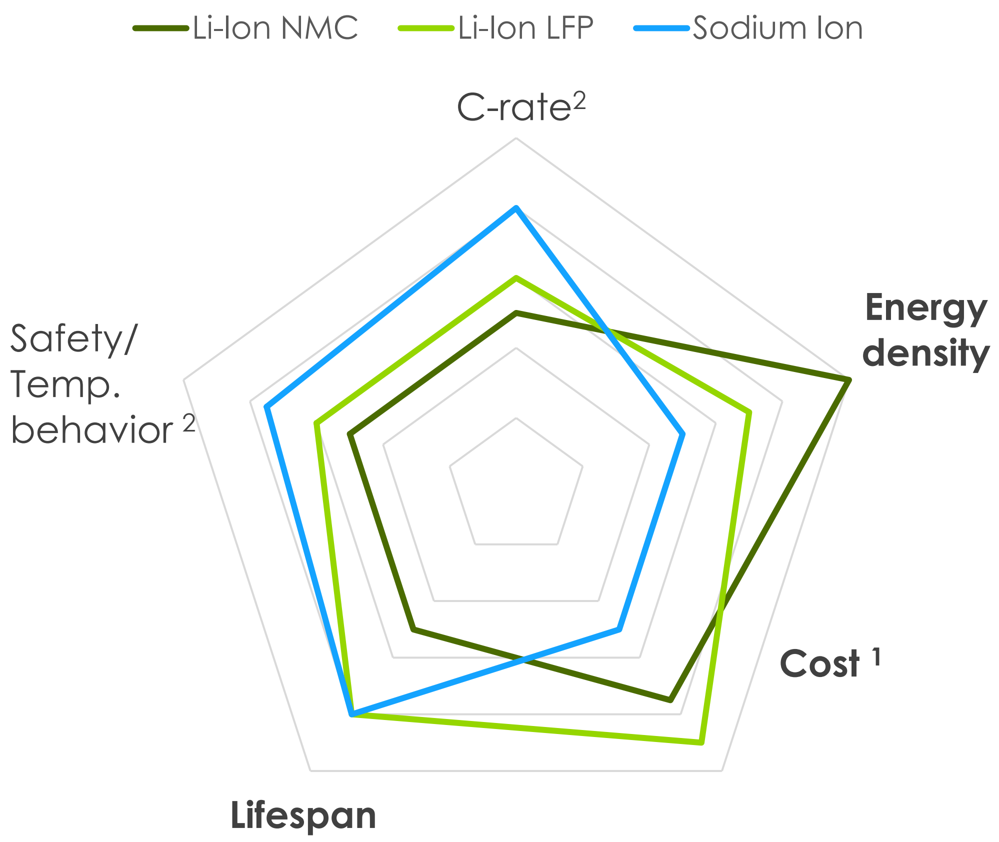
ORGANISATIONAL

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

Source: Fraunhofer ISI (2024),

SIB technology advances rapidly, reaching similar technology KPIs compared to LIBs in the near future, next to cost and safety benefits

Radar chart of relevant dimensions of SIBs compared to LIBs

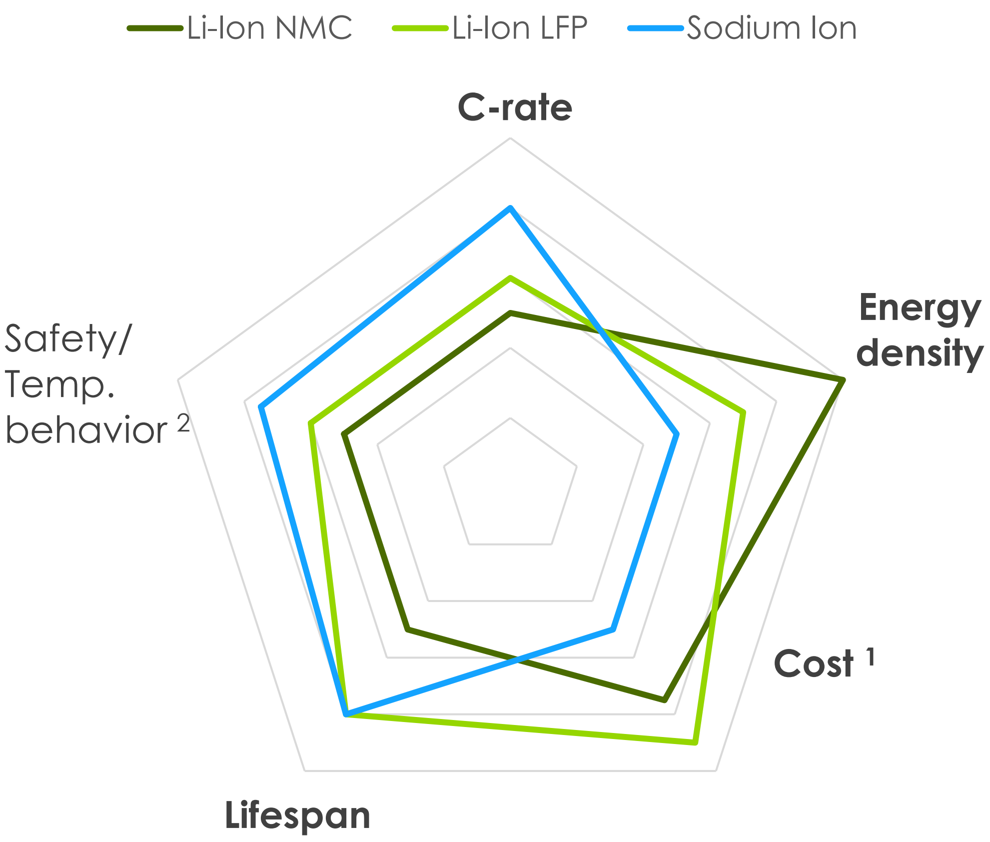


Category	Sodium-ion	Lithium-ion batteries (LIBs)
Max. C-rate	2 – 4 C	4 – 6 C
Gravimetric energy density	~200 Wh/kg announced by CATL in 2024	~500 Wh/kg via condensed battery cell announced by CATL
Volumetric energy density	~ 400 Wh/l	600-750 Wh/l
Raw-material cost	Sodium hydroxide is $300-$800 per metric ton	Lithium hydroxide (for NMC) is ~$40,000 per metric ton
Lifespan	Cycle-life similar to LIBs	Steady performance over a high number of cycles
Safety/ Temperature behavior	More thermally stable and safer, with better tolerance to temperature extremes	More temperature-sensitive, requiring strict thermal management for safety

Notes: 1) Cost of Sodium expected to be 20-30% lower compared to LFP once technology is scaled, average price of battery-grade lithium hydroxide experiences significant fluctuations, prices for lithium hydroxide (for NMC) and lithium carbonate (for LFP) converged in 2023, source:, ETC (2023)Lithium for the energy transition, Statista (2024) 2) Max C-rates/ Temperature behavior being less of a concern for stationary applications compared to mobile applications. SIBS are less likely to experience thermal runaway or catch fire when subjected to high temperatures or mechanical abuse.
Source: ETC analysis based on Fraunhofer ISI (2023) Battery technology advancements 2030+ roadmap, Volta Foundation (2024), IRENA (2024) Critical materials: batteries for electric vehicles

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 $78,000 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) 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	⬆ Sodium further reinforces the scalability and economic viability of **battery storage** solutions to potentially **complement stationary storage options**
Final hydrogen use/e-ammonia	⬇ **Sodium** batteries **can excel** at **short-term balancing**, while **hydrogen may remain** for long-duration energy resilience and flexibility
Carbon based fuels (e-SAF, methanol, fossil with and without CCS)	⬇ **New battery chemistries** add to potential storage solutions, allowing more renewables to displace fossil in the grid

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

▨ Focus

	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 needs6. 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

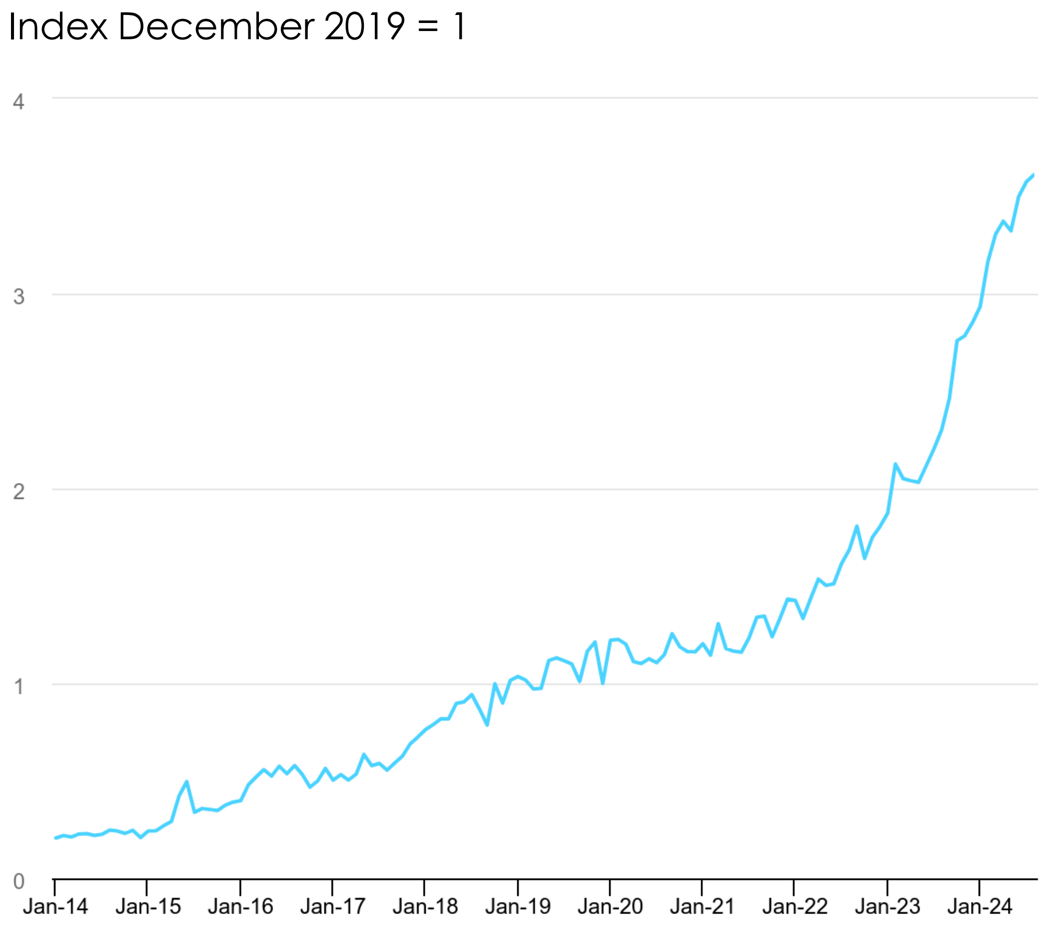
20 year PPA with Constellation Energy of Three Mile Island Nuclear plant

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 cata center campus

Investment in data centres in the United States

2014-2024



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	NUSCALE Power for all humankind ROLLS ROYCE nuward EDF GROUP HOLTEC INTERNATIONAL
	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	OKLO ONTARIO POWER GENERATION
	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	TERRESTRIAL ENERGY TerraPower THORIZON Kairos Power BWXT BWX Technologies, Inc. energy ROLLS ROYCE
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	OKLO USNC ULTRA SAFE NUCLEAR

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

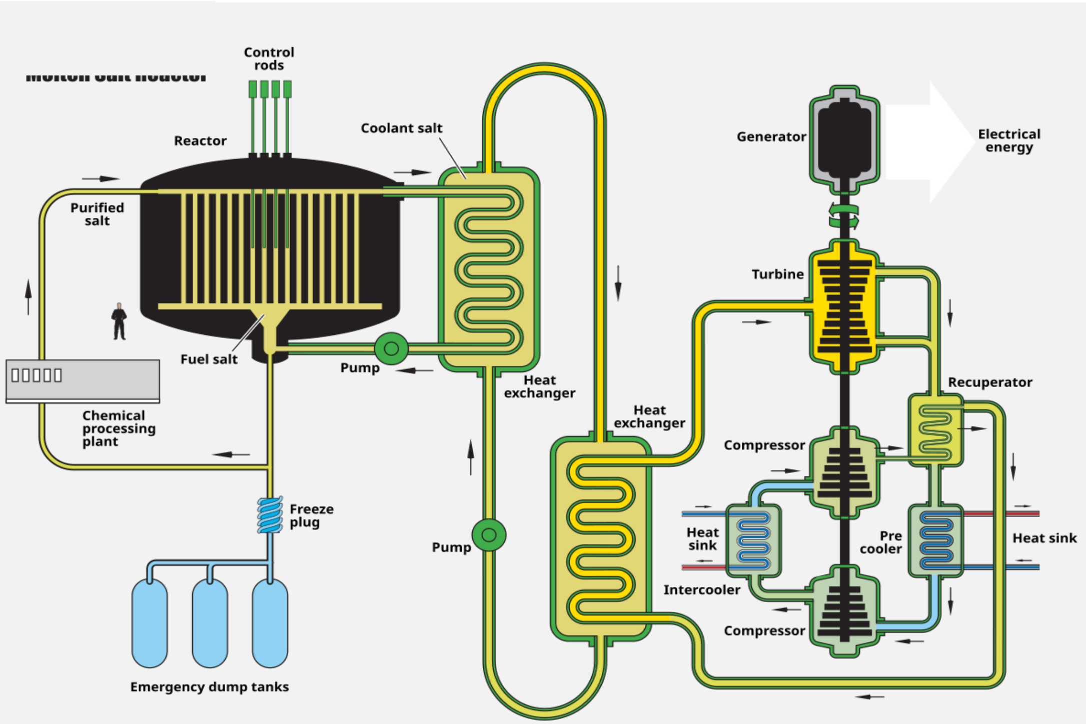
Key advantages

- **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 uses[1]

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 tripe 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:** Fuel[2] 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

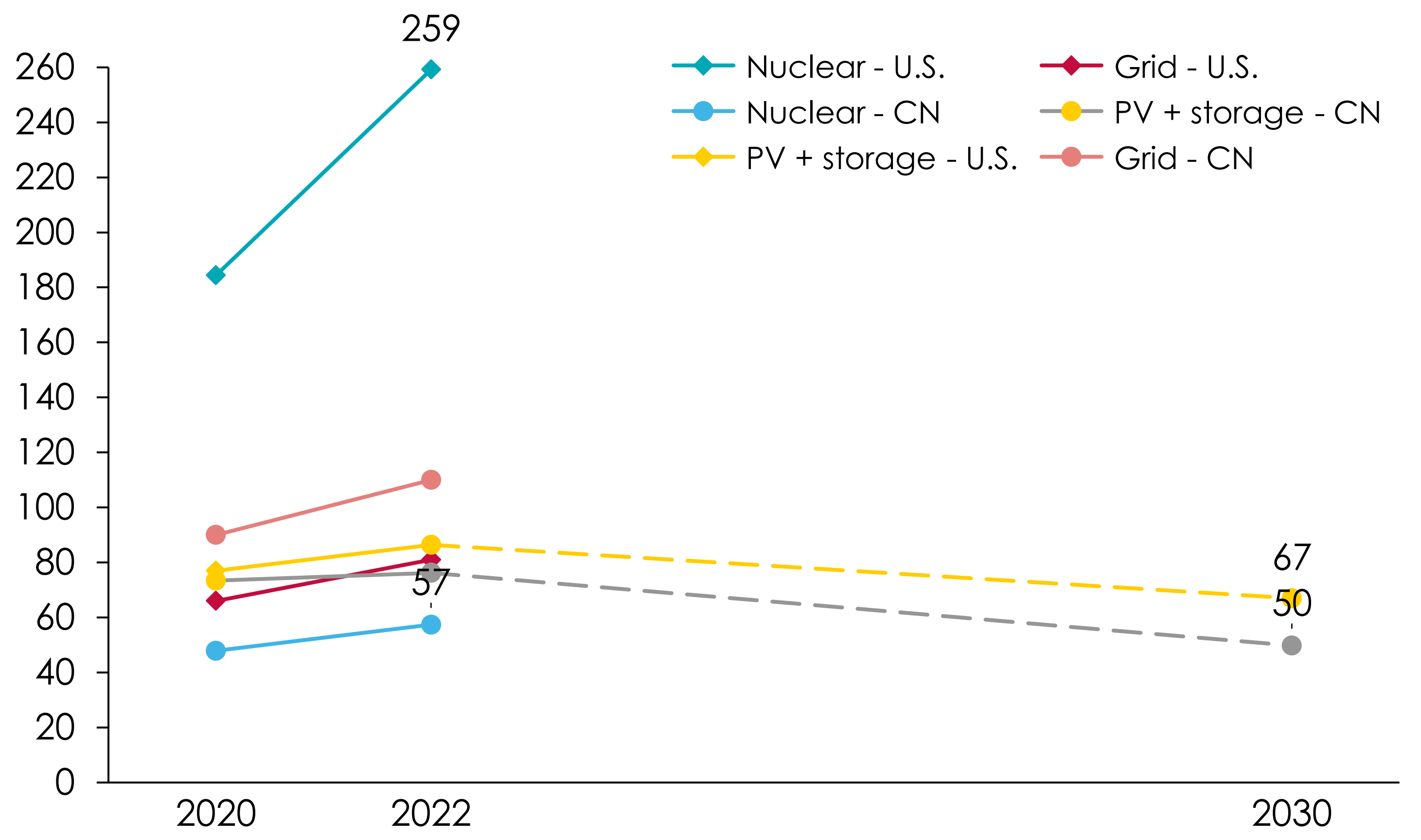
- **Regulatory hurdles:** New reactor types may require updated safety standards and licensing, varying by country
- **Safety and security concerns:** Potential radiological hazards and national security risks remain, with many designs being unpopular among citizens

Notes: HALEU (High-Assay Low-Enriched Uranium)
Source: BloombergNEF (2024), International Atomic Energy Agency (2023), IEA (2023) Nuclear Power

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, Grid[1]

$/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**

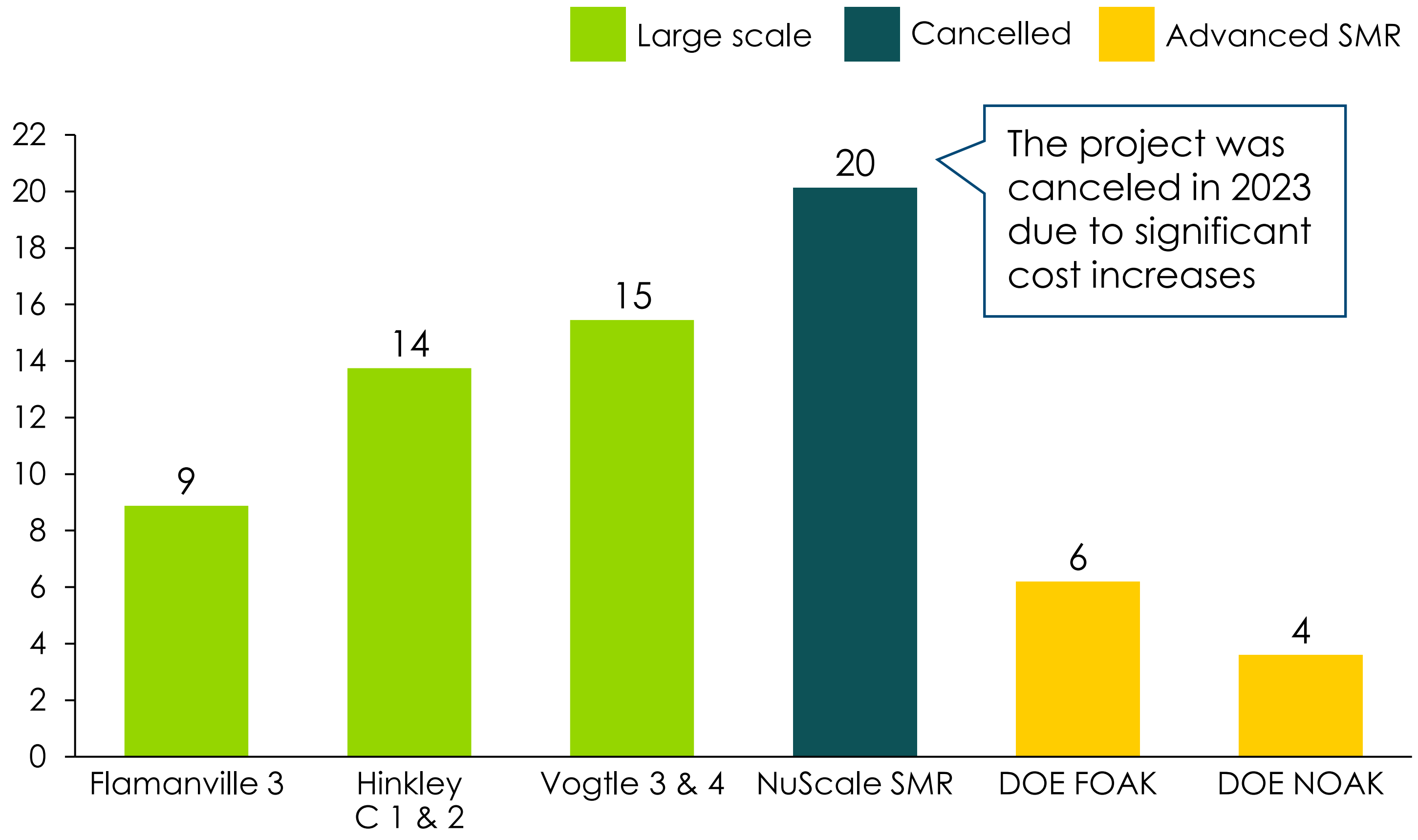
Notes: 1) LCOE mid scenario taken from BNEF For battery storage the LCOE includes a charging costs. LCOE include carbon pricing in markets where policies are already implemented. LCOE of nuclear does not further specify between conventional reactors or SMRs/ NMRs, Average CN, U.S. grid prices for industry 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



The project was canceled in 2023 due to significant cost increases

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.

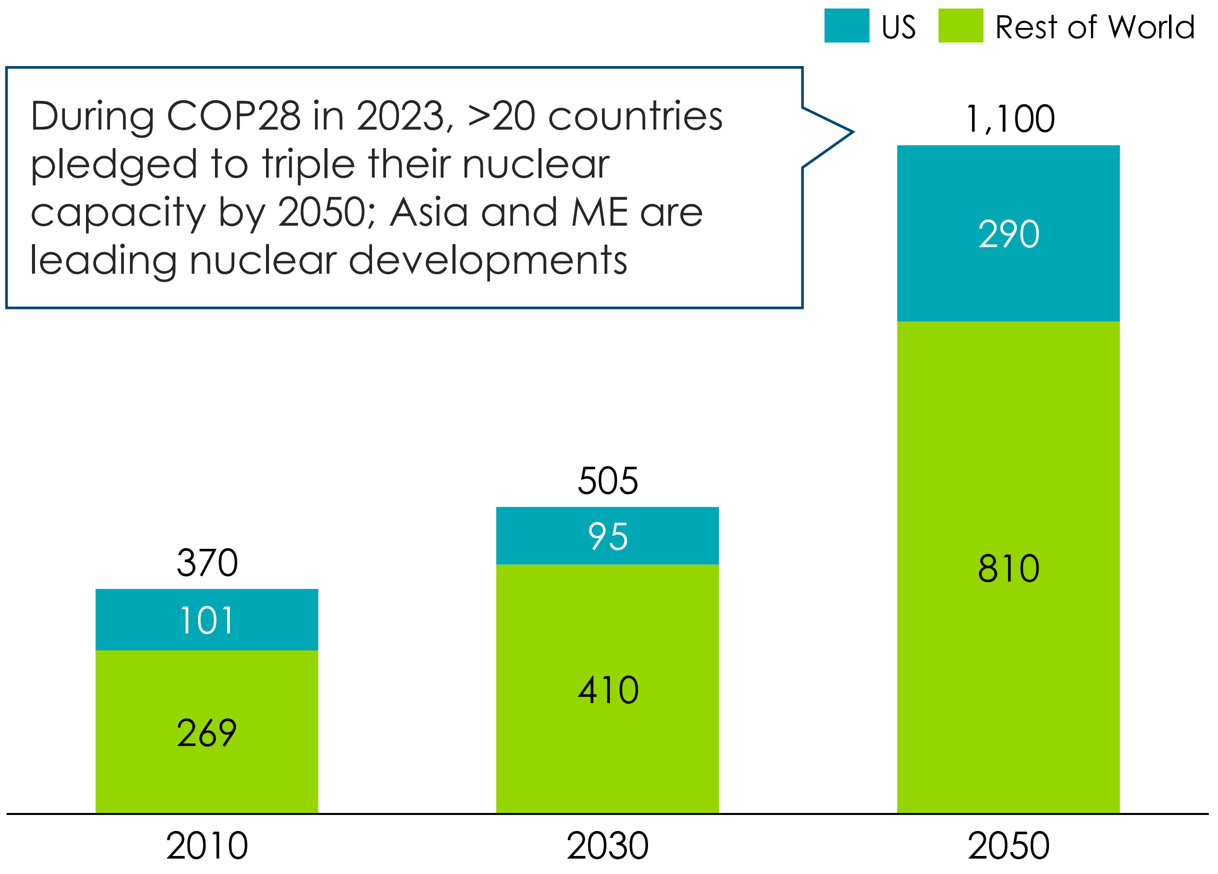
Waste Management Challenges: Long-term disposal of radioactive waste remains unresolved and costly.

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



During COP28 in 2023, >20 countries pledged to triple their nuclear capacity by 2050; Asia and ME are leading nuclear developments

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

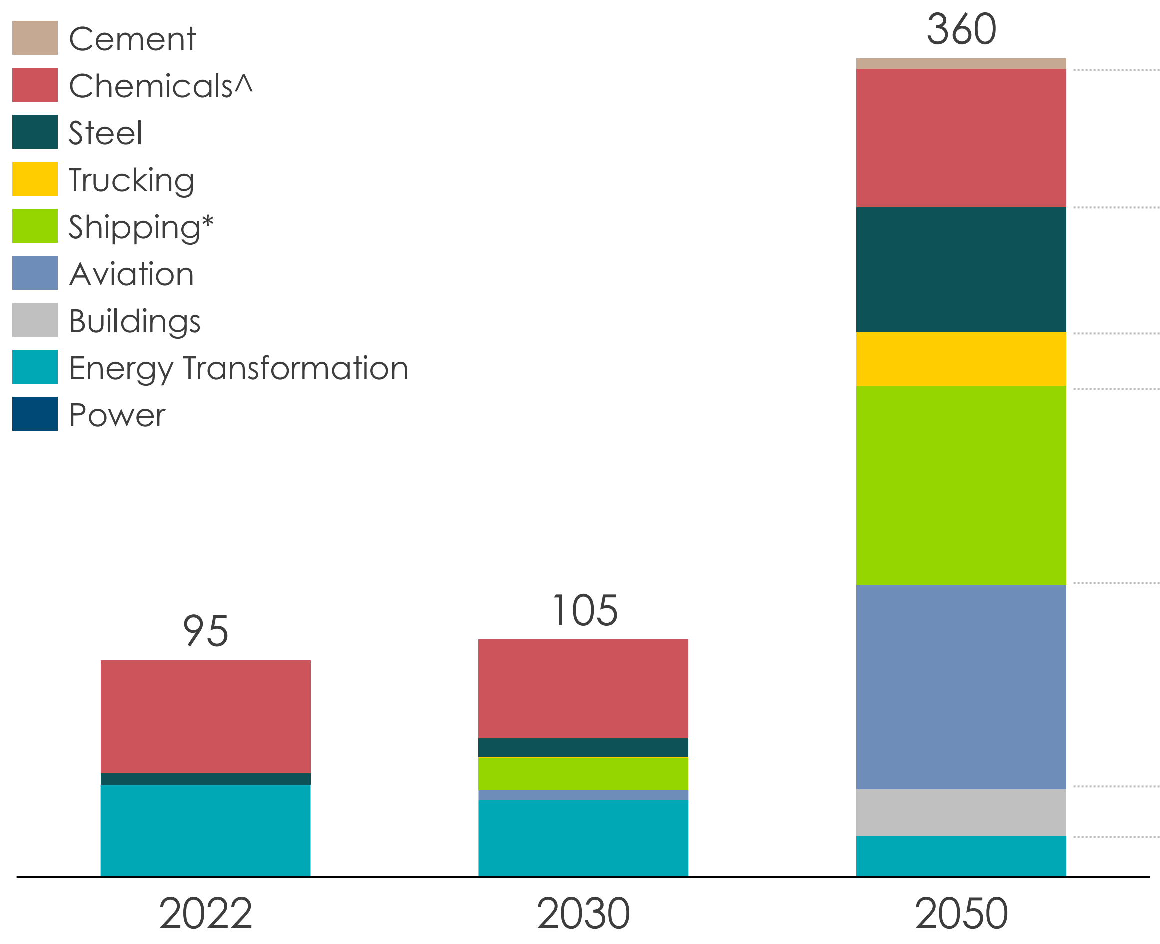
Key questions/considerations

- 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 demand[1], per annum Mt H_2



Hydrogen application

- Cement – heat source *(TRL today =5)*
- Chemicals – feedstock in the production of ammonia, methanol and others *(TRL today =7-8)*
- Steel – heat source and reduction agent *(TRL today =5-7)*
- Trucking – fuel cell vehicles *(TRL today =8/9)*
- Shipping – methanol and ammonia fuelled vessels *(TRL today =6-9)*
- Aviation – synthetic and biomass fuel *(TRL today =5-9)*
- Buildings – heat source *(TRL today =7-9)*
- Energy transformation – energy to convert crude oil to refined products *(TRL today =11)*

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[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'

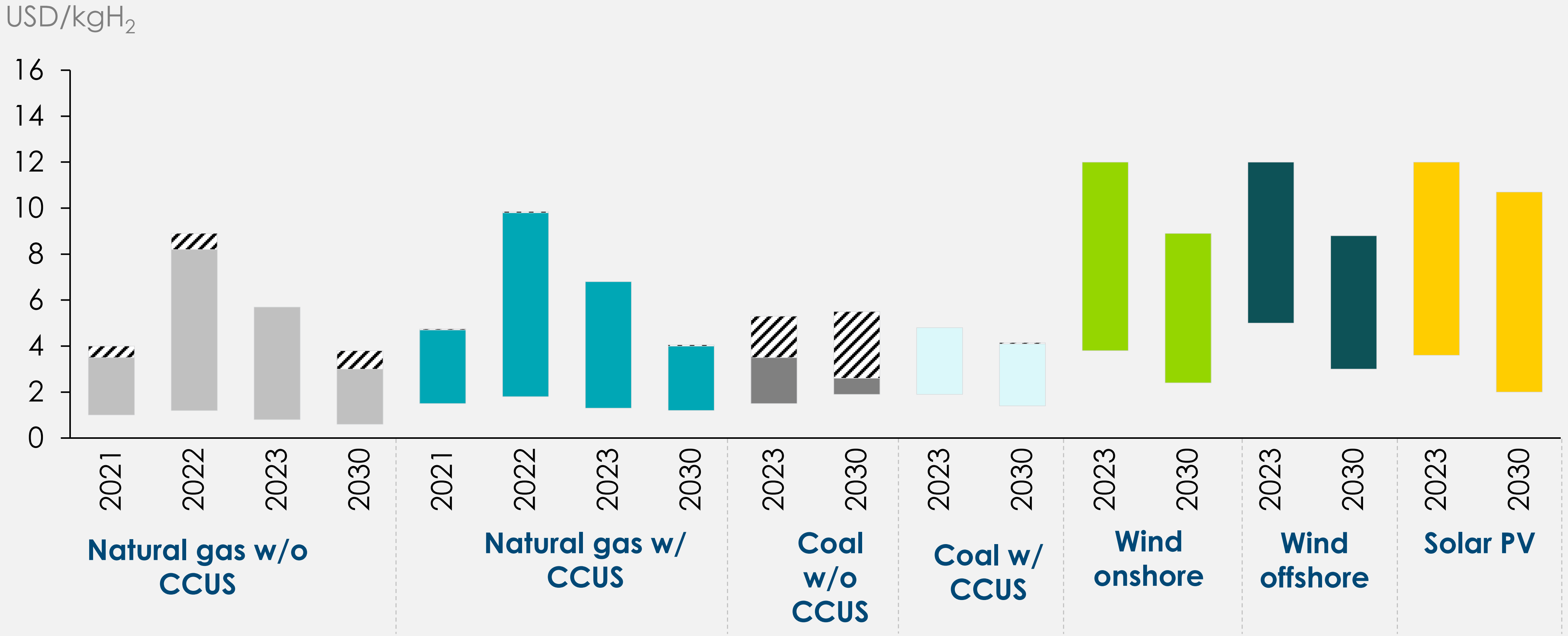
Source: Energy Transition Commission (2023) *Fossil Fuels in Transition*

However, the cost of low-carbon hydrogen will need to come down from todays' 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	HYDROMA HYTERRA
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)	sunfire TOPSOE Bloomenergy
	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

Source: IEA (2024), *ETP Clean Energy Technology Guide.* TNO (2020). *Low temperature electrowinning for steelmaking*

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

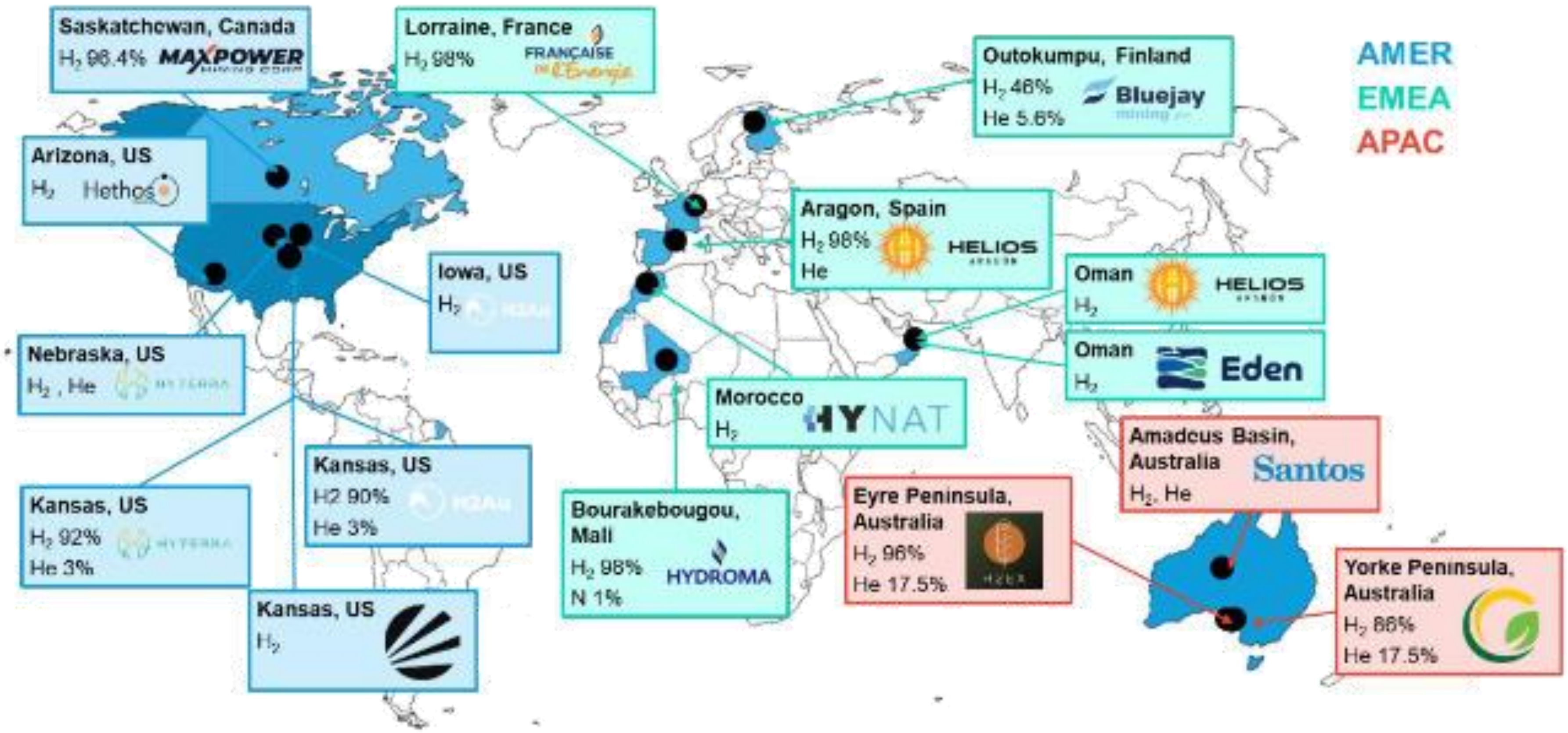
ORGANISATIONAL

- **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

White hydrogen and helium: Projects and exploration activity

Helium co-product can help project economics



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

MARKET POTENTIAL

- **17** exploration projects ongoing for of white hydrogen
- **\$0.5-\$2.4** kg/H_2 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/H_2 per year
  - Combusted to power a nearby village

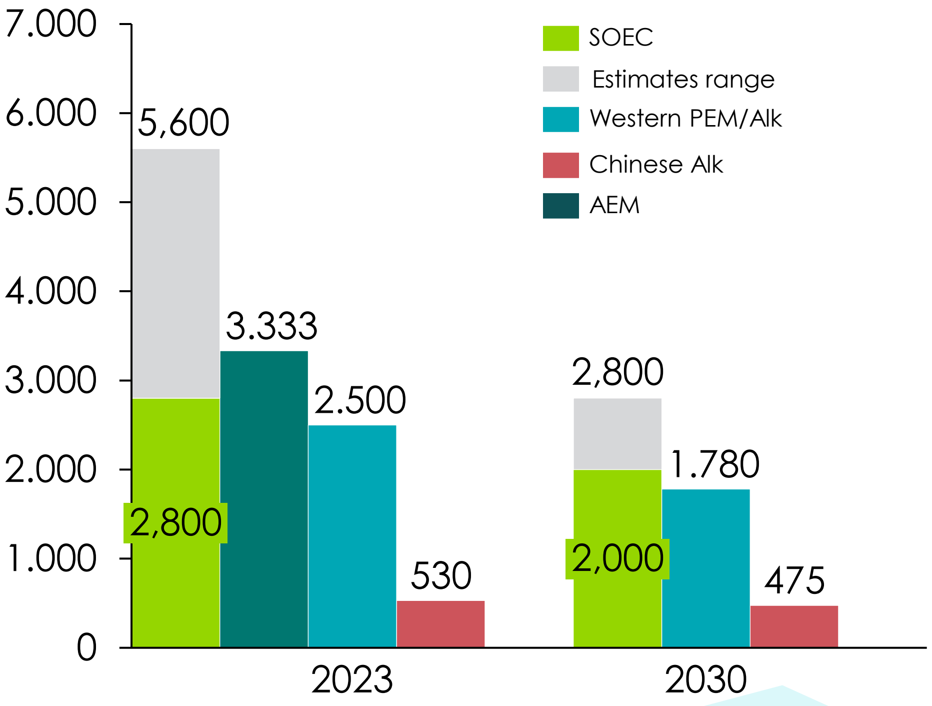
There are four main types of electrolysis technology in the market today

Electrolysis technology>	PEM – Polymer Electrolye Membrane	AEM – Anion Exchange Membrane	Alkaline	HT – High temperature (SOEC)
Electrolyte	Acidic Solid (polymer)	Alkaline Solid (polymer)	Alkaline Liquid	O2 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	• Relatively mature tech • High power densities • Fast startup and fast load changing capabilities	• Does not use expensive minerals • Compact design • Potential to be low capex	• Mature technology • Large capacity possible today • Does not use expensive minerals	• High efficiency • Can co-electrolyze steam and carbon dioxide for syngas production, which can be used to synthesize fuels/chemicals
Disadvantages	• Use of expensive and potentially scarce PGM metals • Long term stability to be proven at MW scale	• Shorter stack lifetimes relative to PEM and Alkaline • Low kW stack sizes driving up balance of plant costs	• Low power densities • Slow cold start-up time • Inefficiencies created due to alkaline liquid used as electrolyze	• High operating temperatures make for durability and lifetime issues • Stack lifetimes can be 4-8 times shorter than Alkaline and PEM

Source: IEA (2024) ETP Clean Energy Technology Guide, Clean Air Task Force (2023) Solide Oxide Electrolysis: A Technology Status Assessment

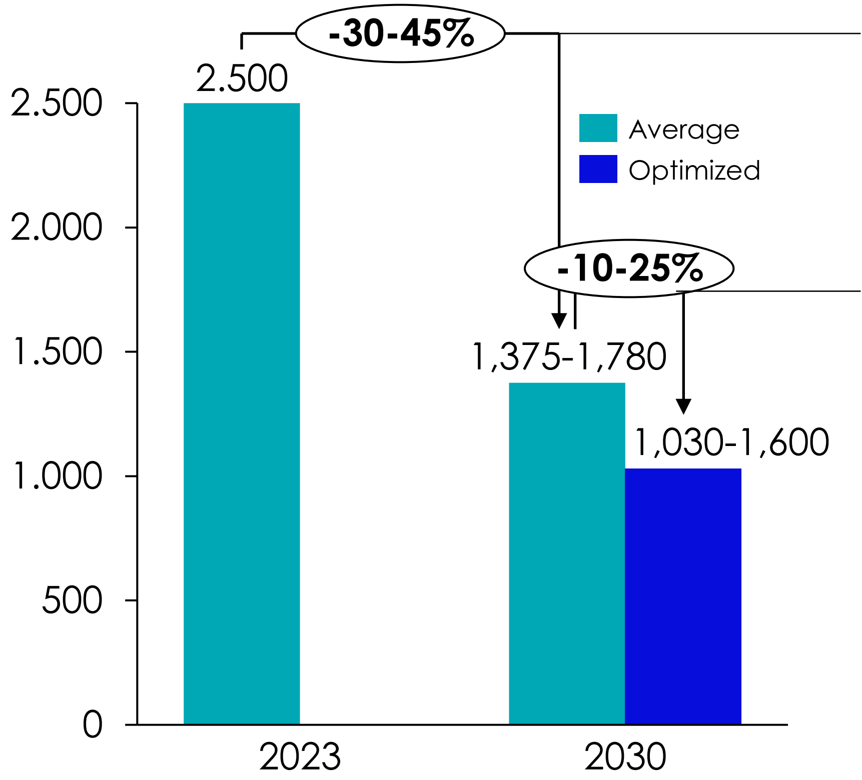
Estimates for highly optimized electrolyzer costs suggest a reduction potential of up to 70% cost reduction from today’s levels

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/Alk[3]



On average – 30-45% reduction

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

Optimized– 10-25% reduction

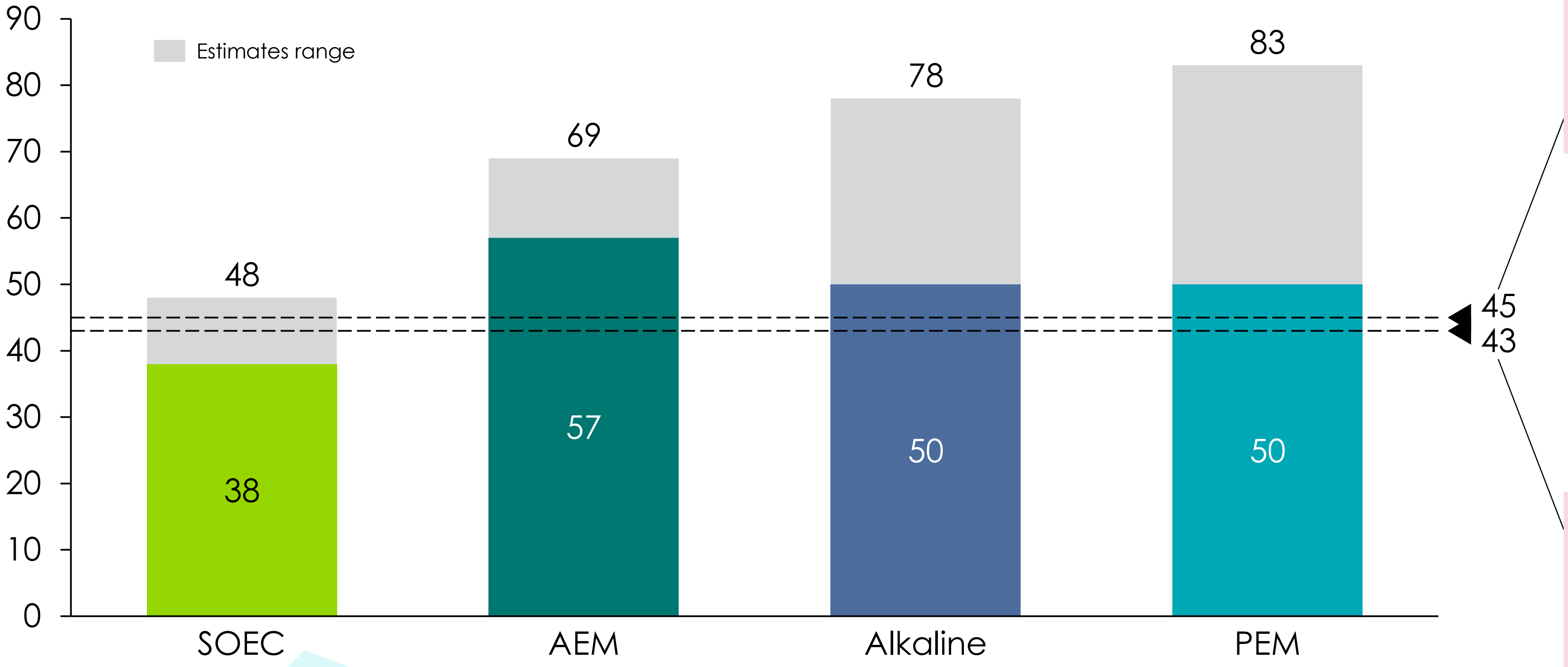
- Successive project build to creating maximum learning rates
- Procure at large volumes
- Rigorous design simplification and standardization

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 Tecyhnology 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 H_2



<45KWh/kg H2 – IRENA key performance indicator for **2050** for **AEM, Alkaline, PEM**

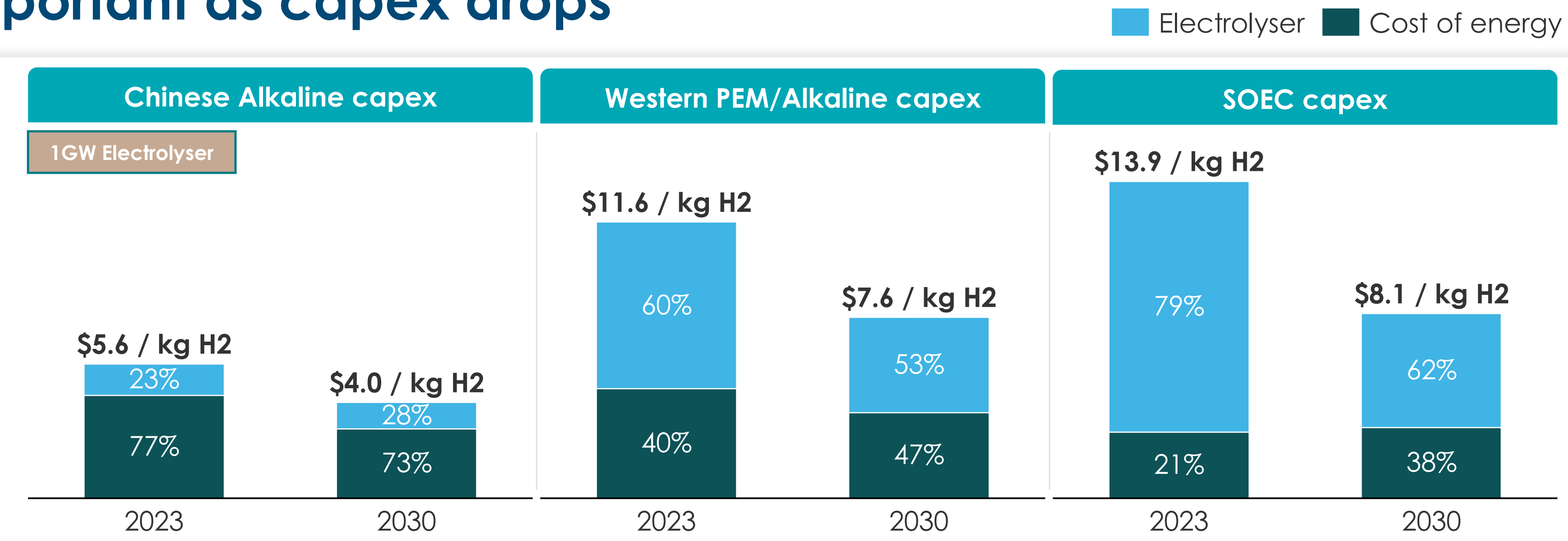
43 KWh/kg – efficiency unveiled by Chinese manufacturer Shuangliang of its large **alkaline electrolyzer 2024**

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 Tecyhnology Status Assessment

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

Utility scale production with Solar PV dedicated renewable[1]



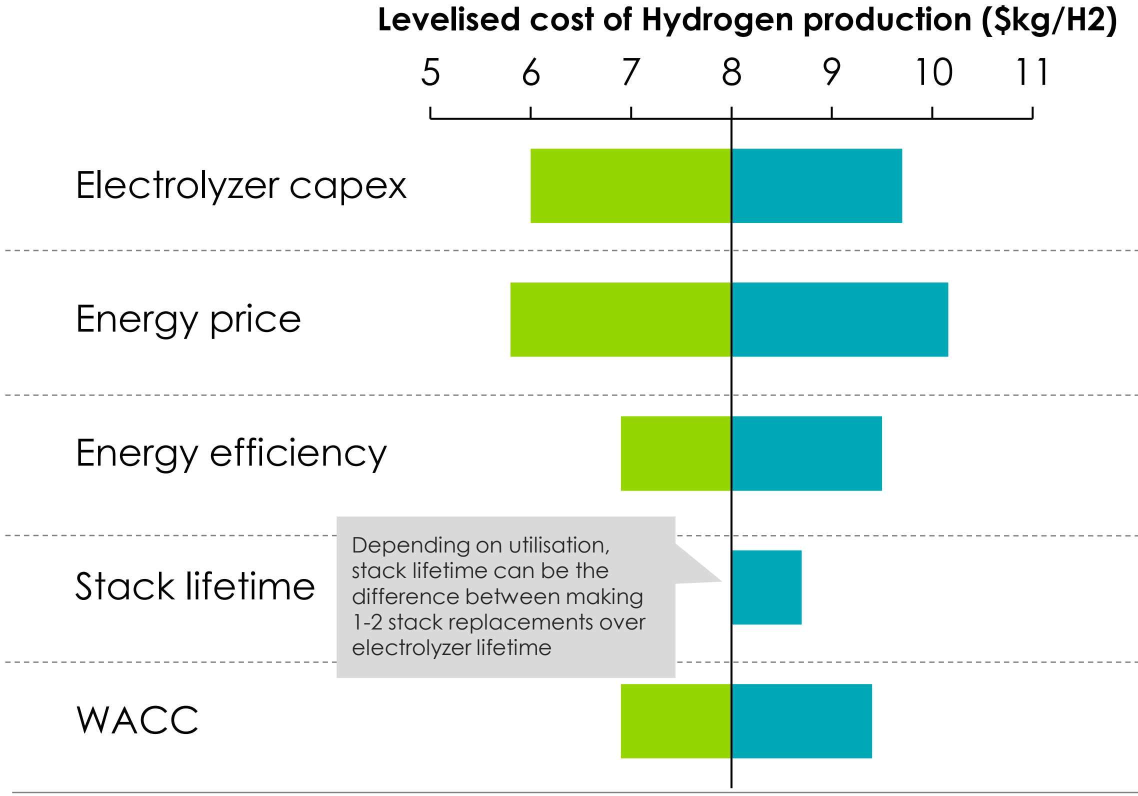
Main assumptions

	Chinese Alkaline capex		Western PEM/Alkaline capex		SOEC capex	
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

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



Depending on utilisation, stack lifetime can be the difference between making 1-2 stack replacements over electrolyzer lifetime

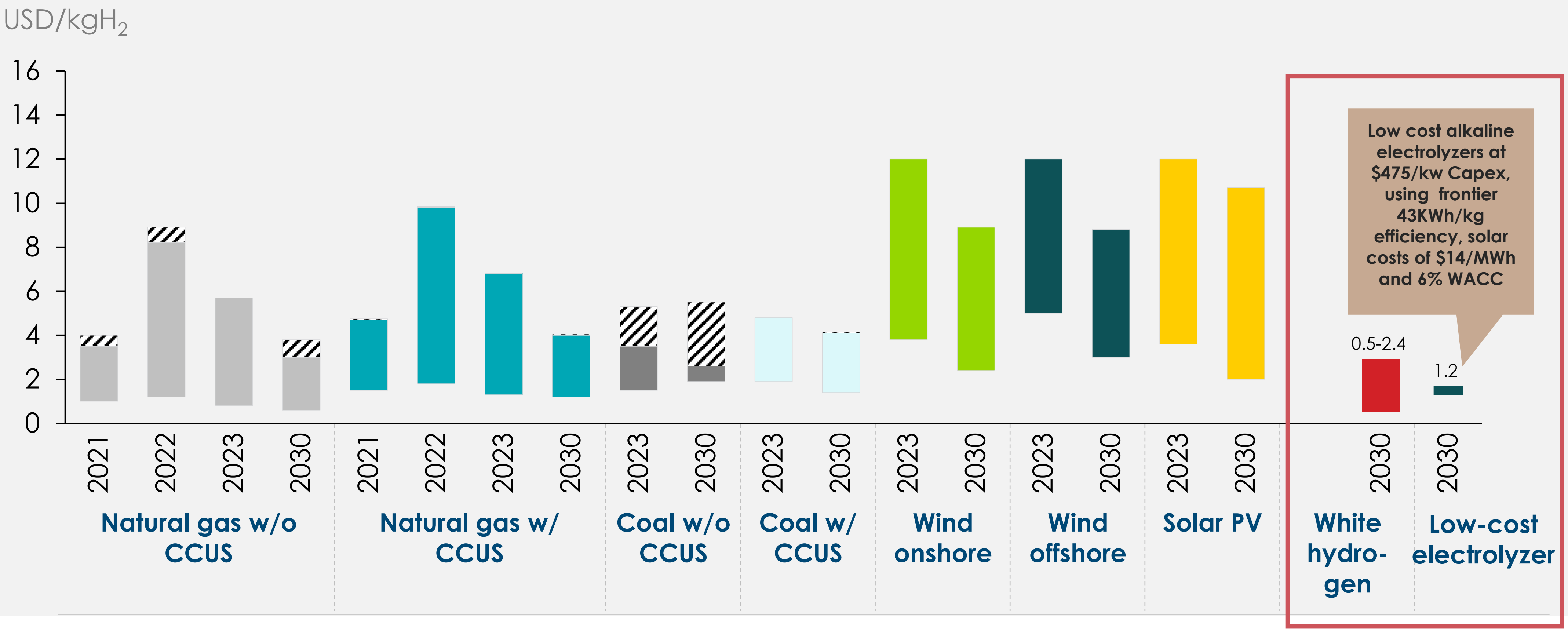
		Sensitivity assumptions		
		Low	**Mid**	**High**
Electrolyzer capex	USD/KW	1,030	1,780	2500
Energy price	USD/MWh	14	52	90
Energy efficiency	KW/h per kg h2	64	55	45
Stack lifetime	Stack lifetime hrs	90,000	70,000	50,000
WACC	WACC (%)	6	10	15

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 costs[1], $ per kg 2023

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

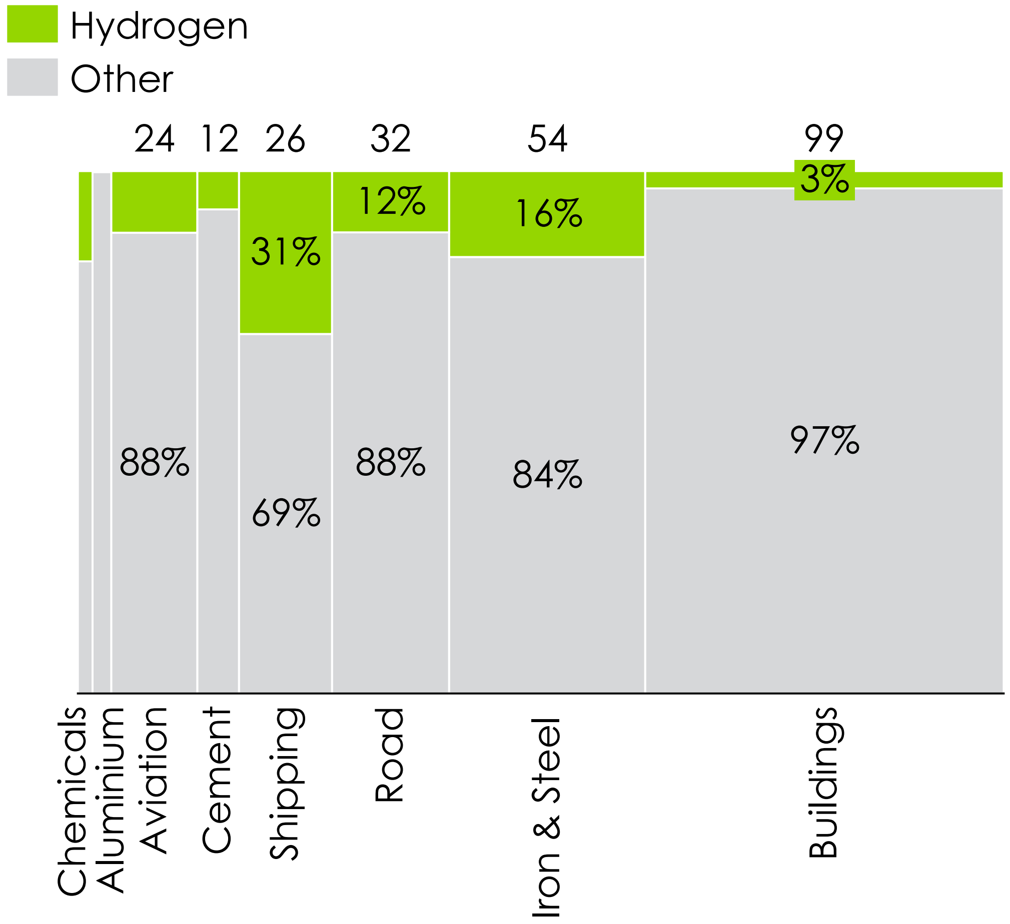


Low cost alkaline electrolyzers at $475/kw Capex, using frontier 43KWh/kg efficiency, solar costs of $14/MWh and 6% WACC

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



ETC (2023) *Fossil Fuels in Transition*

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
① **Industrial heat electrification (>600°C)** – High-temp technologies are advancing. Could be less capital intensive than other decarbonization tech	Has potential to displace potential to displace H2 and other carbon-based alternatives in heavy industry such as **cement, steel** and **chemicals**.
② **Electrical steam cracking** – Cost-competitive electricity and technological advances could see electric crackers scale	Cracking in the **chemical sector** could be shifted to electric, displacing H2 and fossil alternatives
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	Cost-competitive electricity and technological advances could increase demand for electrons to produce iron in the **iron and steel sector**
④ **Li-ion solid state batteries** – Solid-state batteries have the potential to further accelerate electrification in mobility by significantly enhancing energy density.	Steady advancements in battery technology could increase demand for electrons across all **road transport and even short-to-medium haul aviation and shipping**
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	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**
⑥ **Sodium-based battery technologies** – allows a low cost and safe storage option, which could be commercial by 2030	Sodium further reinforces the scalability and economic viability of **battery storage** solutions to enable further renewable penetration in **power system**
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	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
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	For sectors previously estimated to have H2 demand, potential to switch to an alternate decarb tech under high H2 prices

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