Chapter Summary

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The role of direct electrification and hydrogen in a carbon zero emission economy

Why hydrogen and electrification matter in the energy transition

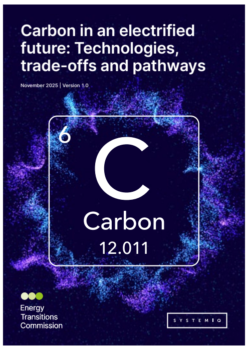
Electrification lies at the heart of efforts to reduce the role of fossil-fuel carbon molecules in the energy system. Clean hydrogen plays an important complementary role, extending the reach of clean power where direct electrification is not technically feasible.

Together, electrification and clean hydrogen could radically reduce the role of carbon-based fuels in final energy demand, cutting their share from around 80% today to about 30% by 2050, with recent innovations potentially driving this share even lower.

Electrification is expected to take a large share of final energy demand in the future, driving reductions in carbon-based fuels and feedstocks. Most major net-zero scenarios, including the IEA Net Zero Emissions and IRENA 1.5°C pathways, project electricity's share of final energy demand rising from about 20% today to at least 50% by 2050. The Energy Transitions Commission's Accelerated but Clearly Feasible (ACF) scenario goes further, with electrification reaching around 62% of final energy demand by mid-century rising to around 71% in the more ambitious Possible but Stretching (PBS) scenario.[1]

Clean electrification and hydrogen are expected to displace fossil fuels across transport, buildings and heavy industry in the future, and in some cases are well on their way today. Electric vehicles are estimated to displace around two to three million barrels per day of oil demand globally and accounted for roughly one in four new car sales in 2025.[2] In buildings, heat pumps have become the leading low-carbon heating option, with sales growing rapidly in several major markets (e.g., Europe, parts of China).[3] In light industry, many low- and medium-temperature processes are already electrifiable with electric boilers and heat pumps.

The appeal of electrification is simple: once electricity is clean, using it directly is more efficient than producing other fuels. On the demand side, heat pumps and electric vehicles typically use two to four times less final energy than fossil fuel alternatives, while electric cooking can use four to five times less energy than traditional biomass stoves.[4]


Carbon in an electrified future: Technologies, trade-offs and pathways

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The ETC's and Systemiq's *Carbon in an Electrified Future: Technologies, Trade-offs and Pathways* report, from which this summary is based, analyses how carbon can be sourced, used and reduced in a net-zero global economy. It focuses on the role of electrification, hydrogen, circularity, and carbon sourcing and management technologies that together can enable the sustainable supply, reuse and permanent storage of carbon molecules. The report also examines the key system trade-offs and innovation priorities needed to achieve deep decarbonisation while balancing cost, resource use and technological readiness. This summary is one of a series drawn from this joint report and focuses on the role of electrification and hydrogen.

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[1] Based on the Energy Transitions Commission's Fossil Fuels in Transition analysis, this report uses the ACF scenario as a reference case, in which around 31% of final energy demand in 2050 relies on carbon molecules. In the more ambitious PBS scenario, this share falls to 22%. The PBS scenario reflects more optimistic assumptions on the pace at which emerging electrification options and enabling infrastructure can be deployed.

[2] IEA (2025) Global EV Outlook

[3] IEA (2025) *Heat pump sales for selected regions, 2019-2024*, and IEA (2022) *The future of heat pumps*

[4] ETC (2025) Energy productivity: Increasing efficiency in an expanded, electrified energy system

The power sector is already moving rapidly in this direction, with renewables meeting all global electricity demand growth in the first half of 2025, driving down average power system costs as low-marginal-cost renewables scale. As a result, the combination of cheap, abundant clean power and increasingly efficient, low-cost electric technologies makes direct electrification the preferred decarbonisation strategy wherever it is technically feasible across transport, buildings and industry.

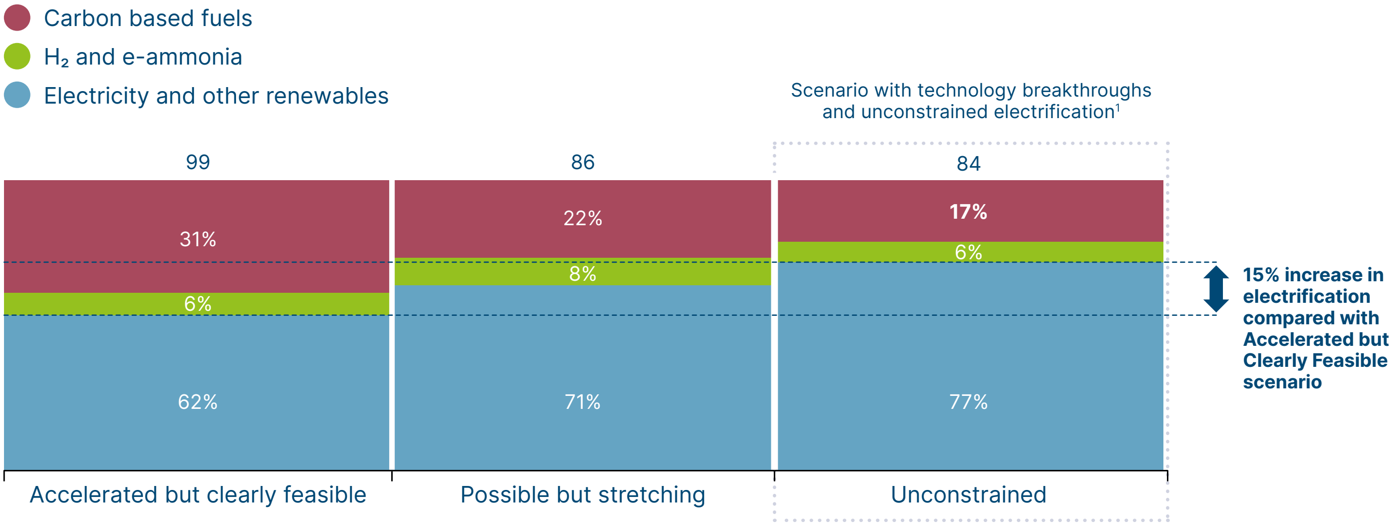
Recent innovations can make electrification an even higher share of final energy demand, reducing carbon remaining by a further 15%, while hydrogen is expected to displace only where electrification cannot. In an ambitious scenario we assume unconstrained electrification and rapid uptake of emerging technologies, where electrification rises from around 62% of final energy demand to approximately 77%. This scenario represents a maximum theoretical level of electrification, where renewables and grid build out is not constrained and clean power supply is widely available at a competitive cost. In this context, hydrogen plays a complementary rather than dominant role in applications where direct electrification is technically or economically challenging. It remains essential in applications where hydrogen is required as a feedstock and constitutes part of the final product itself, such as fertilisers and select chemical value-chains. Together, clean electrification and hydrogen could supply close to 83% of final energy demand in this unconstrained electrification scenario, leaving carbon-based molecules to cover only the remaining 17%, as shown in Exhibit 1. **Understanding where electrification and hydrogen reach their limits, and where carbon molecules will remain essential, is critical for directing investment, infrastructure build-out and policy choices.**

Exhibit 1

An unconstrained electrification scenario with technology disruptions, can reduce the share of carbon molecules to 17% of final energy demand

Global final energy demand by energy source and scenario

Thousand TWh (%), 2050



NOTE: 1) Includes uptake of technologies such as Molten Oxide Electrolysis and Electrowinning for steel, high temperature industrial heat for chemicals and cement, and increased share of batteries for final energy demand in shipping and aviation.

SOURCES: Accelerated but clearly feasible and Possible but stretching scenario based on ETC (2023), *Fossil Fuels in Transition*.

Innovations to minimise carbon in the system

Emerging technologies could extend electrification to applications where it has previously not been feasible (namely, high temperature heat, direct electrochemical production routes and use of batteries to support wider electrification of the power system and mobility), increasing the role of electrification overall, and in some cases reducing the expected role of hydrogen.

High-temperature industrial heat

Advancements in high-temperature heat technologies mean that more segments of heavy industry could be electrified. Technologies such as plasma heating, resistance heating and shockwave-based systems were historically limited to niche industrial uses. Improvements in power electronics, materials science and process control now allow these systems to operate reliably and continuously at temperatures approaching 1,000-1,500°C, expanding their applicability to core industrial processes such as cement kilns. Many of these technologies have reached mid to high technology readiness levels, typically around TRL 6-8, with pilot plants and early commercial deployments already demonstrated.

Electrifying kiln heat could eliminate most cement fuel emissions (which are 35-40% of cement-related emissions), leaving only process CO_2 to address through targeted carbon capture. However, significant constraints remain, including the need for abundant, low-cost clean electricity delivered reliably to industrial sites, challenges around materials durability under extreme conditions, and potentially high upfront capital costs for retrofits.

Electrification of iron and steel-making

Emerging electric production routes for iron/steel-making mean that more fossil carbon can be eliminated from the process and replaced with direct electrification. Technologies such as molten oxide electrolysis and electrowinning offer alternatives to both conventional fossil-based routes with carbon capture and hydrogen-based direct reduced iron processes, and could emerge as a major decarbonisation pathway for steelmaking rather than only a niche complement to hydrogen. These approaches use electricity directly as the reduction agent, eliminating the need for fossil carbon and potentially avoiding the efficiency losses associated with hydrogen production, compression and use. Advances in electrode durability, electrolyte stability and modular cell design are improving feasibility, though the technologies remain around TRL 5, with large-scale commercial deployment most likely in the 2030s.

If successfully scaled, molten oxide electrolysis and electrowinning could reduce total energy use by around 6% compared with hydrogen-based direct reduced iron routes, simplify steelmaking process flows, and materially reduce hydrogen demand relative to earlier net-zero expectations. Key uncertainties remain around long-term materials performance, capital costs and power supply requirements. Molten oxide electrolysis requires near-constant electricity supply to sustain high-temperature operation, while electrowinning can operate more flexibly and better accommodate intermittent power, implying different integration challenges and opportunities depending on power system conditions.

Next generation batteries

Next generation batteries can expand the role of batteries in mobility, including greater range in shipping and aviation, while also supporting further electrification of power systems through stationary storage options such as sodium-ion batteries. Battery technologies, such as solid-sate battery technology, are designed to overcome limitations of conventional lithium-ion systems, improving energy density, safety and charging speeds. These performance gains, together with declining costs, are expected to enable electrification across a wider range of mobility applications beyond passenger road transport. In shipping, these improvements make short- and medium-range electric shipping vessels (e.g., intra-regional shipping routes) increasingly viable. In aviation, battery-electric planes are increasingly feasible, though limited to short-haul routes (few hundred kilometres), with deployment expected before 2030.

Sodium-ion batteries avoid many of the critical raw material constraints associated with lithium-ion technologies and could become a competitive option for stationary storage, where energy density is less critical, helping to scale clean and flexible power grids. As power systems integrate higher shares of variable renewables, demand for multi-hour storage and daily balancing will increase significantly. In these applications, sodium-ion technologies can complement lithium-ion systems by providing an alternative chemistry less exposed to material supply risks.

However, many promising next-generation battery chemistries remain at relatively low technology readiness levels. Development of these promising technologies requires fragmenting R&D efforts across different chemistry pathways, and there is an absence of acute material supply pressure to displace lithium-ion today. As a result, early deployment volumes remain small, keeping unit costs high. Once preferred technologies begin to emerge, rapid scale-up will be essential to unlock learning effects, reduce costs and compete with established battery chemistries.

Hydrogen

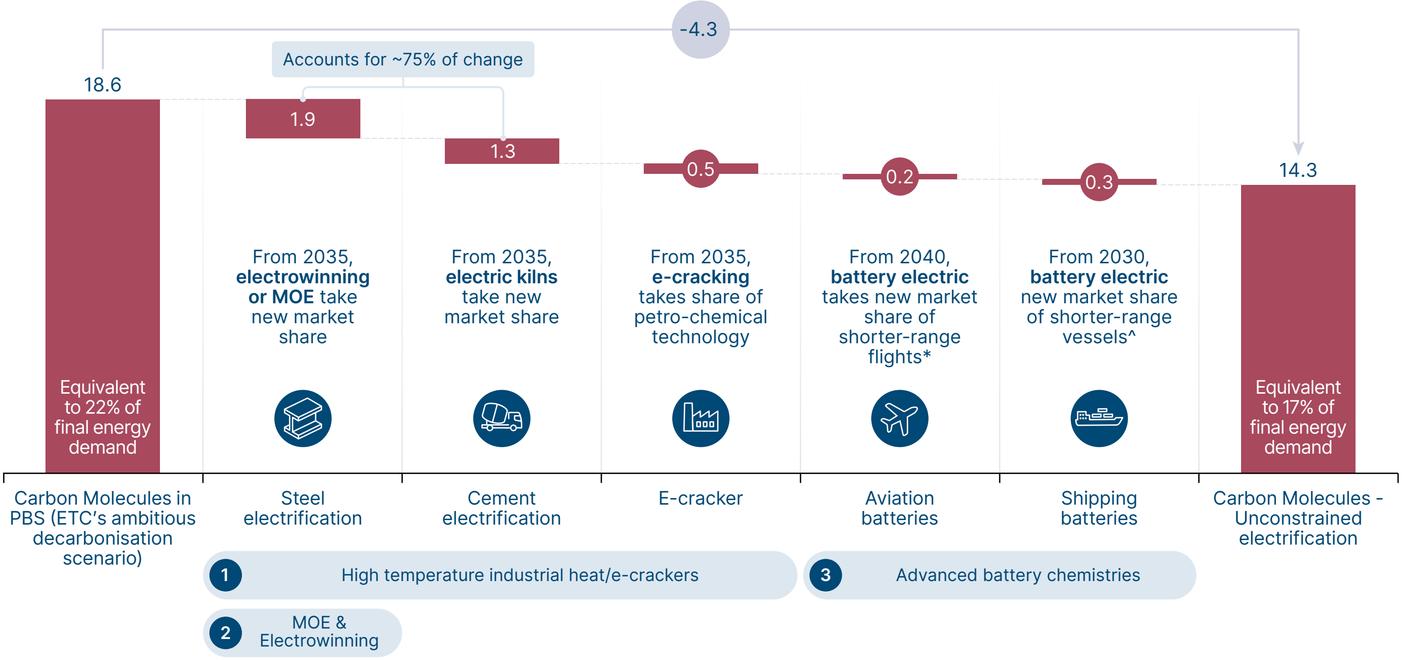
Hydrogen's role in the energy mix is expected to be smaller than earlier projections, reflecting faster-than expected progress in direct electrification and slower than anticipated cost reduction in green hydrogen. In an unconstrained electrification scenario, hydrogen's share of final energy demand remains around 6%, down from 8%, largely due to greater electrification in sectors such as steel, rather than hydrogen displacing fossil fuels at scale. While electrolyser costs are expected to fall, electricity prices are still a major component of hydrogen production costs, and the additional conversion steps involved make hydrogen inherently less energy-efficient than direct electrification, reinforcing hydrogen's role as a strategic complement to electrification rather than a universal substitute.

These innovations could push electrification and hydrogen to the limit of their role in the energy system, potentially meeting 83% of total final energy demand in 2050 and leaving just 17% from carbon-based sources. Carbon molecule use would be concentrated in applications that need high energy densities (e.g. long-distance aviation and shipping fuels), or need carbon as a fundamental building block (e.g., chemical production). At the system level, these innovations could collectively reduce the share of carbon in final energy demand by 5% (from 22% to 17% of final demand) or 4.3 Thousand TWh (Exhibit 2), corresponding to a reduction in carbon use for energy purposes from around 2.2 $GtCO_2$ to about 1.9 $GtCO_2$. The two largest contributors to this reduction are a shift in steelmaking toward direct electrochemical routes, such as electrowinning and molten oxide electrolysis and high temperature heat for cement kilns, accounting for ~75% of the reduction.

Exhibit 2

With 1) high-temperature industrial heat, 2) iron/steel electrification and 3) battery chemistries, carbon demand reduces by 4.3 Thousand TWh

Carbon molecules in the energy system – Possible But Stretching (PBS) to Unconstrained share 2050
Final Energy Demand, Thousand TWh



NOTE: PBS = Possible But Stretching ETC decarbonisation scenario. *estimated at 15% of all nautical miles travelled, ^estimated at 20% of energy demanded

SOURCE: Systemiq analysis for ETC on (2023), ETC *Fossil Fuels in Transition*, Systemiq (2022), *Planet Positive Chemicals* (BAU Net-Zero scenario); Steel: Mission Possible Partnership (2022) Making Net-Zero Steel Possible; Aviation: Mission Possible Partnership (2022) Making Net-Zero Aviation Possible.

Implications and actions: moving from technologies to systems

Scaling electrification and hydrogen, and thereby reducing the role of carbon, depends on four key system shifts: (1) delivering abundant, low-cost clean electricity; (2) unlocking "early wins" in sectors where electrification technologies are already mature, before extending solutions into harder-to-abate heavy industry and long-distance mobility segments; (3) creating reliable demand for low-carbon products; and (4) de-risking early-stage industrial electrification and hydrogen projects. Table 1 summarises the stakeholder actions needed to deliver these system shifts.

1. **Delivery of abundant, predictable, low-cost clean electricity is the critical foundation for electrification and hydrogen at scale.** The cost and availability of clean power shape not only the deployment of mature electrification technologies, but also the viability of earlier-stage options required to reach more ambitious outcomes. Yet uncertainty around the price and availability of near-constant clean power remains a key barrier to extending electrification beyond today's applications. Recent analysis from ETC on Power Systems Transformation finds that a low-carbon power system can be as cheap as, or cheaper than, today's system — but only if generation, grid build-out, firm capacity and system flexibility are developed in parallel.

2. **Rapid uptake of electrification in sectors where technologies are already technically viable is a necessary first step in the transition.** In buildings, road transport and light industry, technologies such as heat pumps and electric vehicles are already technically viable, potential "early wins" but uptake is slowed by stock turnover, upfront capital costs, running-cost perceptions and household decision barriers. Unlocking faster uptake depends on measures such as building and vehicle standards that shift replacement choices, reducing upfront investment through accessible financing, enabling infrastructure such as charging and heat networks and strengthening consumer awareness and confidence in electrified options. Progress in these sectors therefore shape the pace of early electrification and the extent to which demand, supply chains and capabilities are built up to support wider system change.

Beyond these "early wins" for more mature technologies, reaching the most ambitious electrification and hydrogen pathways requires scaling emerging technologies into new heavy industry and mobility segments. In the unconstrained electrification scenario, widespread uptake of emerging technologies depends on the availability of low-cost, reliable clean electricity at scale. Technologies, such as high-temperature industrial heat require a firm and near-constant clean electricity supply, as electrified systems operating at extreme temperatures cannot ramp up and down easily. Extending electrification into the hardest-to-abate industrial segments therefore hinges on the availability of clean power that is both affordable and consistently delivered.

3. **Creating reliable demand for low-carbon products, independent of the underlying technology, will reduce market risk, support early investment, and accelerate cost reductions through scale,** particularly in the early stages of market development. Without clear and predictable demand signals, producers remain exposed to price and volume risk, which delays investment decisions even where low-carbon production routes are technically viable and ready for deployment.

4. **De-risking early-stage industrial electrification and hydrogen projects will allow technologies to move from demonstration to commercial deployment and scale to achieve cost reductions.** This is particularly important for hard-to-abate emerging innovations which face high first-of-a-kind capital requirements, limited operating track records, and financing challenges that cannot be addressed by market forces alone. Targeted risk reduction accelerates learning-by-doing, shortens the path to cost competitiveness, and enables faster replication across sectors.

Table 1: Who needs to do what?

System shift	Government and public finance	Energy system planners and utilities	Industry and corporates
1. Delivering abundant low-cost clean electricity	**Reform permitting and planning** to accelerate renewable generation, grid reinforcement and storage build-out **Signal priority industrial zones and grid build-out plans early,** so developers and industrial users can align investment decisions	**Plan and invest in transmission and distribution** sized for industrial electrification not incremental demand **Deliver firmed renewable supply** (renewables plus storage and flexibility) matched to industrial load profiles	**Commit to long-term power offtake (PPAs, CfDs)** when there is line of sight to cost parity or suitable policy drivers in place for a viable business case **Use coalitions and industry bodies to signal demand and grid needs,** strengthening the case for accelerated build-out
2. Unlock mature electrification technologies	**Set building and vehicle standards** to shift replacement choices toward electrified options **Reduce upfront cost barriers** through targeted subsidies, concessional finance and accessible consumer financing **Invest in enabling infrastructure** such as EV charging networks and heat networks	**Anticipate and plan for rapid load growth** from heat pumps and EVs in distribution networks **Streamline connection processes** for distributed electrified loads **Align tariff structures to incentivise** smart charging and flexible demand	**Offer innovative financing and business models** (e.g., leasing, heat-as-a-service, bundled energy-efficiency packages) that lower upfront costs and accelerate consumer uptake. **Invest in installation, maintenance and customer support** networks, and work with governments and utilities to strengthen consumer awareness and confidence in electrified options
3. Creating reliable demand for low-carbon products	**Use mandates and public procurement** to create early, bankable demand for low-carbon steel, cement, chemicals and fuels **Define credible product standards and certification schemes,** including chain-of-custody rules and a trusted registry to validate product-level emissions claims **Introduce product-based contracts-for-difference** that reward emissions reductions	**Coordinate with industry and government to forecast demand for low-carbon products** and reflect this in grid expansion, connection planning and system investment decisions.	**Commit to long-term offtake agreements** of low-carbon materials to support scale-up where there is clear cost-parity trajectory or policy support that makes early procurement investable
4. De-risking early stage projects	**Standardisation and recognition of early production routes** in legislation to ensure eligibility under green procurement targets **FOAK grants, guarantees and concessional finance** to lower cost of capital and to unlock investment **Deploy market-based de-risking tools** (CfDs, two-sided auctions) to move projects from pilots to replicable commercial models	**Integrate early electrified industrial loads into planning and market design** so they can access low-cost power and operate flexibly **Offer clear, time-bound grid connection agreements** and transparent pricing structures for FOAK electrification projects	**Form joint ventures and partnerships** to spread capital risk, pool capabilities and accelerate learning across early projects **Explore emerging markets** with more favourable power costs, policy support and growth prospects to improve early project economics

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