Energy Transitions Commission

Carbon molecules: Introducing our new analytical workstream

ETC Commissioners Meetings

31st October 2024

Objectives for the session

1 Introduce the **ETC carbon molecules project** (supported by QCF) **project objectives** and **deliverables**

2 Test **hypotheses** on the **"unconstrained electrification/ hydrogen scenario"** accelerated by **technology disruptions**

3 Share **next steps** and **opportunities** of offering **inputs**

Agenda

Carbon molecules Project - Carbon molecules within a low emissions energy system

Aim

Global assessment of demand and sustainable, feasible supply of molecules

Carbon molecules in the zero-emission economy: proposed work programme

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

- Develop 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

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

- Develop an **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

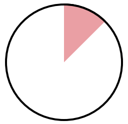
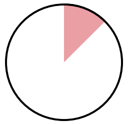
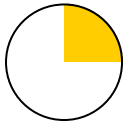
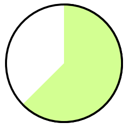
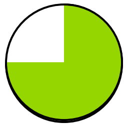
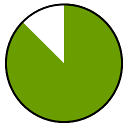
3. The potential to recycle and reuse carbon molecules

- Developing another **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
- Produce **a range of less extreme plausible scenarios** for carbon source demands in a zero-emission economy

4. Sources of primary carbon: costs and sustainability

- Assess whether there is a case for **increasing or decreasing our past estimates** of potentially sustainable bioresource supply
- Review the latest **technology development** and **cost trends** in point source capture and direct air capture of CO_2 (DACCS)
- **Engage with Brazil's distinctive viewpoint** by establishing an ETI Brazil effort to assess the optimal decarbonisation path within Brazil's specific conditions

Molecules will likely be essential in aviation, chemicals, fertilisers, shipping; for other sectors electrification will likely dominate

Likelihood of role	Potential Application	Current Fossil Fuel Demand[1] Coal	Gas	Oil	Sector power demand in 2050 Final and Intermediate	Share of electricity in FED in 2050
Most likely role for molecules	Aviation			5.5 mb/d	5,000 TWh	
	Shipping			5 mb/d	1,000 TWh	
Some role, depending on costs vs. electrification	Plastics and Petrochemicals Fertilisers/Ammonia	230 Mtce	500 bcm	17 mb/d	2-10,000 TWh	
	Iron / Steel-making	900 Mtce	100 bcm		9,000 TWh	
	Other industry	750 Mtce	600 bcm	4 mb/d	7,000 TWh	
Minimal role – electrification wins	Power, Road Transport, Buildings	4,000 Mtce	3,000 bcm	67 mb/d	35-40,000 TWh	

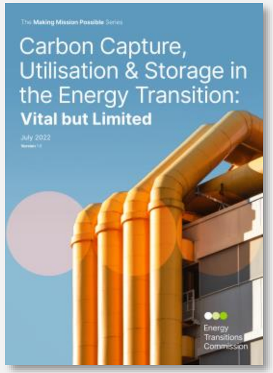
[1] Demand is for direct use of fossil fuels.
Source: Systemiq analysis for the ETC; ETC (2023), *Fossil Fuels in Transition*.

What kind of molecules, from where, is still an open question

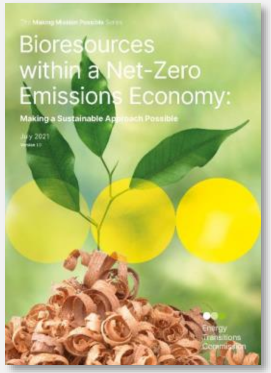
Likelihood of role	Potential Application	Options for low-carbon molecules
Most likely role for molecules	Aviation	• Biofuels (HEFA-based or other e.g., from gasification) • Synthetic fuels enabled by carbon streams (likely from point-source or direct-air capture) and low-carbon hydrogen • Potential for continued use of fossil-based jet fuel together with carbon removals
	Shipping	• Low-carbon hydrogen to make ammonia • Methanol – requires both low-carbon hydrogen and additional carbon atoms
Some role, depending on costs vs. electrification	Plastics and Petrochemicals Fertilisers/Ammonia	• Low-carbon hydrogen in combination with… • … carbon atoms from multiple potential sources: bio-based and recycled feedstocks, from fossil fuels, or captured carbon
	Iron -making	• Low-carbon hydrogen for use in direct reduction of iron • … but also multiple options for recycling of carbon and hydrogen rich off-gases • …and carbon capture may make iron making a source of carbon for other sectors
	Other industry	• Some role for bioenergy or hydrogen in combustion for provision of mid/high-temperature heat
Minimal role – electrification wins	Power, Road Transport, Buildings	• Small role for molecules in: - Storage (low-carbon hydrogen) - Balancing (low-carbon hydrogen or bioenergy) - Heavy-duty trucking (low-carbon hydrogen >> bioenergy)

Source: Systemiq analysis for the ETC; ETC (2023), *Fossil Fuels in Transition*.

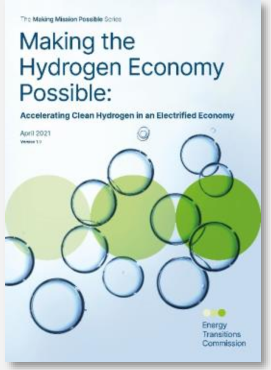
Previous ETC reports have assessed the relative role of role of CCUS, bioresources and hydrogen



- CCUS is vital but limited:
  - Where **alternatives are technically limited** (e.g., Cement process emissions)
  - To provide **least-cost decarbonisation** in key sectors and geographies where CCUS is competitive
  - To provide some **carbon removals**
- Enabling **transport & storage infrastructure** will be crucial – CCUS clusters could be important
- Most recent ETC analysis estimates **7-9 $GtCO_2$ of CCUS**, of which 4-5 $GtCO_2$ is point-source applied to fossil fuels and 3-4GT CO_2 is DAC



- Use of Bioresources faces **strong land use competition** and **sustainability constraints**
- A "prudent" estimate of sustainable biomass supply would be **40-60 EJ in 2050** – could rise up to 120 EJ in a "max. potential" scenario
  - Producing 50 EJ/yr could need **~2.8 million km^2 of land** (~8% of agr. land)
- Use of biomass should be **prioritized for sectors where alternatives are limited**:
  - Pulp and paper, timber
  - Plastic feedstocks
  - Aviation
  - Some high/mid-temperature heat



- **Green hydrogen** could be competitive with grey by 2030s (though latest progress slow)
- **Blue hydrogen** will also have a role – competitiveness depends strongly on cost of gas and availability of CCS
- Priority should be to **displace existing ~95 MtH_2 of grey hydrogen demand first**, then expand into wider sectors
- Enabling **transport & storage infrastructure** will be crucial
- Most recent ETC analysis estimates **350-600 MtH_2 of demand in 2050**, with greatest role in chemicals, steel, aviation and shipping

Source: ETC (2021), *Bioresources within a net-zero emissions economy*; ETC (2021), *Making the hydrogen economy possible*; ETC (2022), *Carbon capture, utilisation and storage in the energy transition*; ETC (2023), *Fossil fuels in transition*.

Phase 3 and 4 will get to the heart of the molecules question

The potential to recycle and reuse carbon molecules

Assessment of:

- Combined energy and materials system demand for carbon molecules
- Linear vs. circular systems
- Novel recycling processes – including mechanical recycling, depolymerization, gasification & pyrolysis
- Relative energy requirements, costs and emissions implications.

Output: high and low recycling scenarios to understand volume of low-carbon molecules that may be required.

Sources of primary carbon: costs and sustainability

Assessment of:

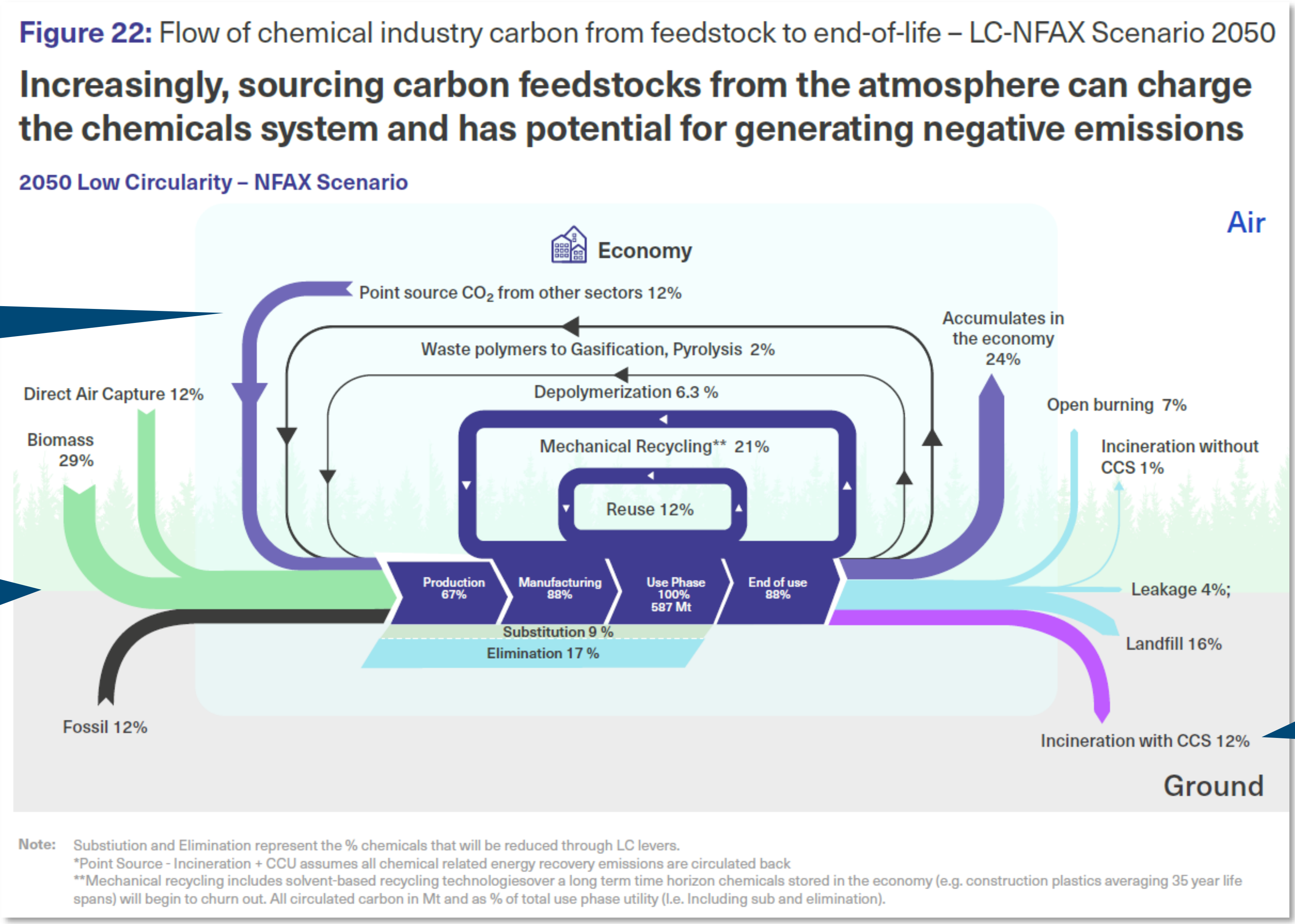
- Latest technological developments and cost trends in point source carbon capture (CCS) in different applications.
- Latest technological developments and potential future costs trends in direct air capture of CO2 (DACC).
- Potential to extract and use bioresources in a cost effective and truly sustainable way, considering sustainability parameters like: full life-cycle carbon emissions, local biodiversity impacts, competition with other uses of land including food production and local community impacts.

Output: revised vision of low-carbon molecule use in a net zero energy system.

Carbon capture offers an opportunity to “recycle” carbon atoms

Multiple avenues for recycling of carbon-intensive molecules

Range of potential input sources for carbon atoms



Utilisation of captured carbon from incineration could be another input stream

Source: Systemiq/Centre for Global Commons (2022), *Planet positive chemicals*.

Innovation could free up land, increase the potential for recycling and reduce the energy inputs needed for molecular transformations

Synthetic biology / precision fermentation > synthetic meat

- Huge theoretical potential to reduce food land use, given inherent inefficiency of both photosynthesis and cattle-based conversion of vegetable to meat protein
- Challenges of cost-competitiveness and consumer acceptance

Bioreactors/ microbial biocatalysts (e.g. Lanzatech)

- Reducing energy demands for multiple variants of molecular transformation
- Enabling lower cost conversion of waste, residues and CO2 streams into ethanol, other fuels, chemicals

Chemical recycling

- Depolymerization (via e.g. catalytic cracking – breaking down long hydrocarbons)
- Feedstock recycling (via e.g. pyrolysis or gasification)
- New catalysts significantly reducing required energy inputs

Electrochemical technologies

- e.g CO_2 electrolysis ("Twelve") reducing cost of CO_2+H_2 synthesis into jetfuel

How fast can these technologies develop and cost-reduce?

What implications for balance between:

- **Continued fossil fuel use + CCS**
- **Sustainable bioenergy supply and bioenergy applications**
- **Continuous recycling of carbon atoms**

Today we focus on sprint 1: evaluating the role of direct electrification, hydrogen and its derivatives in achieve a zero-emission economy

	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

Project overview

Previous projections on electrification and hydrogen

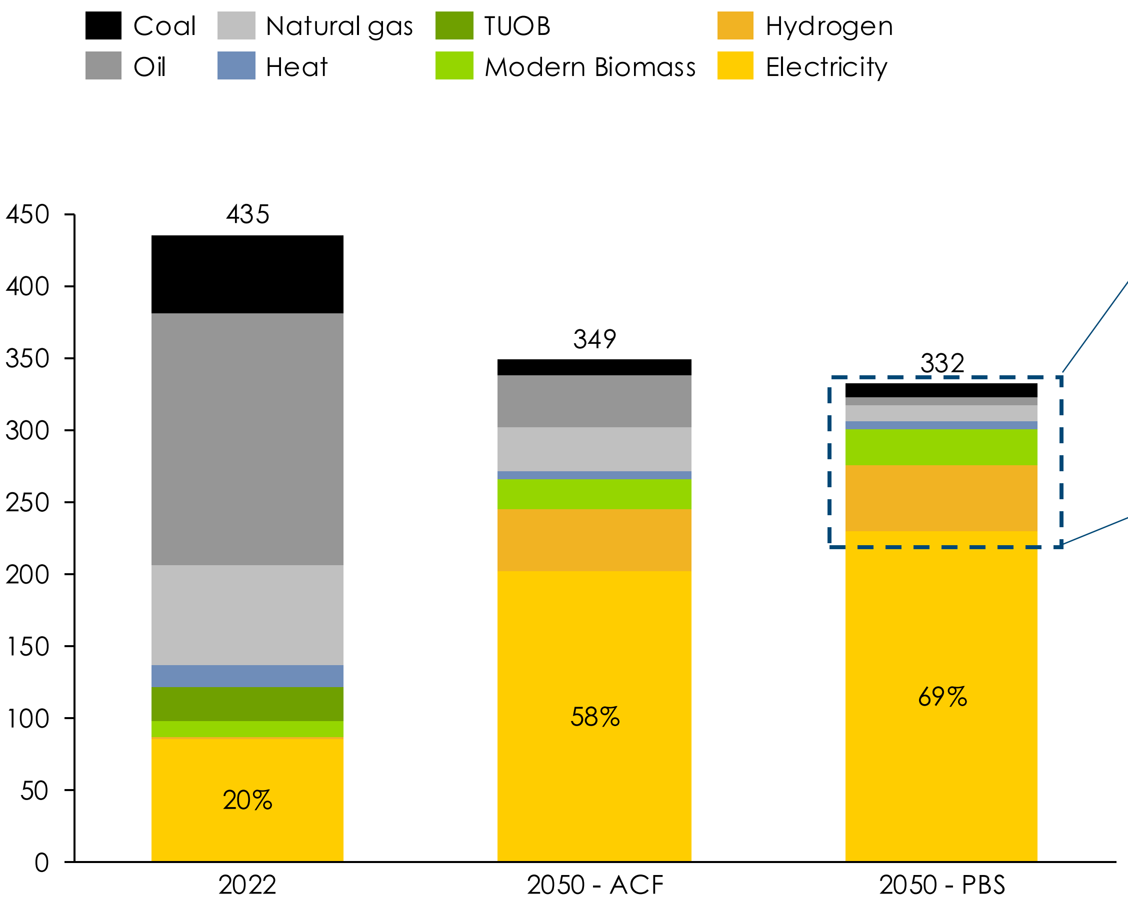
Trends and tech disruptions shaping ETC scenarios

Sectoral deep-dives

The ETC updated its total final energy demand view in the Fossil Fuel phase down report published last year

Electricity will need to go from 20% → 55-70% by 2050

Final Energy Consumption, EJ



Role of Molecules:

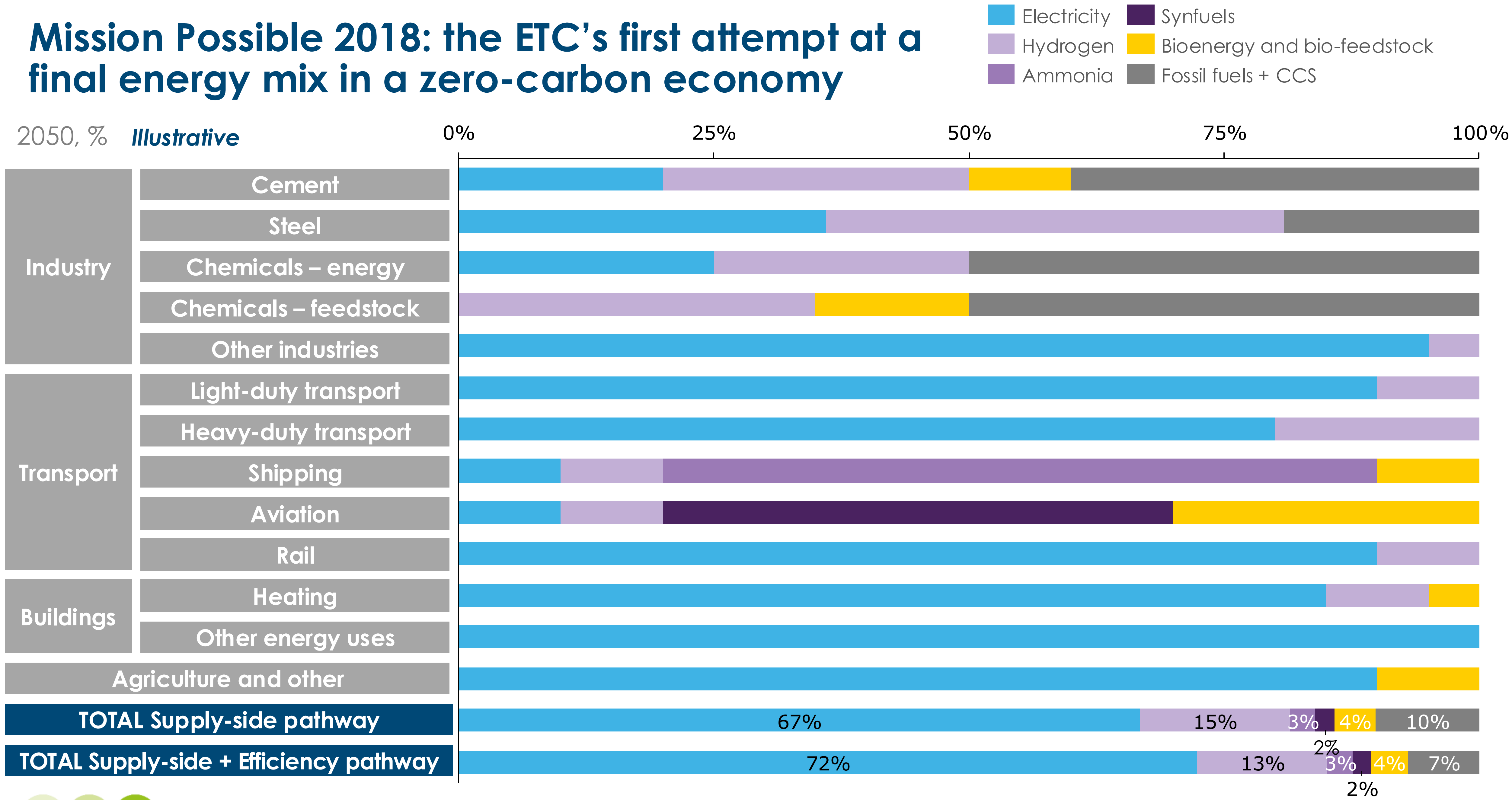
- **30-45% of overall Final Energy Demand**, of which:
  - 10-15% is **hydrogen or derivatives**
  - 5-10% is **biomass-derived carbon**
  - 10-25% is **fossil carbon**

Areas where ETC will refine:

- Volume of hydrogen demanded, particularly in the chemicals sector
- Indirect power consumption from hydrogen consumption, accounting for blue/green split
- 'Other industry' energy demand

Note: ACF = Accelerated but Clearly Feasible; PBS = Possible but Stretching. Wood products and pulp and paper excluded from modern biomass
Source: ETC (2023), *Fossil fuels in transition*.

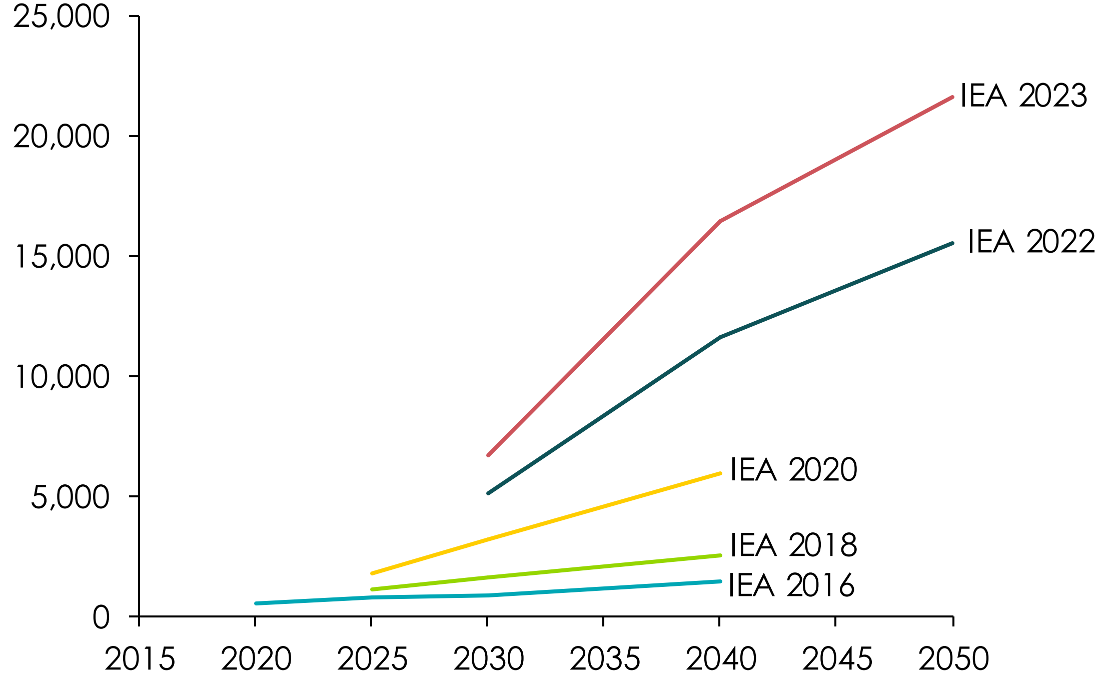
Mission Possible 2018: the ETC's first attempt at a final energy mix in a zero-carbon economy



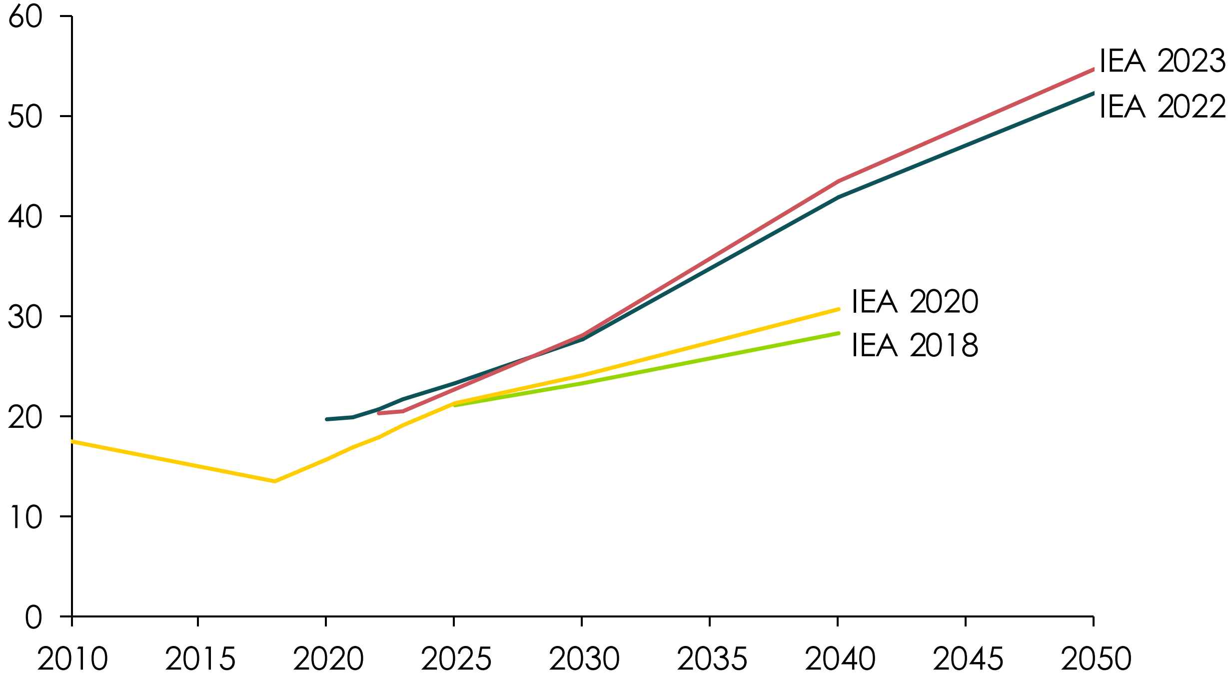
Note: Steel energy mix represents the supply-side pathway only. For chemical feedstock, inputs are not used as energy but in order to provide the molecules required to build the chemicals. In our model, for comparison we express it in EJ equivalent.
Source: SYSTEMIQ analysis for the Energy Transitions Commission (2020)

“When the facts change, I change my mind”: Informed observers and experts have consistently updated upwards their electrification deployment forecasts

Deployment of solar PV generation in IEA progressive scenarios, GW



Level of electrification in global final energy demand, %



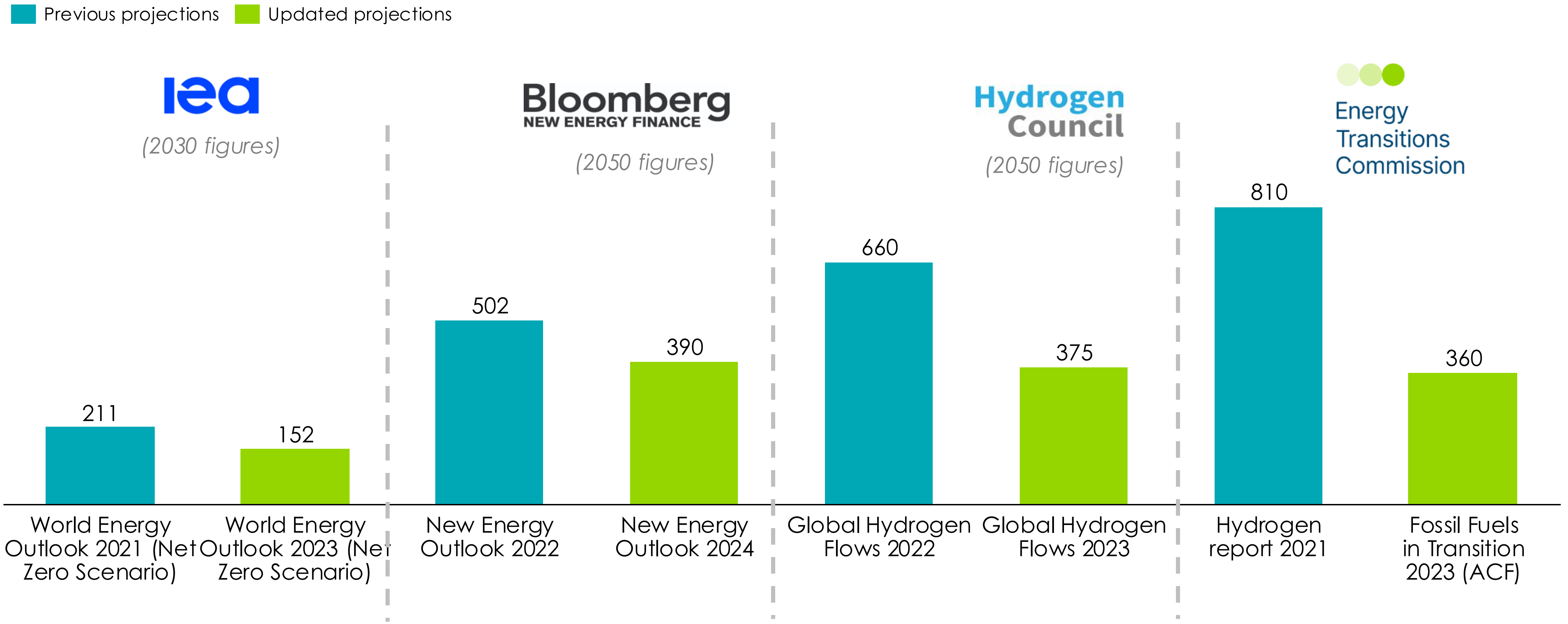
IEA scenarios in World Energy Outlook reports

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

Most recent forecasts on hydrogen are revising down its role in the decarbonization 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

Incremental trends and disruptive innovations require analysis to understand how far electrification and hydrogen can go towards decarbonization

Returning to ETC's view will involve taking stock of

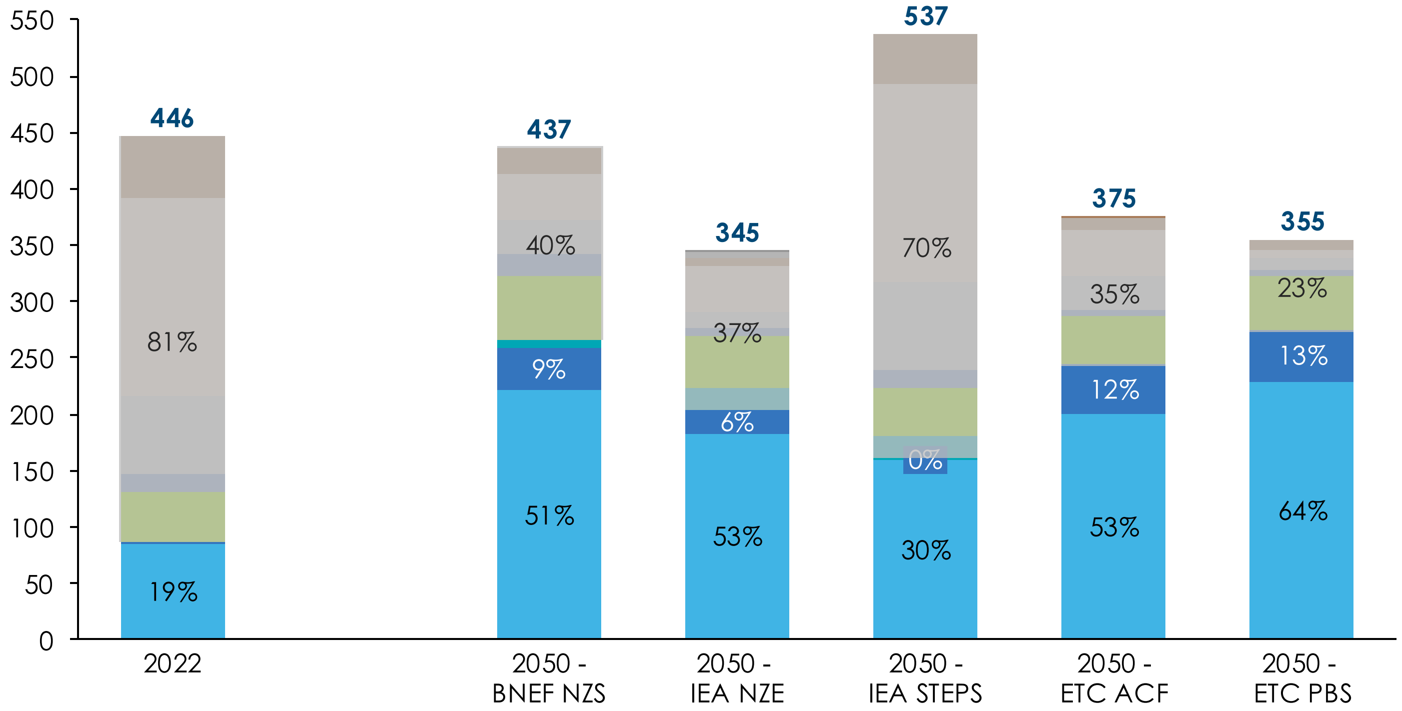
1. **Incremental Changes –** reviewing latest trends and what has changed particularly in usage and cost of renewables, batteries, new energy demand (e.g. data centres), CCS and biofuels

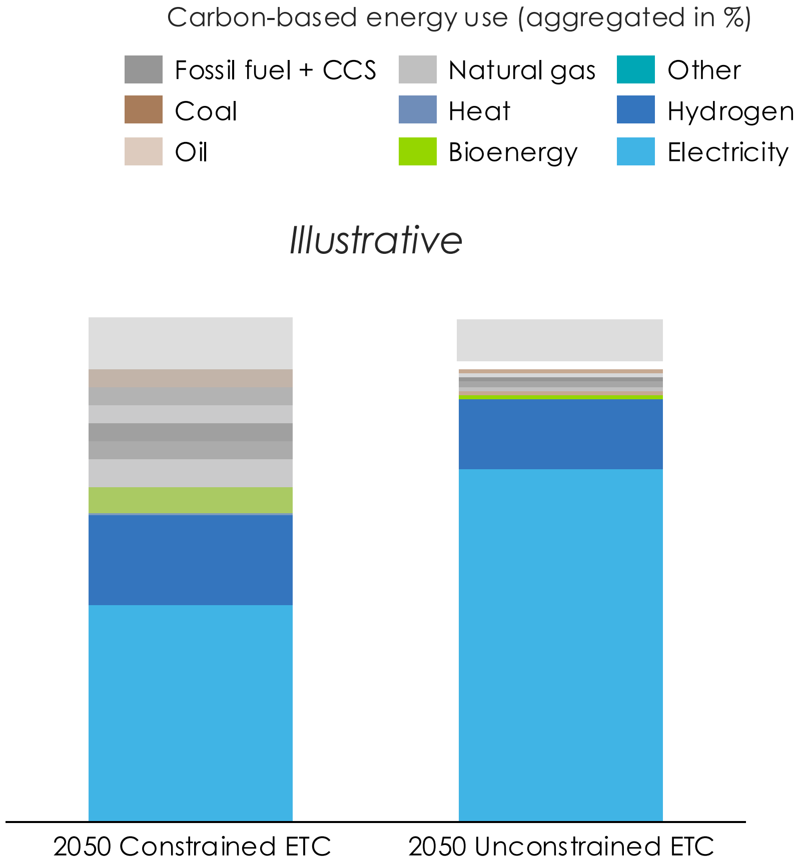
2. **Disruptive/innovative technologies** – new technologies, such as Molten Oxide Electrolysis for steel making or electric steam crackers for the chemical industry. What does it take to believe that these disruptions will materialize?

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

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

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





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

Agenda

Three main energy sources in a net-zero economy

Electron-based molecule

Electrons | **Molecules**

Direct electrification

Usage in…

- Battery electric vehicles
- Industrial heat electrification

Hydrogen and ammonia[1]

- Fertilizer products
- Shipping fuel

Carbon-based fuels

- Sustainable aviation fuels
- Chemicals sector feedstock

Notes: 1) Non carbon energy carrieres, potentially produced using carbon (blue routes)

The three main energy uses in a net-zero economy are clear – uncertainty lies in their relative sizes

Non-carbon final energy, which can use carbon for its production (blue routes)

Carbon-based fuels

Hydrogen and ammonia

Direct electrification

First best solution:
Attractiveness:
- Emission abatement: Zero-carbon if from renewable electricity
- Energy efficiency: >95%

Applicability:
- all uses which can be plugged to a grid or hold a battery

Affordability
- cheapest form of energy in most cases

Second best solution:
Attractiveness:
- Emission abatement: Zero-carbon if from renewable electricity
- Energy efficiency: up to ~80% from prod to storage and use

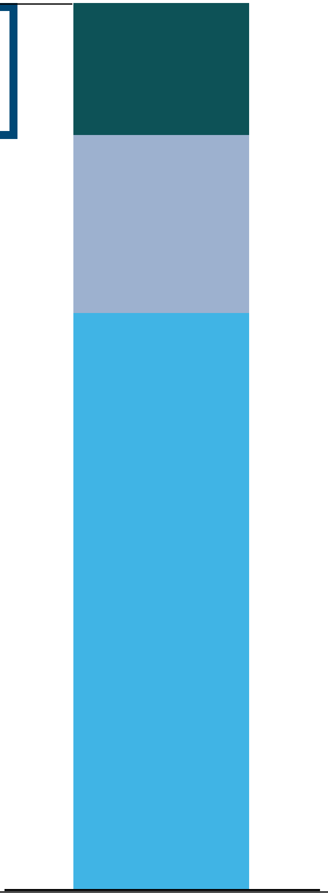
Applicability:
- broad due to high energy density. Needs storage and transport infra.

Affordability:
- still low

All other uses:
Attractiveness:
- Zero carbon if from sustainable sources
- High energy losses in combustion

Applicability:
- high (drop in fuels) density and easy storage

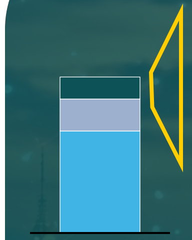
Affordability:
- still low



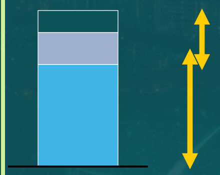
Electron-based molecule

Electrons

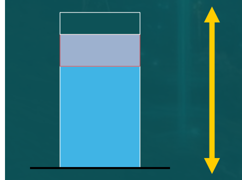
Molecules



Focus of the next sprint
- How much carbon do we need in a net zero economy?
- How much can be sourced by recycling and reuse?
- How much remaining carbon must be sourced by non-fossil carbon sources?



Focus of this sprint
- How much can electrification and hydrogen cover in term of uses?



Estimated in ETC's FFIT report[1]
- How much energy demand do we need in a net-zero economy?

Notes: 1) FFIT = Fossil Fuels in Transition Report, ETC (2023)

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

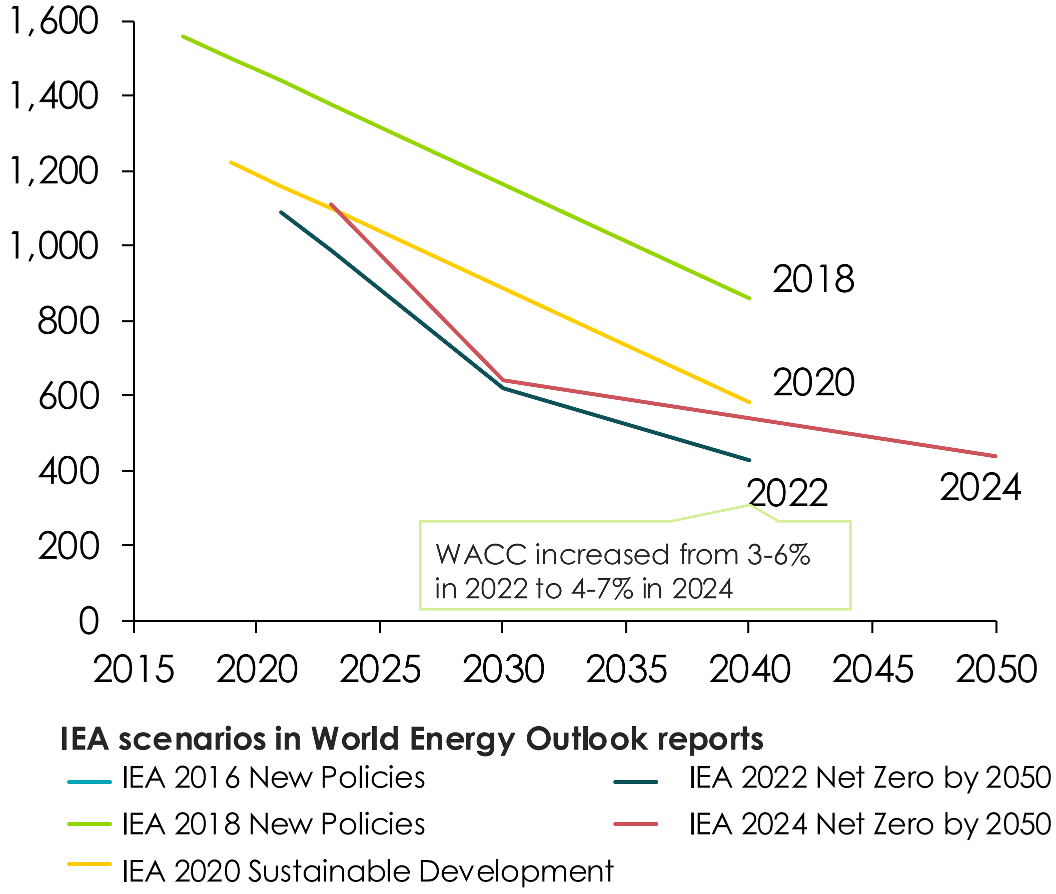
Trends related to

Direct electrification: ACCELERATING		Non carbon use of hydrogen: STAGNATING		Carbon-based fuels: PLANETARY BOUNDARIES & LOCK-IN TRENDS	
TREND	**PROOFPOINT**	**TREND**	**PROOFPOINT**	**TREND**	**PROOFPOINT**
1 **[Cost] Solar PV costs decreasing faster than anticipated**	75% reduction in average estimated Solar PV LCOE and 75% reduction of panel cost in the past 10 years	4 **[Cost] Much lower price decline due to inflation and system costs**	BNEF electrolyzer cost estimate increasing 90% between 2022 & 2024	7 **[Cost] Biofuels and CCS prices expected to remain relatively flat**	Medium to long term projections from MPP, BNEF and OECD
2 **[Cost] Battery costs decreasing faster than anticipated**	85% cost reduction over the last decade	5 **[Use] Scale up of green hydrogen production stagnating**	Only 4Mt of 118Mt H_2 production in pipeline at FID/operational	8 **[Use] Methane leakage issue not solved**	Large methane emission events rose by 50% in 2023 compared with 2022
3 **[Use] Expanding energy uses add extra power demand**	short term energy demand from AI and AC (IEA 2024)	6 **[Use] Use cases are increasingly shifting from H_2 to electrification**	Abandon of H_2 for buildings and trucking projects	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

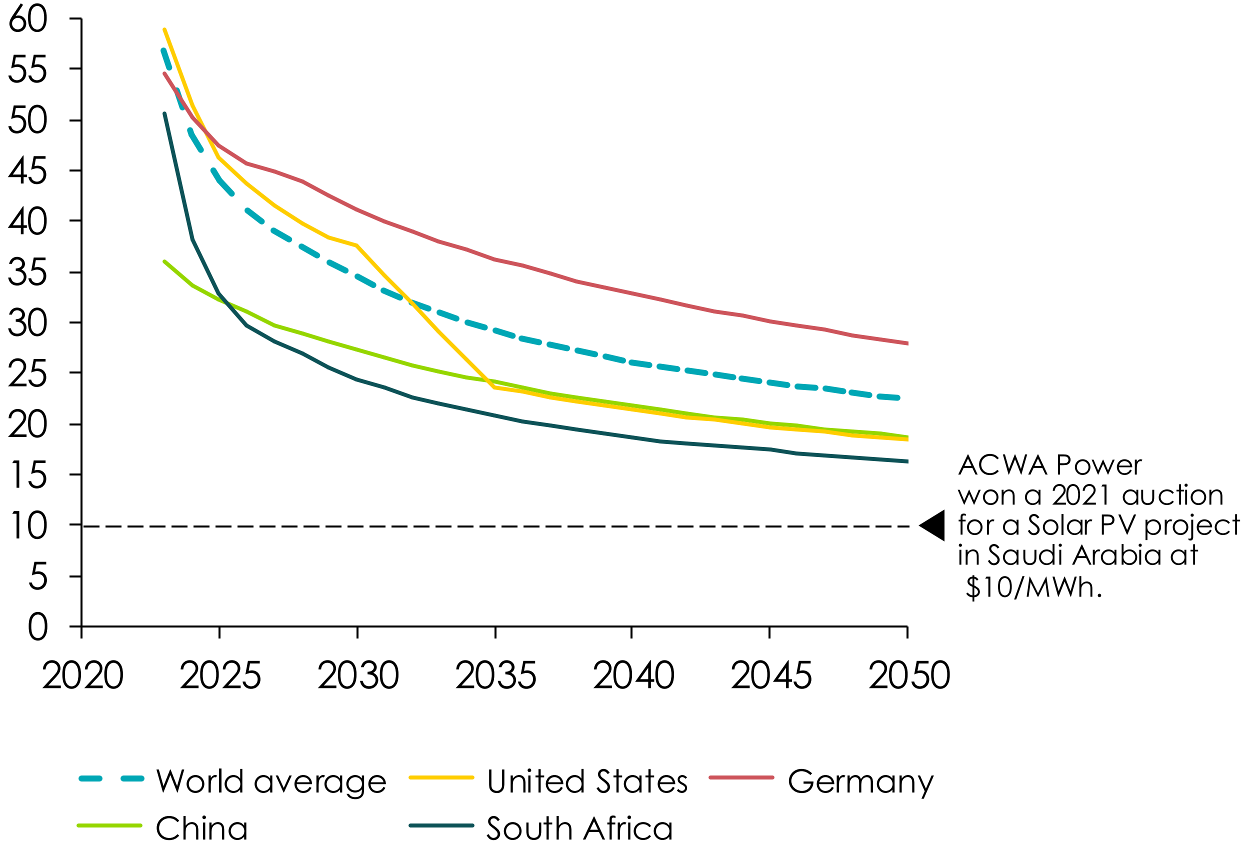
Sources: BNEF (2023), *2H 2023 LCOE: Data Viewer Tool*. BNEF (2023), *3Q 2024 Global PV Market Outlook*. IEA (2024) *Global Methane Tracker 2024*, *IEA (2023) Chemical*, IEA (2024), Electricity

[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



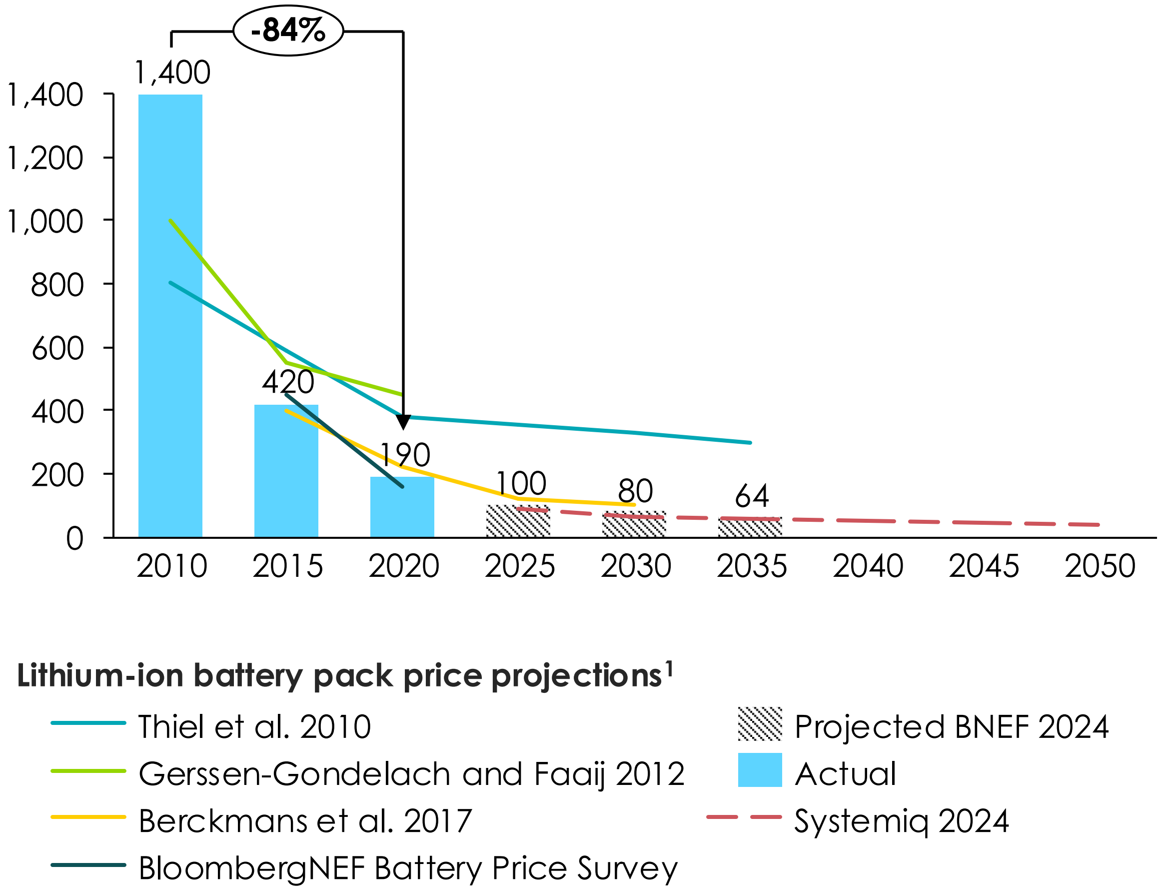
BNEF projected LCOE of Solar PV[1] globally & select countries
USD/MW (2022 real)



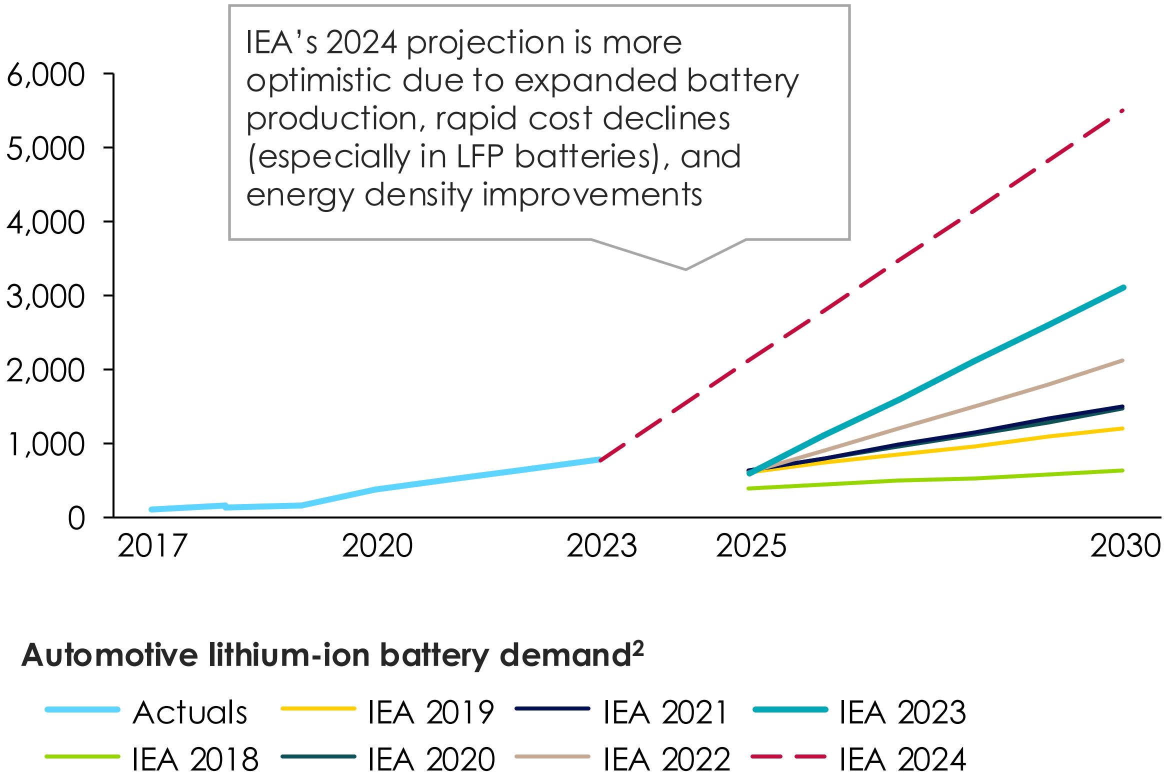
Note: 1. Based on solar PV tracking.
Sources: IEA World Energy Outlook, Bloomberg New Energy Finance 2023, *2H 2023 LCOE: Data Viewer Tool.*

[Batteries] Significant improvements in battery cost (and energy density) are accelerating demand in automotive with domino effects in other sectors

Battery costs were consistently overestimated
USD/kWh storable



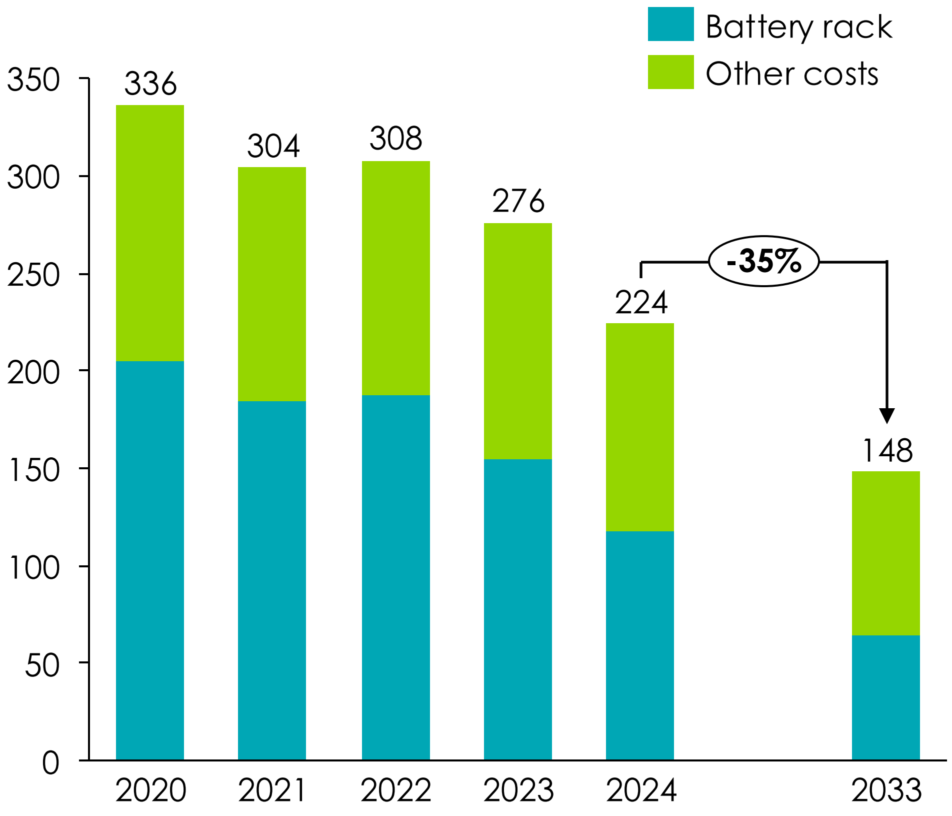
This has led to an underestimation of battery demand
GWh/y



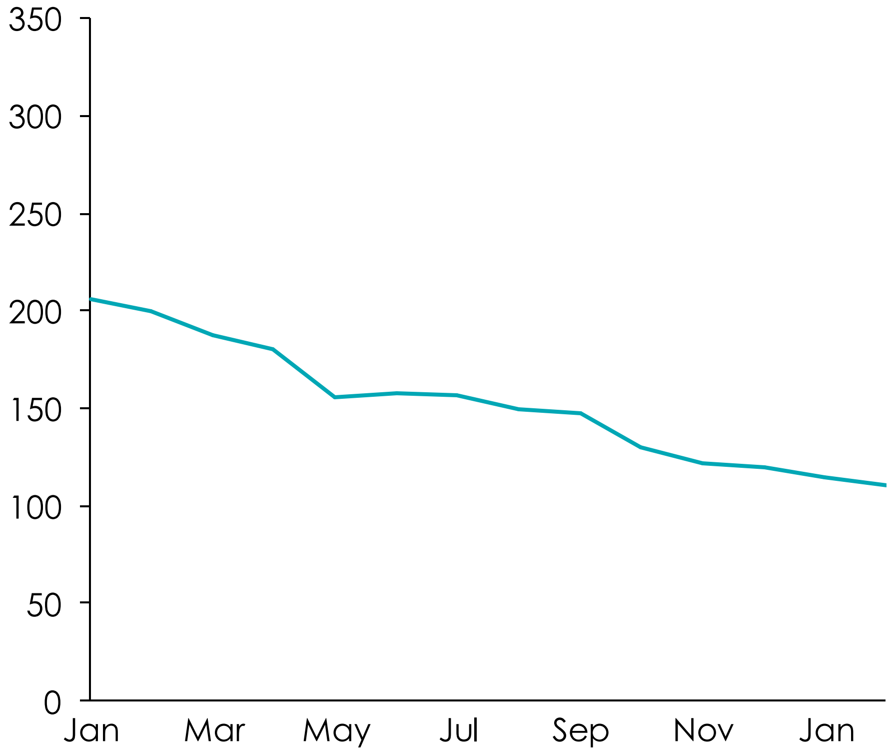
Sources: (1) Based on Royal Society of Chemistries (2021) Battery Cost forecasting: a review of methods and results with an outlook to 2050; BloombergNEF (2024) New Energy Outlook; 2) Systemiq analysis based on RMI (2023) X change batteries, IEA Global EV Outlook (2018-2024)

[Batteries] costs have increased in 2022 but have gone due to innovations in applicable minerals to use and reduction of EV demand

Full system cost of two-hour energy storage
USD/kWh



Chinese battery costs, Jan 2023 – Feb 2024
USD/kWh



Key trends

- **Battery rack prices surged** in 2022-2023 due to rising demand for EVs and shortages of critical materials like cobalt and nickel.
- **Battery costs declined in 2023** as LFP batteries, which do not rely on nickel or cobalt, gained market share, offering a cost-effective alternative.
- **LFP batteries dominate energy storage**, making up 80% of new storage installations in 2023, thanks to their lower cost and longer lifespan, while nickel-rich chemistries remain crucial for EVs due to their higher energy density.

Notes: LFP = Lithium iron phosphate battery, Battery racks contain multiple battery pakcs or modules arranged to provide higher capacity
Source: BNEF; IH 2024 Energy Storage Market Outlook, IEA (2024) Global EV Outlook

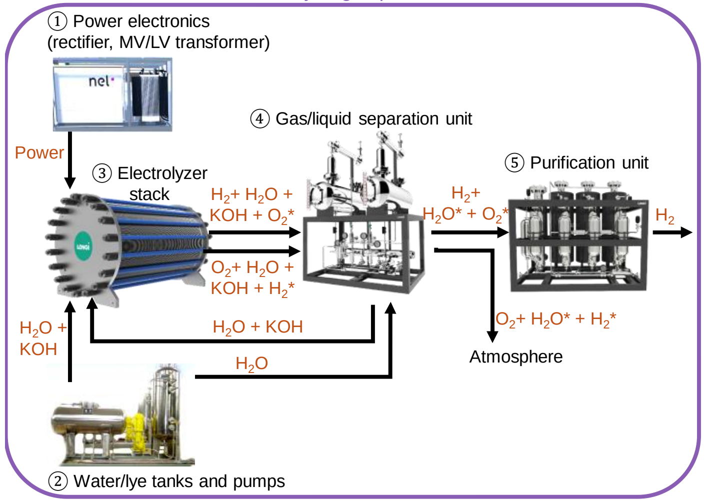
[Hydrogen] Electrolysis system costs are higher than initially expected; reflecting better understanding of full system complexity

Previous understanding of the costs

Installed costs

Direct costs

Hydrogen production



Current understanding of the costs

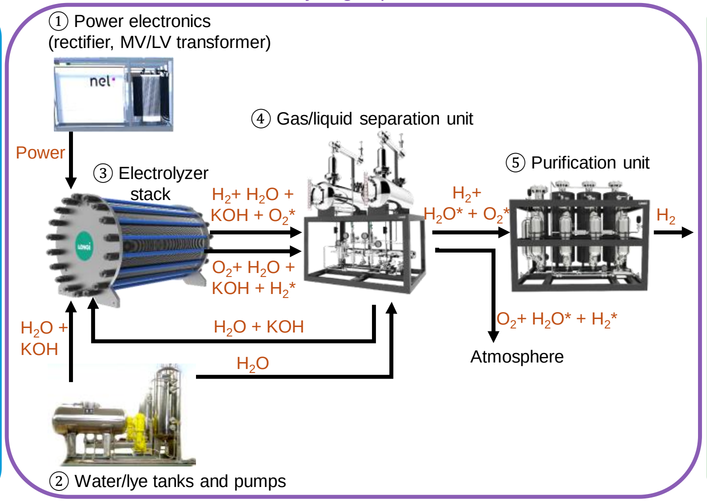
Installed costs

Direct costs

Utilities

- Power (HV transformers, switch gears, long-distance cables)
- DM water generation (raw water purification, water desalination, connection to a remote water source, water buffer tanks)
- Cooling (chiller, cooling water tower)
- Nitrogen supply (to render the system inert and create a safe environment upon startup and following electrolyzer system maintenance)
- Other ancillary service (fire fighting, lightning protection, lighting, central control, telecommunication, etc.)

Hydrogen production



Further process

- Temporary hydrogen storage
- Hydrogen compression (up to 40 bar)

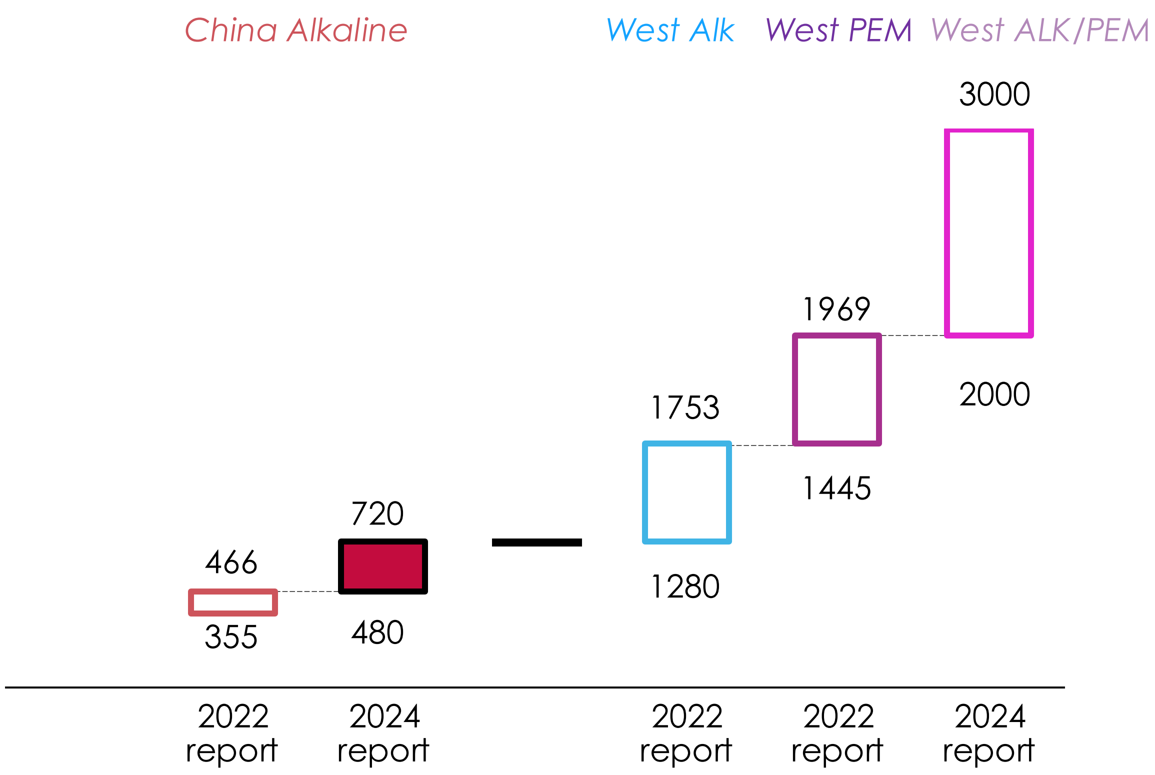
Indirect costs

- EPC management (EPC contractor selection and management)
- Owner's costs (land and grid fee, insurance, permitting, financial arrangement, feasibility study, pilot tests/ramp up costs, etc.)
- Contingency (budget put aside to cover any unforeseen costs, risks and events)

Sources: adapted from Bloomberg NEF (2024), *Hydrogen Outlook for Europe and the Mediterranean*

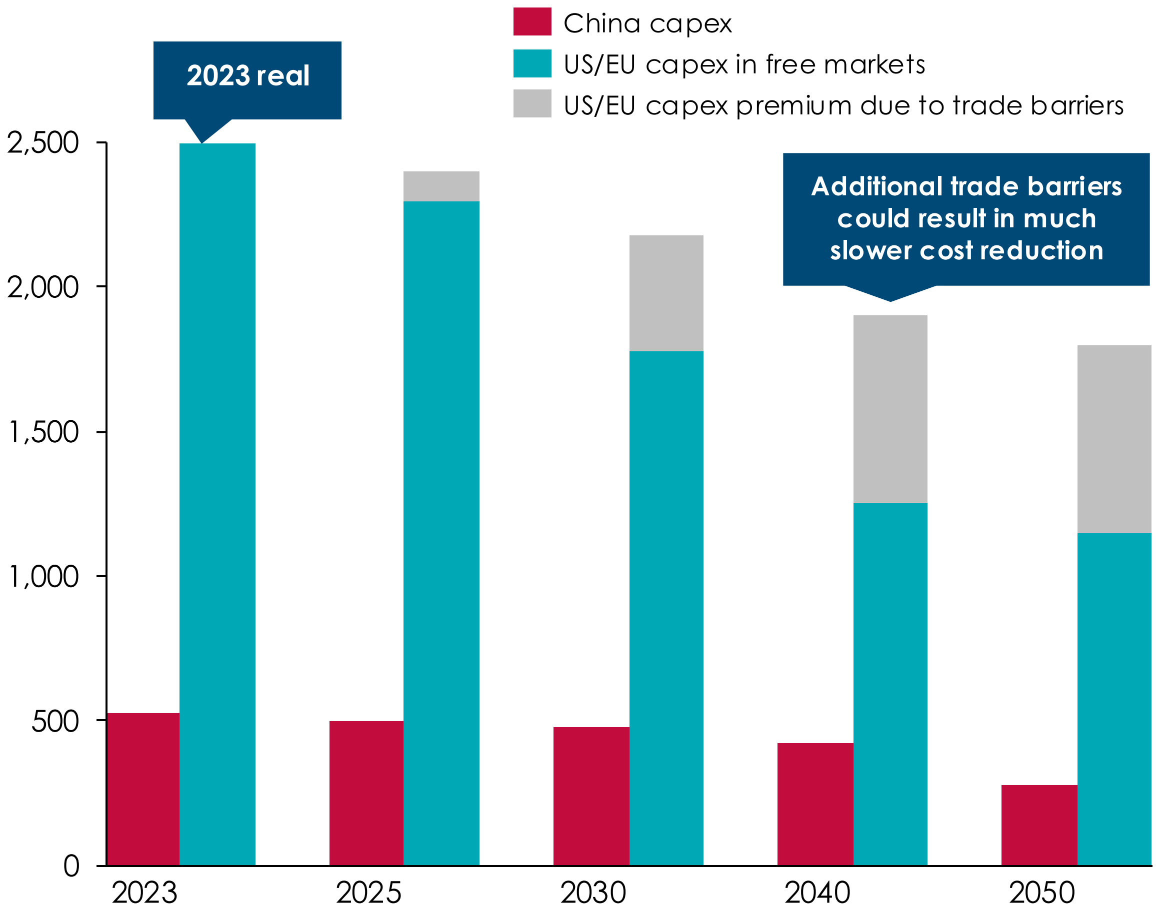
[Hydrogen] Costs of hydrogen remain high, and anticipated to fall less steeply than anticipated in light of higher system capex

System capex forecast of large alkaline electrolysis projects
$/kW



BNEF electrolyzer survey reports

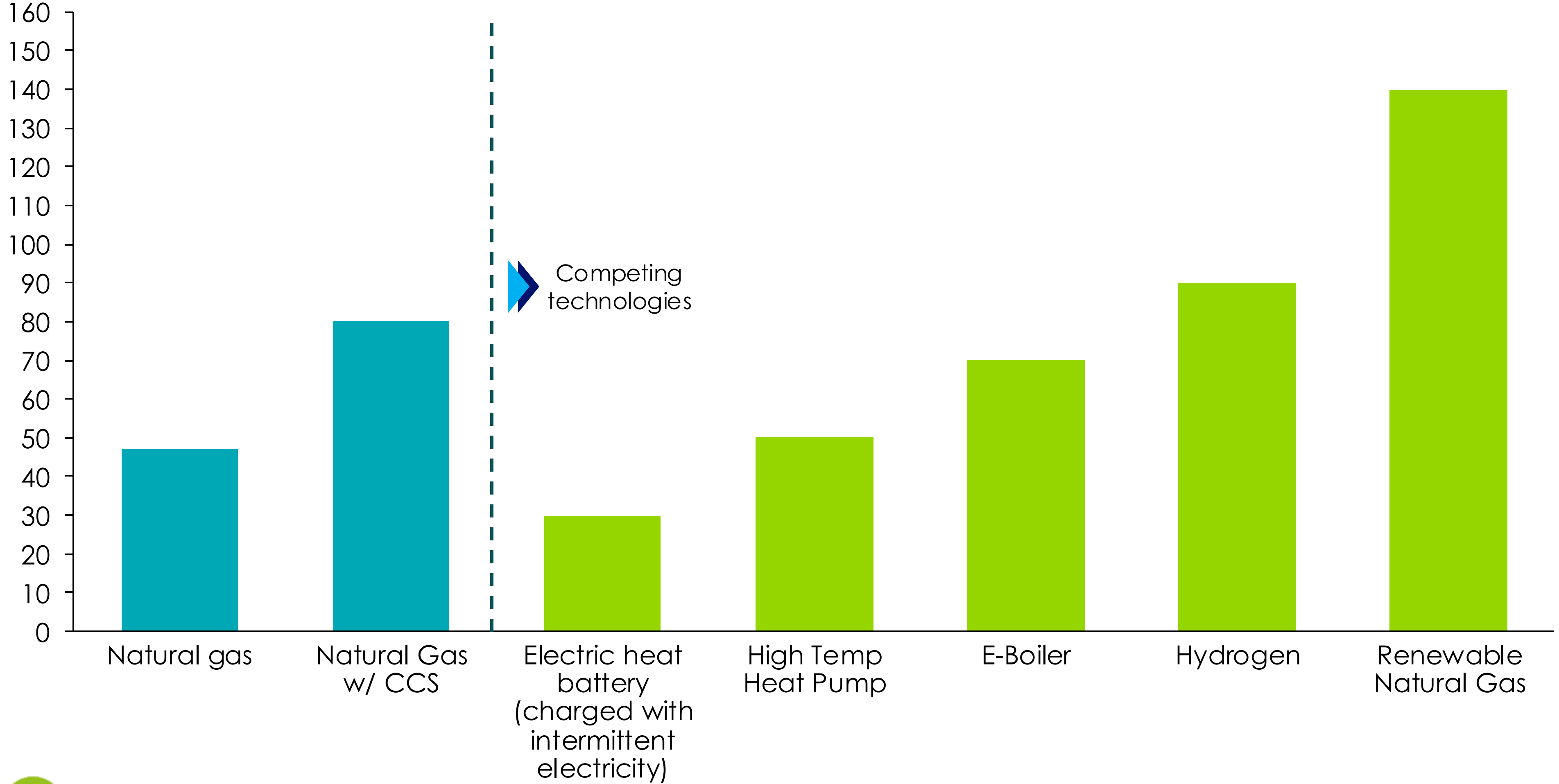
Electrolyzer system costs
$ per kw of hourly hydrogen yield



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 '0.2Nm³/h' is equivalent to kw under the current industry consensus
Source: Bloomberg (2024) BNEF Hydrogen Market Outlook

The cost of high temperature heat electrified solutions are competitive with more carbon intensive alternatives

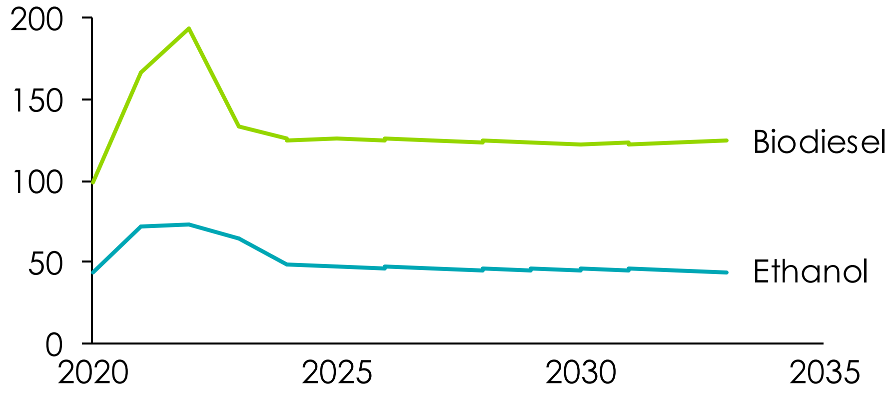
Levelised Cost of Heat (LCOH) for temperatures >100 degrees Celsius
$/MWh



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?*

No significant economy of scale or learning curve effect for biofuels and CCS, which costs are expected to remain flat in the next decade

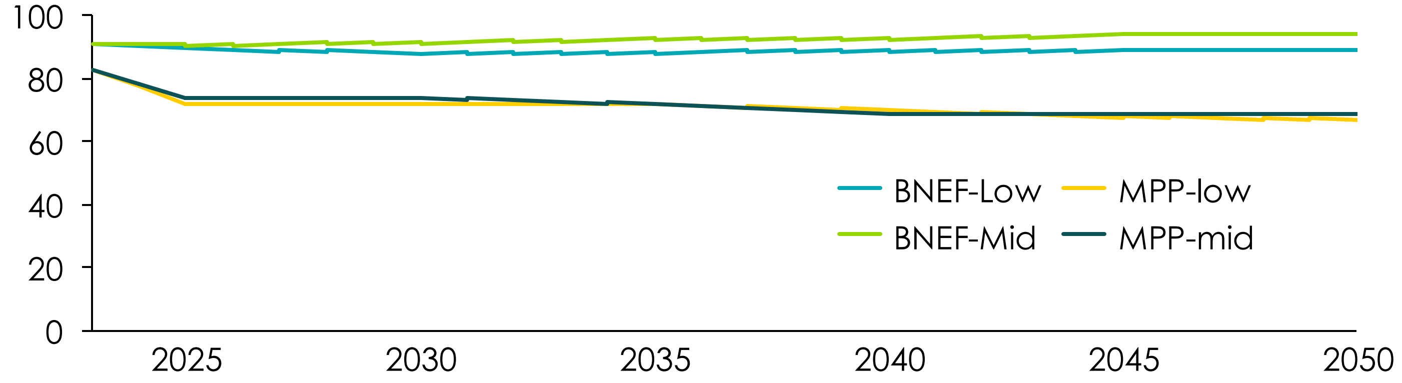
Biofuel prices,
USD/HJ (Real price)



Key trends

- Gradual decrease of ethanol and biodiesel over the next decade
- Stagnating demand growth due to diminished demand for transport fuel, with the prevalence of EV

Cost of Carbon capture and Storage, Point Source
USD/t CO2



Key trends

- No clear cost reduction for CCS expected, but significant cost decreases possible with modular capture units
- The lack of transport and storage capacity is going to be a major bottleneck for deployment

Sources: Mission Possible Partnership (2022) Internal analysis; BloombergNEF 2023) Carbon Capture Cost Model. OECD (2024) OECD-FAO Agricultural Outlook 2024-2033; ETC (2022) Carbon Capture, Utilisation & Storage in the Energy Transition: Vital but limited

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

Electrification | Nuclear | Hydrogen

		Technology disruption	Assessment of disruption	Sectors impacted	Certainty[1]
Cross sectoral	1	Sodium-based battery technologies	Enable low-cost, long-duration storage, challenging hydrogen and nuclear	Power, Industry, Mobility, Buildings	High
	2	Advanced Direct Air Capture (DAC)	Boosts e-fuels (synfuels) efficiency and lowers costs, outcompeting biofuels	Industry, Chemicals, Aviation, Power	Medium
	3	Nuclear micro reactor and/or fusion	Provide ultra-cheap round-the-clock power generation	Chemicals	Low
	4	White hydrogen AND/OR Advanced electrolyser efficiency	Drives (green) hydrogen to cost parity with carbon fuels and CCS	Power, Chemicals, (Heavy-) industry	Low
Sector specific	5	Li-ion solid state batteries	Outperforming other batteries in compactness, weight and charging speed	Trucking, Shipping, Aviation, Power	High
	6	Molten Oxide Electrolysis	Enables fully electric primary steel production	Steel	Medium
	7	Electrical steam cracking	Replace fossil-fuel cracking by electric cracking for ethylene and propylene	Chemicals	Medium
	8	Industrial heat electrification (>600°C)	Make electrification feasible and cost-competitive with CCS until high temperatures	(Heavy-) industry (cement)	High

1) Indicates the expected level of certainty that this technology will disrupt the described sectors and change share of electrification by 2050.

The eight key disruptions are shaping our unconstrained scenario

→ ↗ ↓ ↑ *Changes in energy demand*

Electrification | Nuclear | Hydrogen

	#	Technology disruption	Impact assessment *(What changes, by how much?)*	Impact on energy demand and size of the impact in 2050: Direct elec	H2 +derivatives	Carbon-based
Cross sectoral	1	Sodium-based battery technologies	Enabling >90% of zero-carbon power supply with low-cost, long-duration storage	↑ + X EJ	↗ - Y EJ	↓ - Y EJ
	2	Advanced Direct Air Capture (DAC)	Increase synfuels share to [60%] v biofuels for aviation	↘ + X EJ	↑ - Y EJ	↗ - Y EJ<
	3	Nuclear micro reactor and/or fusion	Enabling >90% of renewable power supply	↑ + X EJ	↗ - Y EJ	↓ - Y EJ
	4	White hydrogen AND/OR Advanced electrolyser efficiency	H2-based fuels and tech will be cheaper, faster	↓ + X EJ	↑ - Y EJ	↓ - Y EJ
Sector specific	5	Li-ion solid state batteries	Enabling higher shares of electrification in long-haul transport	↑ + X EJ	↗ - Y EJ	↓ - Y EJ
	6	Molten Oxide Electrolysis	[100%] electrified steel production	↑ + X EJ	↗ - Y EJ	↓ - Y EJ
	7	Electrical steam cracking	[X%] electrified chemicals production instead of CCS	↑ + X EJ	→ - Y EJ	↓ - Y EJ
	8	Industrial heat electrification	Electrified low-med. °C increasing share of direct elec. to [>80%]	↑ + X EJ	→ - Y EJ	↓ - Y EJ

1) Indicates the expected level of certainty that this technology will disrupt the described sectors and change share of electrification by 2050.

Example - A disruption of electric kilns could replace fossil fuels, raising electricity needs from 12EJ to 19 EJ

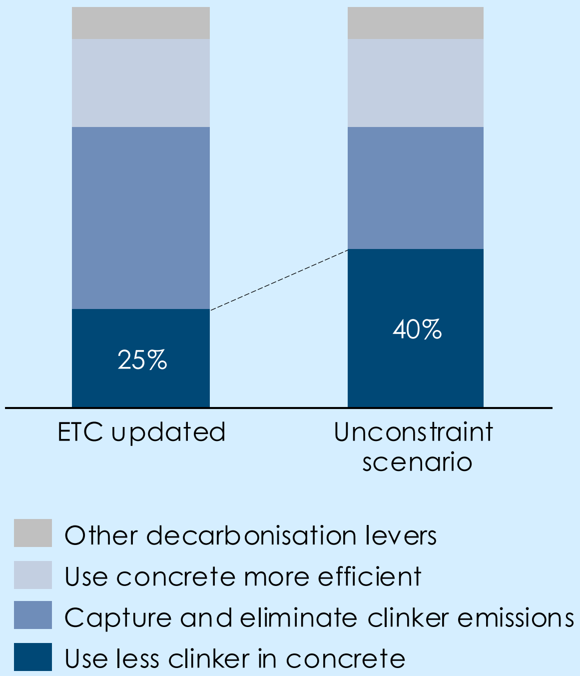
Description: Electric kilns can reach 1400°C, converting limestone into clinker, the main ingredient for cement production. Switching to electric kilns can cut energy emissions, which contribute to 45% of total cement production emissions.

What we need to believe in

	Today	2050
TLR	5-6	9 (in 2040)
Energy cost to be competitive (EUR/MWh)	[50]	[35]
Barriers mitigated	• High temperature requirements • Pilot testing and scaling up • Reducing upfront high capital cost	
Latest developments	• In 2023, COOLBROOK successfully completed test of 1000 C • SaltX working on an electric arc calciner • Several MoU with steel and cement producers (CEMEX, UltraTech, Dalmia cement) to electrify the manufacturing process	

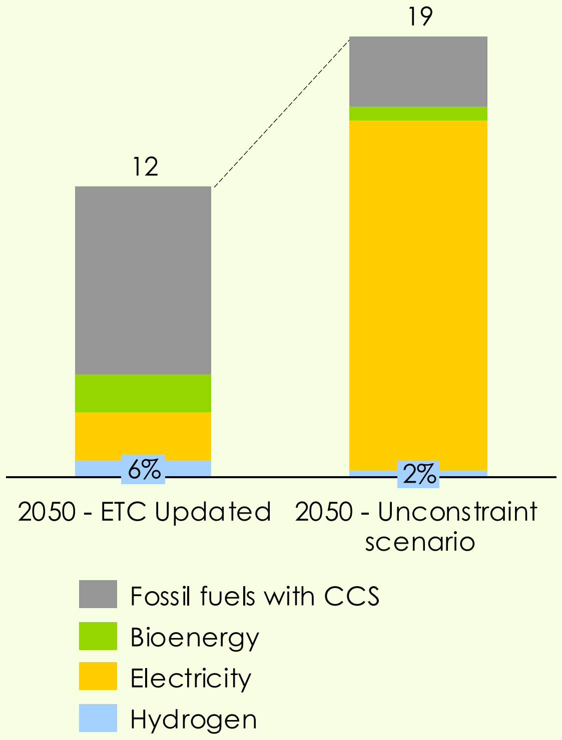
Abatement levers in the unconstrained scenario, % of cumulative abated emissions

Illustrative



Impact on energy demand, EJ per year

Preliminary



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

Different types of heat generation that can be used for cement electric kilns

Type of heating generation	Description	Companies exploring tech
Resistance heating	▪ Uses electric resistance elements to generate heat. ▪ Common in smaller kilns and for specific heating zones within larger kilns. ▪ Proven use in electrifying the calcination process	NORCEM HEIDELBERGCEMENT Group; SINTEF
Electric Arc (plasma) heating	▪ Electric arc calciner (EAC) technology, which converts electricity directly into high-temperature heat with a plasma generator ▪ Designed to complement existing fuel-fired kilns	SaltX Technology
Roto Dynamic Heating	▪ Rotating machinery using electricity to generate heat through friction ▪ Ready for commercial scale launch in 2025 ▪ Also applicable to heating in production of iron and steel and chemicals	COOLBROOK
Induction Heating	▪ Heat generated as a product of resistance to electrical currents within a material to produce heat ▪ Commonly used in metalworking, automotive	n/a
Microwave heating	▪ The transmission of heat via microwave radiation into the material to be heated ▪ Can be inefficient due to the microwave absorbing capacity of cement raw material	n/a

Sources: Cemex company website; SaltX (2024) Electrification's promising path; Cementproducts.com (2024) Electric Cement Production: The Technologies

Agenda

Project overview

Previous projections on electrification and hydrogen

Trends and tech disruptions shaping ETC scenarios

Sectoral deep-dives

Ingoing hypothesis about dominant solutions, potential barriers and breakthroughs will help inform scenarios

No doubt electrification sectors	Fading barriers	Potential breakthrough
Passenger cars: Cost parity with fossil vehicles already possible	**Long distance trucking**: lowering power and battery costs makes full electrification achievable in nearly all use cases	**Power sector**: nuclear and sodium batteries
Short to mid-haul trucking: Cost parity projected to be reached in 2030's	**Other industry**: lowering power cost and new tech allows cost-competitive electrification to reach >600°C	**Primary steel**: Molten Oxide Electrolysis enables fully electric primary steel production
Secondary steel production: already electrified	**Buildings**: tolerance towards NG fading, leaving room for multiple electrification technologies	**Short haul aviation**: Battery technology and cheap renewables enabling more adoption of short-mid range H2 and battery electric aircraft
Rail: already mostly electrified	**Long haul aviation**: Lowering power and DAC costs make synfuels competitive with biofuels	**Cement:** electric kilns uptake (high temperature industrial heat electrification)
Aluminium: already electrified	**Shipping:** Lowering power costs make ammonia competitive with biofuels	**Chemicals:** new and efficient hydrogen production, e.g. white hydrogen, SOEC. Also electric steam crackers and methane pyrolysis

Appendix

Hypothesis for Phase 1 – how far can electrification take us?

Exam questions:

- How large can and should the role of direct electrification be in a zero-emission economy?
- What is the role of hydrogen and derivatives (i.e., ammonia) in a zero-emission economy?

Summary

1. Intro: "When facts change, I change my mind". The ETC has previously undertaken analysis, estimating the required final energy demand mix to 2050 required for net-zero alignment.
   a) However, informed observers and experts have consistently updated upwards their electrification deployment forecasts
   b) Trends around deployment of renewable energy have continually been revised up, while some recent forecasts of hydrogen's role have been revised down
   c) To understand the role of carbon molecules, in light of evolving incremental trends and incumbent technology disruptions, it is necessary to revise the ETC's view on the energy mixed required
2. The role of direct electrification, electron based molecules (ammonia and H2) and carbon based fuels is clear in decarbonization of the energy system, but less certain is how much is required of each
   a) In view of capacity and cost trends in these three areas by 2050, we expect future energy demand to be even more electrified than we thought
   b) Trends and short-term foreseeable development should be considered such as: higher deployment of RE, more conservative cost reductions in H2, reducing costs of batteries, cost competitive solutions for electrifying industrial heat, and biofuels and CCUS cost projections flatlining
   c) From a longer-term POV: 8 critical technology disruptions shape our unconstrained scenario and have implications on a sectoral energy use and the split between electrification, electron based molecules and carbon based fuels as solutions.
3. Hypotheses on sectoral help shape an unconstrained scenario, split between
   i. No doubt electrification sectors (e.g. road, secondary steel)
   ii. Fading barriers sectors (e.g. buildings and long-haul trucking)
   iii. Potential breakthrough sectors (e.g. steel and cement)