

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

Key messages / The Story

Headline Message

Electrification will drive the global transition to net zero, powering cleaner industries, homes and transport. But even in a world where electricity dominates, carbon molecules will play a remaining role in producing essential fuels and materials. Managing this finite resource wisely – by sourcing sustainably, maximising reuse and recycling, and ensuring responsible end-of-life storage – is crucial to creating a balanced and resilient carbon system.

Achieving net zero is not about eliminating carbon entirely, but rather about transforming how we source, use and manage it at end-of-life in a highly electrified, sustainable energy and materials system.

The path to net zero will require navigating complex trade-offs between technology readiness, cost, energy use, and environmental impact. Progress will depend on overcoming systemic barriers through coordinated policy, robust carbon pricing, and investment in infrastructure and innovation.

Ultimately, the world faces a double challenge: minimising the amount of new carbon entering the system, while ensuring all the remaining carbon is sourced, used, and managed at end-of-life in harmony with both nature and society.

Messages

1. **Electrification will be the key driver of the transition to net zero, powering a sustainable and resilient energy system for the future.**
 - a. The report finds that electrification is the biggest lever to eliminate the majority of carbon use in the energy and material sectors, and that new and emerging technologies will play a central role in carbon displacement and reducing fossil fuel dependency.
 - b. In an ambitious scenario, up to 77% of the final energy demand could be met via the direct use of electricity. Electrification and clean hydrogen

combined could meet up to 83% of total final energy demand, reducing the role of carbon to as little as 17% by 2050 instead of 80% share today.

- c. Technology breakthroughs, such as electrification for iron and steelmaking, as well as electrification of high-temperature heat in cement production, could further expand electrification's reach. Advanced battery chemistries may also unlock electrification potential in short-haul shipping and regional aviation.
- d. Hydrogen remains an essential feedstock for ammonia in fertiliser production, as a building block for maritime fuels (i.e. e-methanol) and as a process reagent in steel production. However, as electrification advances, hydrogen is being displaced from applications where it would primarily serve as a heat source, i.e. iron ore reduction, cement heat generation, and road transport.

2. Even in an electrified world, carbon molecules will have a reduced but remaining role in a net-zero energy and materials system

- a. In an electrified system, global demand for carbon molecules in energy and materials would fall by almost 60%, from 11.5 Gt today to 4.7 Gt in 2050.
- b. However, direct electrification will not be technically or economically viable in all sectors, and certain sectors will still require carbon-based fuels and feedstocks. Industries such as aviation and chemicals will continue to rely on carbon molecules to meet their specific needs.
- c. It is feasible for approximately 29% of the carbon molecules that remain in the system to be sourced from sustainable biomass, 13% from recycled carbon, and 58% from abated fossil fuel sources.
- d. Achieving a low-carbon future will therefore depend on developing a balanced, clean, and resilient energy mix that combines electrification with low-carbon solutions.

3. Circularity also plays a significant role in reducing primary carbon demand, but requires substantial policy interventions to achieve scale

- a. A maximum of a third of carbon used in 2050 could be from circular sources; however, circularity solutions currently do not offer discrete drop-in solutions, and require a more holistic and integrated systems approach to scale.
- b. Upstream solutions such as material re-use can lower carbon demand while offering cost savings; however, it requires major behaviour change along the value chain.

- c. Mechanical recycling of paper and plastic is proven and scalable, but particularly for plastics, scale-up depends on sufficient quality feedstocks and competition against low-cost virgin fossil production.
- d. Further downstream technologies like carbon utilisation and chemical recycling face business case challenges primarily through the high costs of feedstock inputs.
- e. Realising circularity's potential demands a coordinated operational transformation (product design, manufacturing, consumer behaviour, waste systems) underpinned by robust regulation, carbon pricing, and public incentives.

4. Sustainably sourcing carbon across the energy and materials system is essential to achieving net zero

- a. Carbon that cannot be made circular needs to come from primary sources. While there is potential to increase sustainable biomass supply through emerging technologies, it is currently limited at around 60 EJ, largely constrained by land and must be carefully governed to avoid food security and biodiversity risks.
- b. Emerging technologies such as direct air capture (DAC) and ocean-based carbon removal could play an important role in the future carbon mix, but these technologies are either costly or still in early stages of development and will need rapid scaling to contribute meaningfully by mid-century.
- c. Managing the continued use of fossil carbon is a defining challenge. Fossil-based carbon is abundant and low-cost, but reliance on it will increase dependence on safe and scalable carbon management solutions. The more we draw carbon from the ground, the greater our responsibility to ensure it is disposed of or abated effectively.

5. End-of-life carbon management is critical for a sustainable carbon system

- a. Sourcing carbon sustainably is only part of the challenge. Ensuring permanence and preventing re-emission at the end of life is essential, making large-scale CO₂ storage indispensable for achieving net-zero.
- b. By 2050, analysis indicates that 8.8 Gt must be captured each year – roughly 6.8 Gt requiring permanent storage, and 1.8 Gt directed to utilisation pathways. Current deployment stands at just 0.05 Gt/year, highlighting the need for a more than 100-fold scale-up.
- c. Solid carbon storage, methane-stabilising landfill systems can reduce emissions from residual waste and safely sequester carbon from materials such as plastic.

6. Achieving net zero will require an optimal mix of solutions in the carbon value chain, navigating complex technology trade-offs between readiness, cost, energy use and environmental impact

- a. Technology viability depends on readiness and scalability. Many technologies are nearing commercial deployment, but others remain at earlier stages and need accelerated development.
- b. Energy input costs will shape competitiveness. High-energy processes such as DAC and chemical recycling are currently expensive, but could become viable with falling renewable power costs, especially in regions rich in solar or wind.
- c. Technology costs vary widely across the carbon value chain. Mature circular solutions like mechanical recycling could generate cost savings today, but require established infrastructure and behavioural change. In contrast, early-stage CCU options such as e-methanol remain costly. Mid-range technologies, including point-source CCS and industrial electrification, could become competitive as carbon prices rise towards \$150/tCO₂ by 2030.
- d. Environmental and resource efficiency must guide choices. Bioenergy solutions could demand significant land use, while circular approaches such as reuse and recycling offer higher resource efficiency and lower biodiversity risks.

7. Coordinated policy action (e.g., a combination of carbon pricing, certification frameworks, standards, incentives) is essential to accelerate infrastructure development and scale mature and emerging carbon solutions

- a. Economic and infrastructure constraints, including infrastructure bottlenecks, high capital and operating costs, heavy dependence on low-cost clean energy and feedstock availability, limit competitiveness with fossil incumbents.
- b. Carbon pricing is a critical technology-neutral lever in scaling these key low-emissions technologies. Findings suggest that prices of up to \$200 per tCO₂ may be required to bring many essential emerging technologies to cost parity. This must be supported by instruments such as mandates, Extended Producer Responsibility schemes, design standards and public procurement.
- c. At the same time, policy and market uncertainty further complicate the situation. Fragmented regulations, inconsistent standards, and weak demand signals delay investment and slow technology scale-up.