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Hitachi Imperial Centre for Decarbonisation and Natural Climate Solutions
Briefing Paper

Destination Net-Zero: what is your best path?

Insights for decision-makers navigating the low carbon transition

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Executive Summary

This briefing paper provides a comprehensive, scenario-based assessment of global pathways to net-zero emissions by 2100, drawing on interdisciplinary research from the Hitachi-Imperial Centre for Decarbonisation and Natural Climate Solutions. Grounded in systems thinking and analytical frameworks, it identifies the technological, environmental, economic and socio-political levers critical to delivering effective and sustainable decarbonisation strategies.

At its core, the paper recognises that there is no single pathway to net zero. Instead, it presents four contrasting global decarbonisation scenarios—**Conservative Continuity**, **Innovative Balance**, **Accelerated Decarbonisation**, and **Slow Transition**—each achieving the same climate target of limiting global warming to 1.5°C by 2100, but through different combinations of energy demand management, technology adoption, and carbon dioxide removal (CDR). These scenarios reveal trade-offs between early versus delayed mitigation, behavioural shifts versus technological reliance, and nature-based versus engineered carbon removal solutions.

Using the transport sector as a case study, the paper explores how mitigation options in high-emission sectors interact with broader energy system transitions. It assesses the performance of emerging technologies, comparing their economic cost and viability, environmental footprint, integration potential, and scalability. While focused on transport, the systemic approach and decision-making framework presented here are applicable across all sectors.

Key takeaways include:

- **Multiple viable pathways to net zero:**
  The four scenarios presented demonstrate that net-zero emissions can be achieved through diverse strategies. Early action and energy efficiency reduce dependence on large-scale engineered removals, while high energy demand pathways rely more heavily on CDR technologies later in the century.

- **Hard-to-abate sectors require tailored, system-level strategies:**
  Transport is used in this report as a case study to explore the complex interplay between sector-specific technologies, energy systems, and infrastructure. Decarbonisation in hard-to-abate sectors—whether freight, aviation, or maritime—requires a portfolio of context-specific solutions. As in other emission-intensive sectors such as energy and heavy industry, trade-offs between technology readiness, infrastructure needs, resource demands, and emissions impact must be carefully balanced.

- **Critical role of Carbon Dioxide Removal:**
  All climate scenarios depend on CDR to address residual emissions, and its role extends beyond reaching net zero to removing historical emissions. A portfolio approach combining the near-term deployment of nature-based solutions with the longer-term scale-up of engineered CDR is essential.

- **Ecosystem impacts and biodiversity must be integrated:**
  Carbon mitigation strategies that require high land use risk undermining biodiversity and ecosystem services. The report emphasises the need to embed ecological considerations into decarbonisation strategies to ensure long-term system resilience and support vital services such as food production, water purification, and climate adaptation.

- **Policy, monitoring, and investment are enablers:**
  Effective decarbonisation depends on enabling conditions including clear policy frameworks, robust carbon accounting across Scope 1–3 emissions, and aligned financial mechanisms. The report stresses the importance of tools like emissions trading schemes and coordinated investment to accelerate technology deployment and track progress.

This paper goes beyond scenario and technology assessment to present an integrated framework for navigating the complexity of net-zero transitions. It empowers policymakers, industry leaders, and researchers to design adaptive, resilient, and equitable decarbonisation pathways. Ultimately, it calls for urgent and coordinated action that aligns mitigation, removal, biodiversity, and societal goals. The path to net zero is not only a technical endeavour, but also a governance and systems transformation challenge.

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1. Introduction

Limiting global temperature rise and achieving net zero emissions is critical to mitigating the impacts of climate change. The pathways to net zero vary widely, depending on energy system design, resource consumption patterns, technology deployment, and policy interventions. The choices made today – whether in energy production, carbon removal strategies, or sectoral mitigation efforts – will determine the ease, costs, and trade-offs of different decarbonisation pathways in the coming decades. While the end goal remains the same i.e., reaching net zero emissions, there is no single pathway to achieving it. Different combinations of mitigation measures, technological transitions and policy frameworks can shape the route to net zero in dramatically different ways.

This paper is part of the research conducted at **Hitachi-Imperial Centre for Decarbonisation and Natural Climate Solutions** which focuses on providing solutions and research to help tackle the issue of global pollution with an initial focus on addressing key challenges in decarbonisation and climate repair. This paper explores a range of possible net-zero pathways by presenting contrasting future scenarios. Rather than identifying a 'best' or 'preferred' route to reach our net-zero targets, these scenarios illustrate the diverse ways in which energy demand, mitigation strategies and carbon removal interact. Across all scenarios, we assess here the implications of different energy demand levels, mitigation strategies, and carbon removal pathways.

While this paper primarily uses mobility and transport as a case study, the findings and methodologies presented are applicable across other high-emission industries, including and not limited to power, industry, and land use sectors. The option space is examined by analysing the range of available technologies and approaches for reducing emissions, and the implications associated with the options. However, even in the most ambitious decarbonisation pathways, some residual emissions will remain, requiring the deployment of carbon dioxide removal (CDR). Beyond emissions reductions and removals, biodiversity must also be a key consideration in net-zero strategies, as large-scale mitigation and CDR measures can have significant ecological impacts. Additionally, accurate carbon accounting and effective financing mechanisms will be essential to mobilizing investment and ensuring that mitigation and removal efforts are both measurable and scalable.

The objective of this paper is to provide insights into the diverse pathways to net zero and their associated trade-offs, supporting decision-makers including policymakers, industry leaders and researchers in navigating the complexities of decarbonisation. By examining contrasting net-zero scenarios, this paper highlights the key choices, challenges, and interdependencies that shape decarbonisation strategies across different energy systems and sectors.

To achieve this, we explore how these scenarios can influence energy systems and demand, carbon removal strategies, and biodiversity, emphasizing the need for holistic, integrated approaches rather than isolated sectoral decision-making. Finally, we discuss the policy measures, innovation strategies, and forms of cooperation that will be required to implement these pathways, ensuring that decarbonisation efforts remain resilient, adaptable, and effective in mitigating climate change.

Box 1: The Hitachi-Imperial Centre for Decarbonisation and Natural Climate Solutions

The Centre for Decarbonisation and Natural Climate Solutions is a collaboration between Hitachi Ltd, Hitachi Europe, and Imperial College London, dedicated to advancing the transition to net zero pollution. Through a multidisciplinary, systems-thinking approach, the Centre addresses the interconnections between carbon management, decarbonisation of energy and transport, and carbon dioxide removal (CDR). By integrating technical, socio-economic, and policy aspects, the Centre aims to develop holistic solutions that support industry, government, and society in achieving sustainable and scalable pathways to net zero.

Our research is structured around three key pillars:

1. Carbon Management and Decarbonisation (Energy and Transport) – Developing sector-specific mitigation pathways, enhancing carbon accounting methodologies, and exploring emissions reduction strategies across industries.

2. Climate Repair and Nature – Evaluating the role of DAC, BECCS, afforestation, and other approaches to address residual emissions in net-zero pathways understanding the role of biodiversity and nature-based solutions.

3. Social System and Transition – Focusing on socio-economic and policy research, identifying the enablers and barriers to decarbonisation, ensuring that policies, business models, and financing mechanisms align with long-term climate goals.

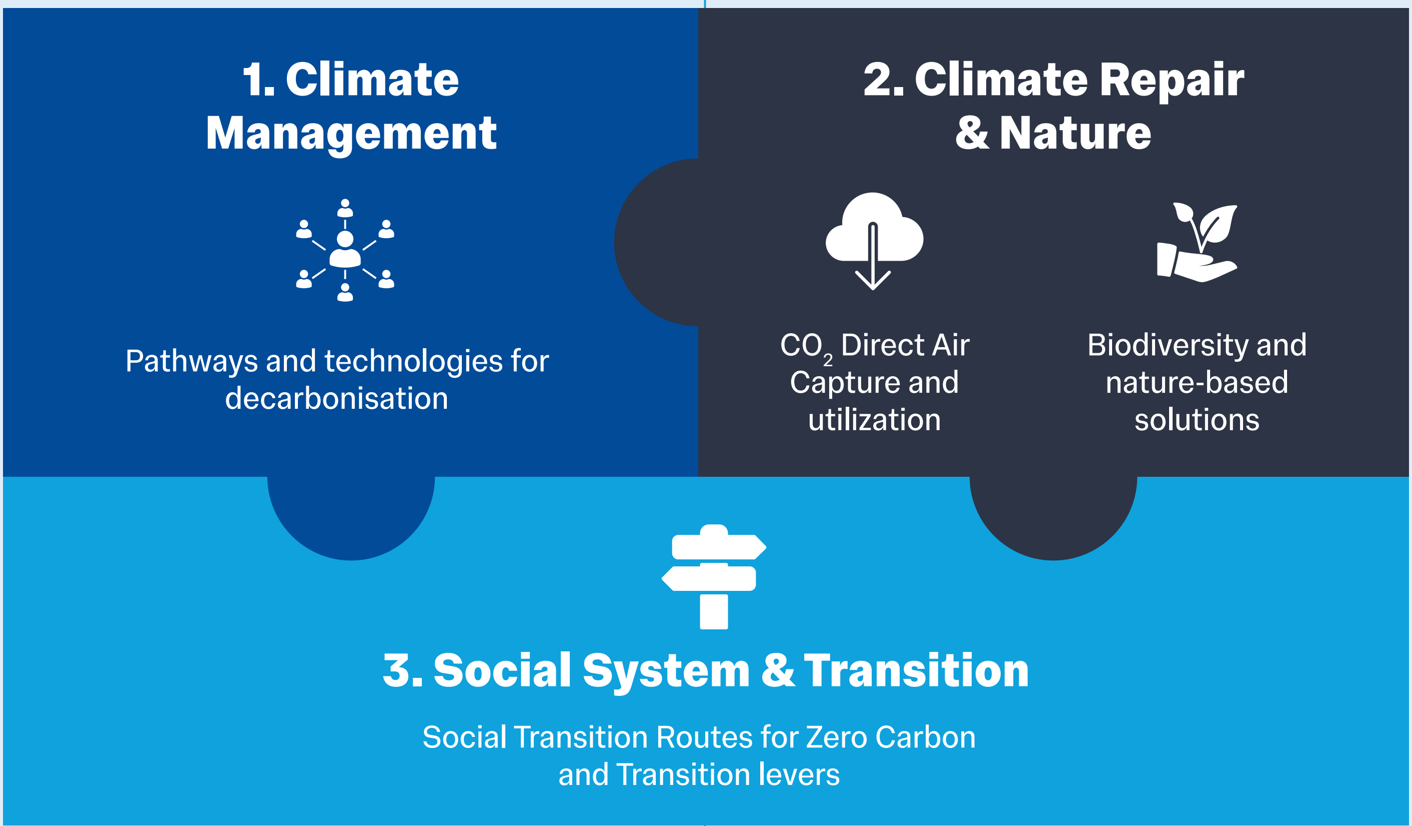


Figure A. Hitachi-Imperial Centre research pillars.

The Centre builds upon Imperial's Transition to Zero Pollution initiative, bringing together a team of multidisciplinary researchers from the Faculties of Engineering, Natural Sciences, and the Business School, alongside experts from the Energy Futures Lab and Grantham Institute – Climate Change and the Environment. Our goal is not just to achieve net zero but to understand the broader environmental and societal challenges that will persist beyond it, including long-term atmospheric CO_2 levels, biodiversity impacts, and resource constraints.

The work covered in this paper includes five research projects, each contributing to a better understanding of how to transition industries, cities, and economies towards a net-zero future. By working across disciplines and engaging with industry stakeholders, policymakers, and researchers, the Centre is developing actionable insights and practical solutions that can be applied across multiple sectors to drive meaningful and effective climate action.

2. Scenario Analysis

There is no single trajectory for reaching net zero – the future will be shaped by policy choices, technological advancements and economic developments that unfold over the coming decades. To explore a range of potential outcomes, this work presents four contrasting scenarios. These scenarios are not ranked in terms of desirability or likelihood; rather, they highlight how different assumptions about energy demand, mitigation strategies and carbon removal can lead to diverse net-zero futures.

Integrated Assessment Models (IAMs) are essential tools for exploring these future pathways. IAMs take a top-down approach to climate mitigation, simulating how policies, technologies, and societal trends could interact to reduce greenhouse gas emissions. They incorporate assumptions about population growth, economic development, and climate policies to model different decarbonisation trajectories. Many of the scenarios included in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) are derived from IAMs, providing a foundation for understanding potential trade-offs and system-wide implications [1].

Building on this approach, we illustrate the multiple routes to achieving the same climate goal, by presenting four contrasting scenarios (Table 1) which were selected via an assessment framework developed at the Hitachi-Imperial research centre (Figure 1). The scenarios were selected based on economic feasibility, environmental impacts, resource availability, and broader societal factors such as risk, fairness, and resilience. This was done using an open source framework developed at the Hitachi centre [2]. All scenarios considered achieve net zero and limit global warming to 1.5°C above pre-industrial levels by 2100, yet they differ in how they balance mitigation, energy transitions and carbon removal.

Table 1. Scenario names and main themes

Scenario	Name	Theme
A	"Conservative Continuity"	Highlights the slow, incremental nature of the change, relying heavily on CCS and legacy systems.
B	"Innovative Balance"	Policy-driven shift with a balanced approach, including DAC, CCS, and renewables.
C	"Accelerated decarbonisation"	Aggressive shift to renewables, rapid phasing out fossil fuels and focusing on traditional sequestration.
D	"Slow Transition"	Slow progress, with heavy reliance on traditional methods.

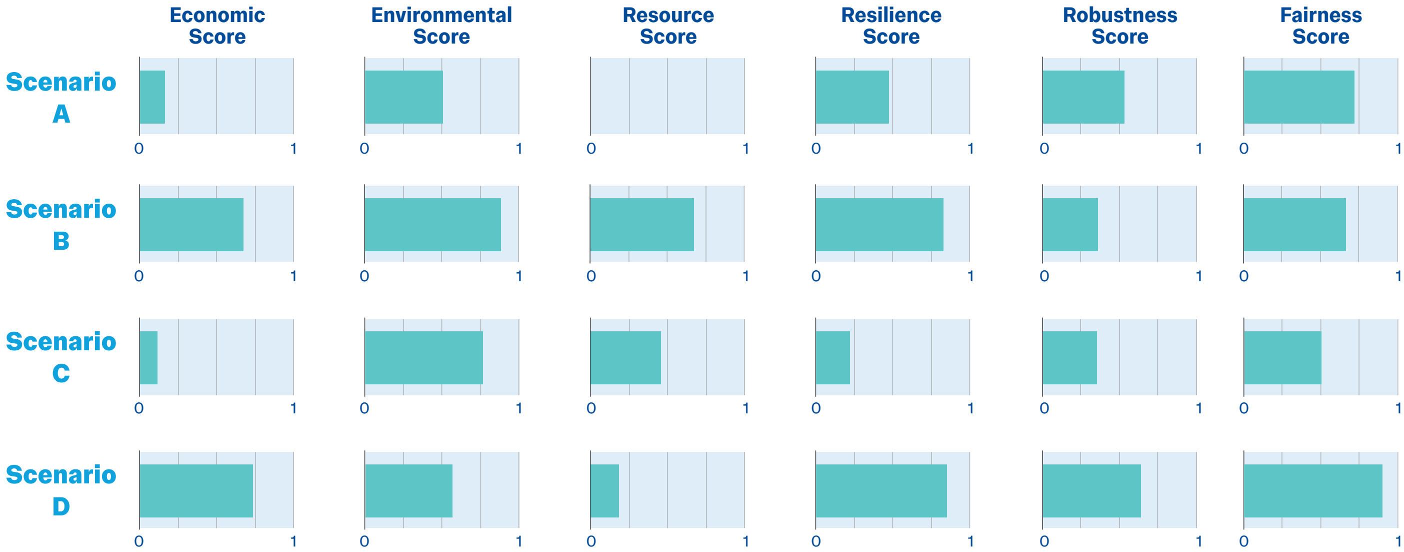


Figure 1 : Comparative assessment of four contrasting net-zero scenarios based on key evaluation criteria. Each radar chart represents a different scenario – Scenario A (Conservative Continuity), Scenario B (Innovative Balance), Scenario C (Accelerated decarbonisation) and Scenario D (Slow Transition). The scenarios are assessed across six dimensions: economic feasibility, environmental impact, resource efficiency, resilience, robustness and fairness. A higher score on any given dimension represents higher relative challenges in that area.

For more information on this work refer to Beath, H., Mittal, S., Lamboll, R., & Rogelj, J. (2025). An exploration and evaluation framework for climate change mitigation scenarios with varying feasibility and desirability.

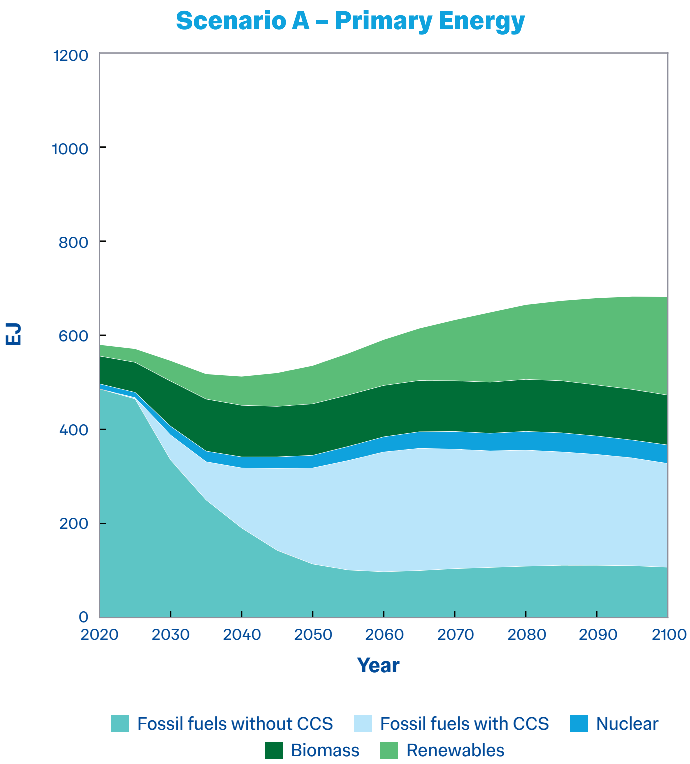
2.1 Scenario A: "Conservative Continuity"

2.1.1 A Future of Modest Energy Demand and Gradual Change

In this scenario, energy demand grows at a slow and steady pace as policy, infrastructure and as societal preferences favour gradual improvements in efficiency and emissions reductions rather than large-scale system transformations (Figure 2). Fossil fuels remain significant, with CCS used to manage emissions. Renewables grow steadily but fail to dominate. Land-use changes (e.g., reforestation) are the primary method for removing CO_2, as energy-intensive technologies like DAC are absent. Low-carbon energy demand reaches 660 EJ, the lowest among the scenarios.

This scenario can be achieved with the following:

- **Energy Efficiency:** Moderate improvements in buildings, transport, and industry keep energy consumption in check.
- **Extreme Behavioural Shifts:** Societies adopt low-energy lifestyles, prioritising local consumption, reduced energy demand, and efficiency-driven choices over high-energy consumption patterns.
- **Slow Electrification:** Adoption of electric vehicles, clean heating systems, and renewables occurs gradually.



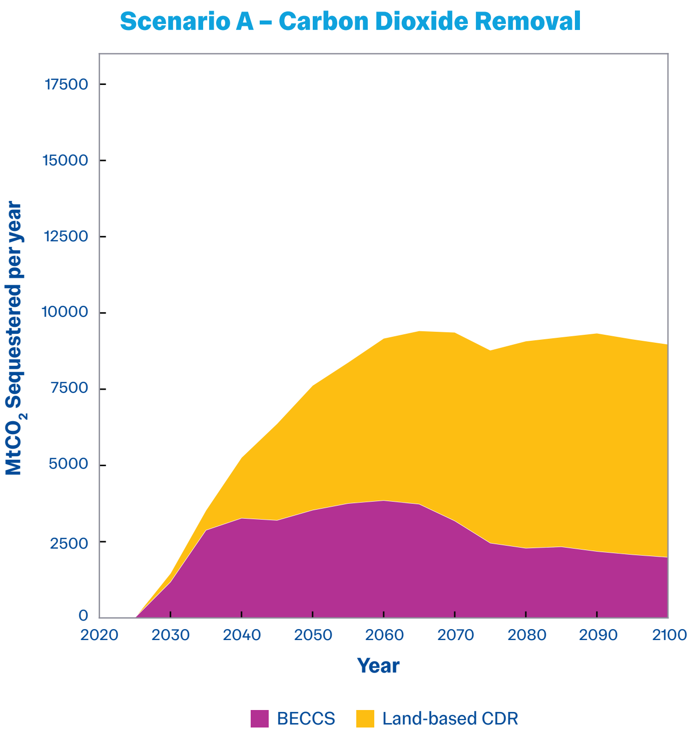


Figure 2. Scenario A: "Conservative Continuity" primary energy demand (top) and Carbon Dioxide Removal (bottom). The primary energy demand shows that fossil fuels remain dominant throughout the century, with only a modest decline, while renewables and biomass grow slowly. Carbon capture and storage (CCS) plays a limited role in mitigating emissions. The bottom panel indicates that carbon sequestration relies primarily on land-use changes, with minimal deployment of engineered carbon dioxide removal (CDR) solutions such as bioenergy and carbon capture and storage (BECCS). This reflects a future of slow decarbonisation, where emissions reductions are largely driven by nature-based removals (e.g., reforestation) rather than technological transformations.

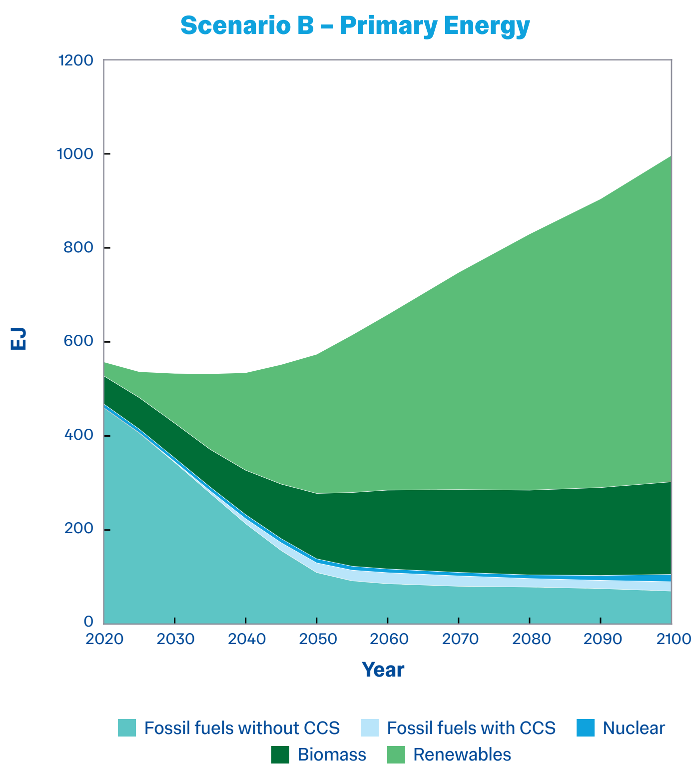
2.2 Scenario B: "Innovative balance"

2.2.1 A High-Energy Future Fuelled by Innovation
This scenario envisions a future of bold, coordinated action, where energy demand increases significantly to almost 1000 EJ by 2100, driven by widespread electrification across all sectors (Figure 3). For instance, the shift to electric transport, heating, industrial process, and expanding data centers leads to a fundamental transformation of the energy system, requiring rapid scaling of renewable energy and greater reliance on CDR to counterbalance residual emissions.

In this scenario, clean energy dominates, providing more than 90% of the energy mix with less than 2% nuclear power, while direct air capture (DAC) and green hydrogen production expand rapidly. Fossil fuels are largely phased out by the end of the century. Driven by strong policies that drive global collaboration to meet ambitious climate goals, keeping warming below 1.5°C with minimal overshoot.

This scenario can be achieved with the following:

- **Mass Electrification:** Aggressively electrifying transportation, industry, and residential systems drives energy demand higher.
- **Global Collaboration:** Governments, industries, and citizens work together to fund renewable energy and grid expansion.
- **Innovative Technologies:** DAC and green hydrogen play key roles in balancing emissions and decarbonising hard-to-abate sectors.



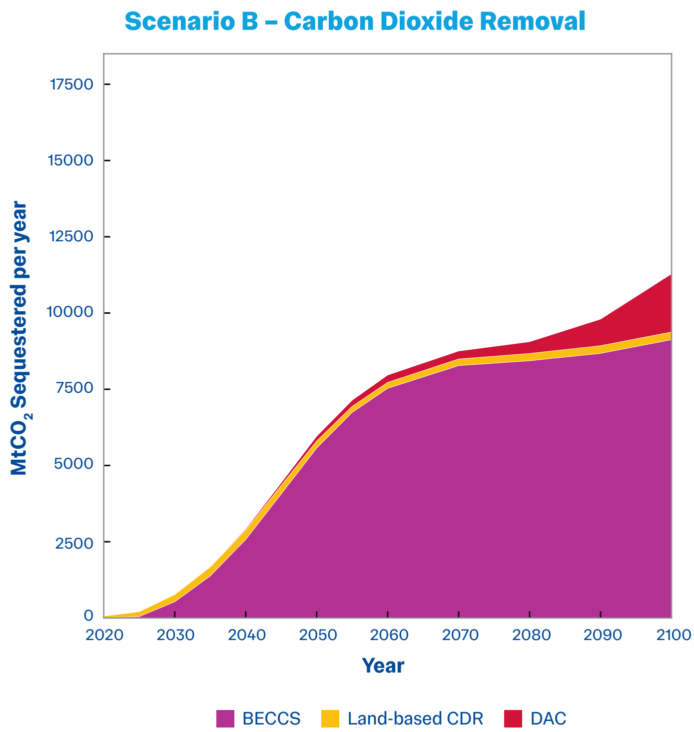


Figure 3. Scenario B: "Innovative Balance" primary energy demand (top) and Carbon Dioxide Removal (bottom). The energy demand illustrates a significant transition away from fossil fuels, with rapid expansion of renewable energy and biomass. Nuclear energy remains small. This transformation supports higher energy demand while maintaining a low-carbon supply mix. The bottom panel shows a much greater reliance on engineered carbon removal such as bioenergy with carbon capture and storage (BECCS) and Direct Air Capture (DAC).

2.3 Scenario C: "Accelerated decarbonisation"

2.3.1 A Low-Energy Future of Careful Efficiency

In this scenario, humanity achieves decarbonisation by promoting energy efficiency and keeping energy demand growth relatively low compared to other scenarios by 2100. Clean energy dominates, providing more than 90% of the energy mix, with fossil fuels eliminated almost entirely (Figure 4). Advanced technologies make buildings, vehicles, and industries ultra-efficient, reducing energy waste. Carbon removal relies on natural solutions and BECCS, without the need for energy-intensive DAC.

This scenario can be achieved with the following:

- **Efficiency First:** Investing in smart grids, ultra-efficient appliances, and optimized industrial processes minimises energy waste.
- **Behavioural Change:** Societies adapt to energy conservation, with smaller, localised energy systems, reduced demand for energy-intensive goods and shifts toward lower-emission diets, such as reduced meat consumption and more locally sourced foods.
- **Targeted Electrification:** Only the most critical systems, like transport and heating, are electrified, keeping overall demand low.

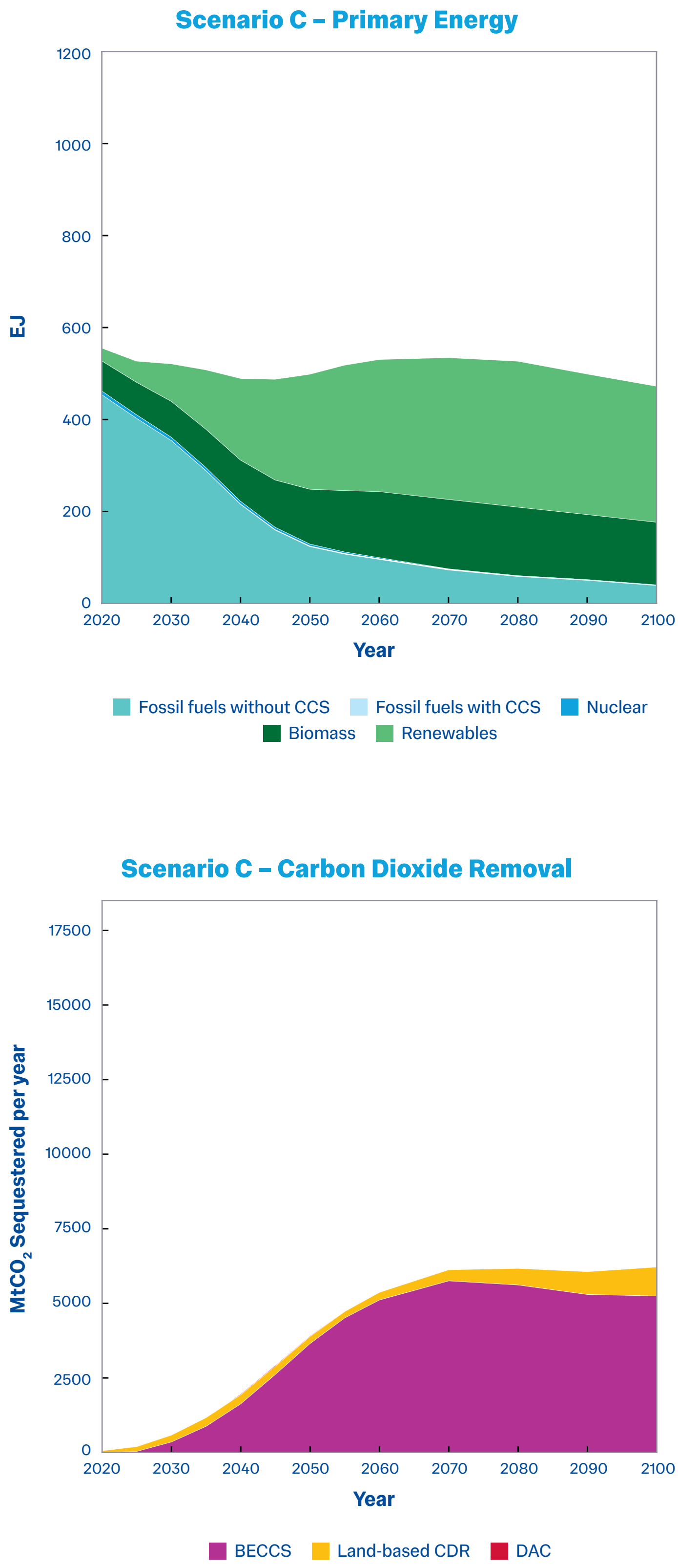


Figure 4. Scenario C: "Accelerated decarbonisation" primary energy demand (top) and Carbon Dioxide Removal (bottom). The top panel shows a rapid decline in fossil fuel use, with renewables and biomass becoming the dominant energy sources by mid-century. The bottom panel indicates a significant reliance on Biomass with Carbon Capture and Storage (BECCS) for carbon sequestration, while land-use-based removals play a smaller role compared to other scenarios.

2.4 Scenario D: “Slow Transition”

2.4.1 A High-Energy Future with delayed progress

Energy demand grows significantly but the transition to clean energy is fragmented and delayed. Fossil fuels remain a significant part of the energy mix for too long, and renewables take longer to dominate (Figure 5). This delayed shift would result in high overshoot in atmospheric GHG concentrations, requiring large-scale carbon dioxide removal efforts in the latter half of the century to meet net-zero targets. Eventually, low-carbon energy reaches more than 1000 EJ, the highest among scenarios, but only after prolonged reliance on fossil fuels has led to significant climate damages and adaptation challenges [3].

This scenario could materialise under the following conditions:

- **Uneven progress:** Some regions electrify quickly, while others lag due to lack of funding, policy alignment, or infrastructure.
- **Heavy fossil fuel reliance:** Fossil fuels remain a primary energy source for an extended period, delaying the full shift to renewables.
- **Late-stage CDR deployment:** Due to slow mitigation and higher energy demand, carbon removal is scaled up significantly post-2050 to compensate for prolonged emissions.

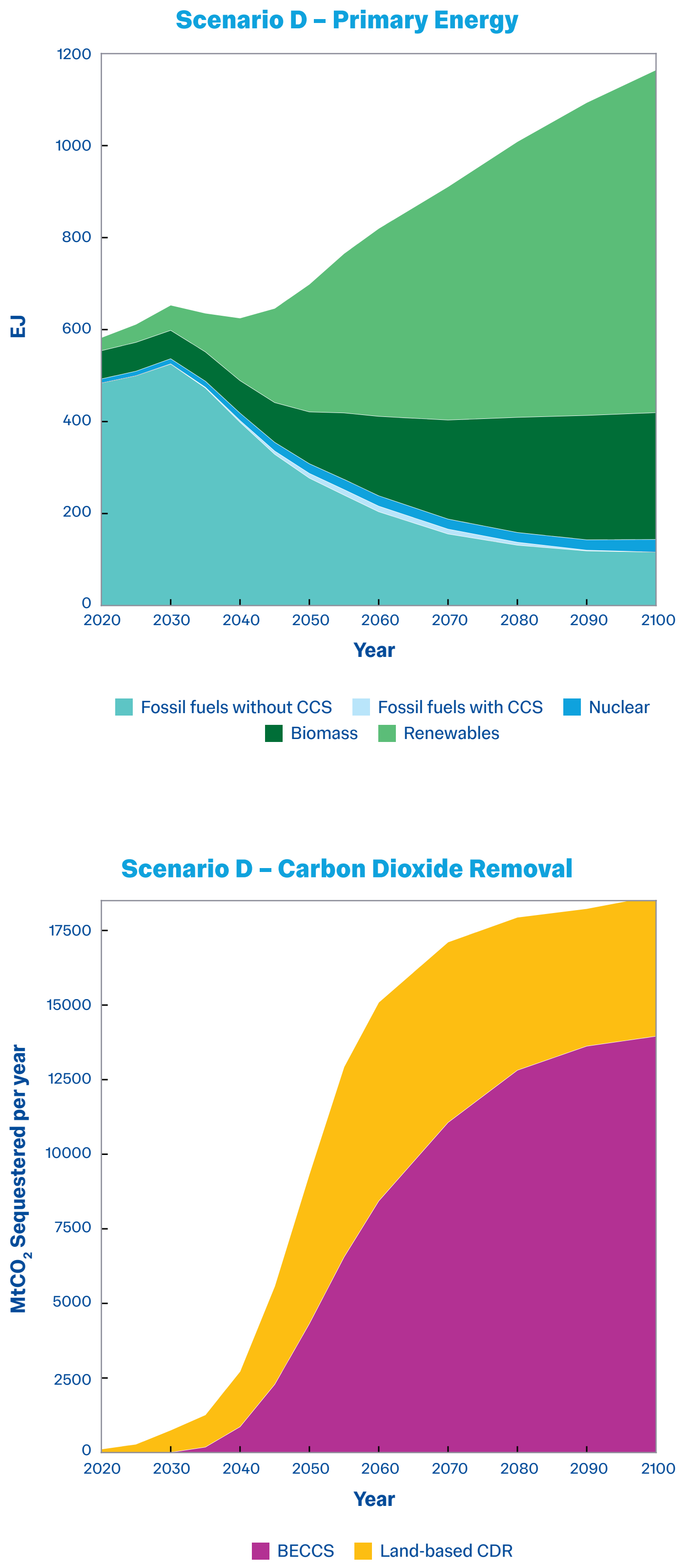


Figure 5. Scenario D - “Slow Transition” primary energy demand (top) and Carbon Dioxide Removal (bottom). The top panel illustrates a high- energy future, where fossil fuels have a considerable contribution to the energy mix for an extended period. The bottom panel shows the Carbon Dioxide Removal (CDR) required to compensate for delayed decarbonisation which hinges largely both on Biomass with Carbon Capture and Storage (BECCS) and land-used based removals like (e.g., reforestation).

2.5 Summary

Across all scenarios, achieving net-zero emissions requires both deep mitigation and some level of CDR. However, the timing and scale of CDR deployment vary significantly. In Scenarios A and C early mitigation efforts and efficiency measures reduce the need for large-scale removals, whereas Scenarios B and D reflect higher energy demand, necessitating extensive deployment of engineered removals such as BECCS and DACS, as well as land-based sequestration later in the century. These variations highlight the critical role of early mitigation in reducing long-term reliance on large-scale removal solutions.

Another key differentiator across scenarios is the extent of climate overshoot. In Scenario D, where the transition to clean energy is delayed, greenhouse gas concentrations rise significantly before being drawn later in the century. This delayed action necessitates not only large-scale CDR but also heightened adaptation efforts, as prolonged exposure to elevated temperatures may cause irreversible ecological and socio-economic consequences. The risks associated with climate overshoot emphasize the importance of integrating biodiversity into planning and implementing effective land-use strategies to ensure that mitigation efforts do not exacerbate environmental degradation.

A major factor shaping these pathways is primary energy demand, which refers to the total amount of energy extracted from natural resources before any conversion into electricity, fuels, or other usable forms. The scale of this demand varies depending on the pace of energy transitions, efficiency improvements and technological deployment. Scenarios A and C emphasise lower energy demand, achieved through structural efficiency measures, technological advancements and behavioural shifts that reduce overall consumption. In contrast, Scenarios B and particularly Scenario D reflect high-energy demand futures, where industrial growth and economic pressures drive an expansion in energy use. These differences in energy demand trajectories directly impact the required scale of CDR, land use, and the feasibility of different decarbonisation strategies. Lower energy demand pathways allow for faster emission reductions with less reliance on removals, while high-energy demand futures require more extensive technological interventions to reach net zero.

The scenario analysis demonstrates the possible variety of pathways to net zero that exist, each with different implications for technology deployment, carbon removal and land use. However, regardless of the scenario, certain key elements remain critical to achieving deep decarbonisation. The following sections examine these elements in greater detail. The following section explores the full range of mitigation technologies available to reduce emissions across selected sectors. This is followed by a dedicated discussion on CDR, assessing the role of both engineered and nature-based removal solutions, their trade-offs, and their scalability. Given the land-use and environmental implications of large-scale mitigation and CDR deployment, the paper then turns to biosystem interactions, considering the effects of decarbonisation strategies on biodiversity and ecosystems. Finally, the paper addresses carbon accounting and financing mechanisms, which are essential for mobilizing investment, ensuring transparency and tracking progress towards net zero.

By integrating these dimensions, this paper provides a comprehensive view of how different pathways to net zero can be navigated, weighing the trade-offs and opportunities that come with varying approaches to mitigation, removal and energy system transformation.

3. Technological Solutions to Emissions Reductions

All the scenarios above project different energy demand increases, each requiring a unique set of technologies to transform the energy system and a corresponding scale and approach for Carbon Dioxide Removal (CDR). These options vary across sectors, as each presents distinct decarbonisation challenges. This section focuses on the current and emerging mitigation options available for decarbonising the transport sector, as transport is one of the most challenging sectors to decarbonise, requiring a combination of technological advancements, policy interventions, financial investment, and behavioural shifts.

The decarbonisation of transport is a complex challenge, requiring a nuanced understanding of the technologies, systems, and policies that underpin mobility. Transport is a major consumer of primary energy, consistently accounting for at least 12% of total primary energy demand across all the scenarios presented above. It also contributes significantly to global emissions, with the International Transport Forum (ITF) estimating that transport accounted for 23% of global CO_2 emissions in 2020, with road freight being the largest emitter [4]. The sector's heavy reliance on fossil-based fuels, extensive energy demands, and long asset lifetimes create significant decarbonisation hurdles, making it one of the most difficult sectors to transition to net zero.

In addition to its emissions intensity, transport poses unique challenges for carbon accounting and mitigation. Emissions from road, rail, aviation, and maritime shipping often fall under Scope 3 emissions, making accurate tracking and reduction efforts more complex. The sector's fragmented and global nature further complicates uniform decarbonisation efforts, as different regions and transport modes require distinct technological, policy, and financial interventions. Overcoming these challenges requires an integrated approach that combines electrification, alternative fuels, efficiency improvements, and behavioural shifts.

Given the sector's role in shaping future energy demand, decarbonising transport is pivotal to achieving net-zero goals. This section examines the current and emerging mitigation strategies for reducing emissions from transport, illustrating how scenario analysis and systems thinking can be used to support sector-specific decision-making. By analysing mitigation technologies and their trade-offs, this discussion also provides broader insights into how different mitigation pathways can be designed for other hard-to-abate sectors.

Decarbonising the transport sector involves three critical and interlinked components: the transport technologies that directly power vehicles and vessels, the energy production and fuel supply systems that provide the fuels or electricity they consume, and the supporting infrastructure that enables their deployment. While technological advancements in electric, hydrogen, and alternative fuel-based transport are essential, scaling these solutions requires significant investment in infrastructure, such as charging networks, hydrogen refuelling stations, and high-speed rail links. The integration of these three elements is essential for achieving deep decarbonisation in transport.

These components, vehicle and fuel technology, energy supply, and infrastructure, are not unique to transport but are common across other high-emission sectors such as industry and buildings. In heavy industry, for example, decarbonisation requires low-carbon process technologies (e.g., hydrogen-based steelmaking), clean energy inputs, and infrastructure for CO_2 transport and storage. Similarly, in the building sector, electrification relies on heat pumps, clean electricity, and grid infrastructure upgrades. While each sector presents sector-specific challenges, the interplay between technology, energy supply, and infrastructure is a recurring theme in achieving net-zero emissions across multiple industries.

By addressing both transport technologies and energy production, a comprehensive decarbonisation strategy can optimise emissions reductions across the entire mobility value chain. Our research investigates the interplay between transport technologies and energy production across three key sectors: heavy goods vehicles (HGVs), aviation, and maritime. We assess decarbonisation options for each sector, considering their energy density, GHG emissions impact, infrastructure compatibility, scalability, and resource demand. Using radar charts, we provide a comparative analysis of technologies within each sector, offering insights into their relative strengths and limitations.

The study also evaluates the systemic challenges posed by the energy production and fuel supply chains, such as renewable energy integration, carbon capture, and the scalability of alternative fuels. By bridging the gap between these two components, our research identifies pathways for achieving net-zero emissions in the transport sector.

> Decarbonising a sector like transport involves vehicle and fuel technology, energy supply and infrastructure.

3.1 Decarbonisation technologies for the transport sector

3.1.1 Heavy Goods Vehicles (HGVs)

Heavy goods vehicles (HGVs) play a critical role in global road freight transport, which has seen significant growth in energy consumption, with a 50% increase between 2000 and 2015 and projections indicating a further 70% rise by 2030 [5]. The transport sector, responsible for 24% of global CO_2 emissions from fuel combustion, highlights road freight as a major contributor [6,7]. In the UK, HGVs accounted for 16% of transport-related emissions in 2019, underscoring the challenge of decarbonising a sector that has seen only a 3% reduction in GHG emissions since 1990 [8]. Despite plans to phase out sales of medium-sized diesel HGVs by 2035 and larger HGVs by 2040 [8], long-haul HGVs remain difficult to decarbonise due to high costs, infrastructure gaps, and the lack of supportive policies [9].

Several low-carbon technologies offer potential solutions, each with unique benefits and limitations. Battery electric vehicles (BEVs) are well-suited for short-haul operations, offering approximately 60% GHG savings when powered by the UK's renewable energy mix, but are constrained by limited range and payload [10]. Fuel cell electric vehicles (FCEVs) provide higher energy density and scalability for long-haul freight, achieving up to 90% emissions reductions with renewable hydrogen, though they depend heavily on infrastructure development and policy support [11]. Alternative fuels such as liquefied natural gas (LNG) and biomethane are also viable options. While LNG can reduce tank-to-wheel emissions, methane leakage undermines its overall carbon savings. Biomethane, particularly when produced from organic waste, achieves up to 94% GHG savings but is limited by supply constraints and competition with other sectors [12, 13].

A comparative analysis of these technologies, summarized in Table 2, highlights their operational performance, emissions savings, costs, and commercialization levels. BEVs are most suited to urban mobility due to their short range, while FCEVs and LNG show promise for long-haul freight, with the latter already benefiting from partial commercialization. Biomethane remains a short-term solution, offering strong emissions reductions but facing scalability issues. These findings emphasize the importance of tailored policies and investments to address the distinct challenges of each technology and accelerate the transition to a zero-carbon HGV fleet. These findings can be further categories into two key areas, the technologies themselves and the energy systems required to support them, as outlined below:

- **Technologies:** BEVs offer significant emissions reductions for short-haul operations but are constrained by limited energy density and range. FCEVs provide better scalability for long-haul mobility but require substantial hydrogen infrastructure development. Transitional fuels like biomethane and LNG offer moderate emissions reductions but face challenges with methane leakage and scalability.
- **Energy Systems:** Electrification and hydrogen production are critical for decarbonising HGVs. Renewable electricity and green hydrogen must be scaled to meet the sector's energy demands, supported by investments in charging and refuelling infrastructure.

3.1.2 Aviation

The aviation sector, responsible for 2% of global emissions, presents a unique challenge in decarbonisation due to its reliance on high-energy-density jet fuels and its significant non-CO_2 warming effects, such as contrails and ozone formation, which contribute an additional 4.9% to anthropogenic warming [14].

While operational improvements yield incremental efficiency gains, substantial emissions reductions require alternative low-carbon fuels. Among these, synthetic hydrocarbons, produced via Fischer-Tropsch synthesis, show significant promise as drop-in replacements for fossil jet fuels, compatible with existing infrastructure and capable of reducing lifecycle emissions when produced with renewable energy. However, stringent certification requirements and production costs remain barriers to large-scale adoption [15].

Future propulsion technologies, such as hydrogen and power-to-liquid (PtL) fuels, offer long-term potential for aviation decarbonisation. PtL fuels are synthetic liquid fuels produced from renewable electricity, water and captured CO_2, making them a promising drop-in alternative to conventional jet fuel. Hydrogen, despite its zero emissions at the point of use, faces significant challenges in energy density, infrastructure redesign, production scalability and safety considerations related to flammability and combustion risks.

PtL fuels, produced using green hydrogen and CO_2 captured from the atmosphere, can reduce emissions by up to 90% compared to fossil jet fuel, but their resource-intensive production requires substantial increases in renewable electricity generation and storage capacity.

Biofuels, although more mature technologically, are constrained by feedstock limitations and blending requirements, achieving only modest emissions savings. These trade-offs are highlighted in Table 3, which compares low-carbon aviation fuels across environmental impact, resource demand, scalability, and feasibility metrics.

- **Technologies:** PtL fuels deliver up to 90% GHG reductions when produced using renewable energy but face limitations in resource demand and scalability. Biofuels, while compatible with existing systems, are constrained by feedstock availability and blending requirements. Hydrogen offers zero emissions at the point of use but requires extensive infrastructure changes and presents storage challenges.
- **Energy Systems:** Decarbonising aviation relies on scaling PtL fuel production through renewable electricity and direct air capture of CO_2 emissions. Hydrogen production and storage systems must also be developed to enable long-term emissions reductions.

Table 2. Comparative analysis of alternative technologies for heavy goods vehicles (HGV's)

	BEVs	FCEVs	LNG	Biomethane
Operational Performance	Low score due to short range, limited payload, and long charging times.	Superior vehicle efficiency, comparable refuelling times and driving range to diesel.	Similar refuelling times as FCEVs but lower efficiency and reduced range due to cryogenic tanks.	Similar performance to LNG, but lower range when in compressed form.
Carbon Saving Potential	GHG emissions depend on electricity mix and battery production. Approx. 60% savings with UK mix, improves with renewables.	GHG savings dependent on hydrogen production (renewable hydrogen ~90% savings).	Not a long-term low-carbon solution. Offers some CO_2 reductions compared to diesel but remains a significant GHG source.	Up to 94% GHG savings using waste-based biomethane. Reduced emissions from organic waste processing.
Total Cost of Ownership	High upfront capital cost. TCO depends on policy frameworks and technology advancements.	TCO depends on infrastructure maturity. Likely cost-effective by 2030s with scale-up.	Economically viable in the short term due to lower fuel cost and duty rates. Payback period 15 months to 8 years. Long term viability depends on methane regulations and carbon pricing.	Economically viable in short term. Higher TCO if fuel is transported via road rather than pipelines.
Level of Commercialisation	Limited commercialisation for long-haul transport. Only practical for short-haul delivery.	Currently in demonstration phase, dependent on government support for hydrogen infrastructure.	Commercialisation is in place with ready access to refuelling stations, but carbon savings are insufficient.	Currently available but supply is limited due to competition from other sectors. Short-term option for decarbonisation.

Table 3. Comparative analysis of low-carbon technologies for aviation

Fuel type	Environmental impact	Resource Demand	Scalability & Feasibility
Biofuels	Modest CO_2 savings, reduced when blended with kerosene, variable life-cycle impacts	Limited UK feedstock (under 20% of aviation demand), competition with land use	Limited scalability, existing blending infrastructure available
Power-to-Liquid (PtL)	3-10 times lower emissions than fossil jet fuel (with renewable energy & CO_2 capture)	Requires significant increase in low-carbon electricity generation	Currently not produced at scale, needs technological advancements
Hydrogen	Zero emissions at point of use, depends on production method	Requires significant low-carbon electricity capacity, storage and transport challenges	Requires major infrastructure redesign, scalability limited by energy density
Ammonia	Lower efficiency than hydrogen, but lower production emissions	Established infrastructure, but requires renewable energy for production	Easier to store and transport than hydrogen, scalability depends on production capacity

Table 4. Comparative analysis of low-carbon technologies for maritime

Fuel type	Energy Density	GHG Emission Reduction Potential	Infrastructure Compatibility	Production Cost	Supply Chain Efficiency
Hydrogen	Low	High (zero emissions)	Requires significant overhaul	High	High
Ammonia	Moderate	High (zero emissions)	Moderate (existing infrastructure)	Moderate	Moderate
Methanol	Low	Moderate (depends on feedstock)	High (compatible with existing systems)	Moderate	Moderate
Synthetic Hydrocarbons	High	Moderate (depends on feedstock)	Very high (drop-in replacement)	High	Low

3.1.3 Maritime

The maritime shipping sector, responsible for transporting 80% of global trade by volume, is a critical component of the global economy and a significant contributor to greenhouse gas (GHG) emissions, accounting for approximately 2.8% of total global emissions. Larger vessels, like container ships and bulk carriers, dominate fuel consumption and emissions, particularly on long-haul routes. Currently, the sector relies heavily on high-sulphur fuels such as heavy fuel oil (HFO) and marine diesel oil (MDO), with LNG providing limited alternatives. Regulatory measures, including the International Maritime Organization’s (IMO) sulphur content limits and the Energy Efficiency Design Index (EEDI), aim to curb emissions, but achieving the IMO's 2050 target of a 50% GHG reduction will require a transition to low-carbon fuels and technologies.

Future maritime decarbonisation will depend on a mix of technologies and fuels, as highlighted in Table 4. Synthetic hydrocarbons stand out for their high energy density and compatibility with existing infrastructure, offering short-term decarbonisation potential. Ammonia and methanol present scalable alternatives with moderate infrastructure requirements, though ammonia’s lower energy density and safety issues and methanol's efficiency challenges require careful consideration. Hydrogen, while promising zero emissions, demands significant investment in production and refuelling infrastructure, as well as solutions to its low energy density for long-haul routes. These trade-offs underscore the need for a tailored portfolio approach to maritime fuels, balancing emissions reductions, operational feasibility, and infrastructure compatibility.

- **Technologies:** Synthetic hydrocarbons and ammonia provide scalable options for decarbonising maritime transport, though ammonia's lower energy density requires careful consideration. Methanol offers stronger compatibility with existing systems but is less efficient. Hydrogen, while promising for zero emissions, faces challenges with energy density and infrastructure.
- **Energy Systems:** Investments in ammonia and methanol production, coupled with renewable energy, are essential for maritime decarbonisation. Infrastructure for hydrogen production and storage must also be expanded to support long-term transitions.

3.2 Scenario-Driven Pathways for Transport Decarbonisation

Based on the radar charts for the HEVs, aviation, and maritime sectors (Figure 6), the following insights can be drawn:

1. **HEVs:** Biomethane demonstrates strong performance in GHG emissions reduction and infrastructure compatibility, though it faces challenges in scalability and resource demand. FCEVs excel in emissions impact but require advancements in energy density and scalability.
2. **Aviation:** PtL fuels stand out for their emissions reductions but face scalability and resource challenges. Biofuels are limited by feedstock constraints, while hydrogen offers a zero-emissions solution requiring significant infrastructure overhaul. However, given the difficulty of fully eliminating CO_2 emissions from aviation, particularly due to non-CO_2 effects and lifecycle emissions, residual emissions will still need to be addressed through CDR. Additionally, CO_2 utilisation plays a role in PtL fuel production, linking the transport sector to broader decarbonisation strategies explored later in the paper.
3. **Maritime:** Synthetic hydrocarbons and ammonia offer scalability and compatibility, though ammonia's lower energy density requires optimisation. Methanol provides compatibility with existing systems but is less efficient. Hydrogen remains a long-term solution with infrastructure and energy density challenges.

These insights underscore the need for a portfolio approach to decarbonisation. No single technology can address the diverse demands of transport sectors. Instead, a combination of solutions tailored to each sector's needs will be essential. Balancing emissions reductions, resource demands, infrastructure compatibility, and scalability will require coordinated regulatory and infrastructural investments across all transport modes. This is where the use of scenario-analysis can support decision-making, helping to address trade-offs between different decarbonisation strategies and their broader system-wide impacts.

The choice of transport decarbonisation strategies depends on the broader energy system trajectories, which is shaped by different scenario pathways as shown in Section 2. Scenario pathways provide insights into possible futures, highlighting how energy demand, technology adoption, and policy choices interact to influence transport sector emissions. Some scenarios prioritise rapid technology deployment, while others rely on efficiency and incremental improvements – each requiring different levels of infrastructure investment and regulatory support.

Scenario A and C from Section 2 prioritise efficiency and lower energy demand. The two scenarios focus more on incremental improvements, behavioural shifts, and policy incentives rather than large-scale infrastructure

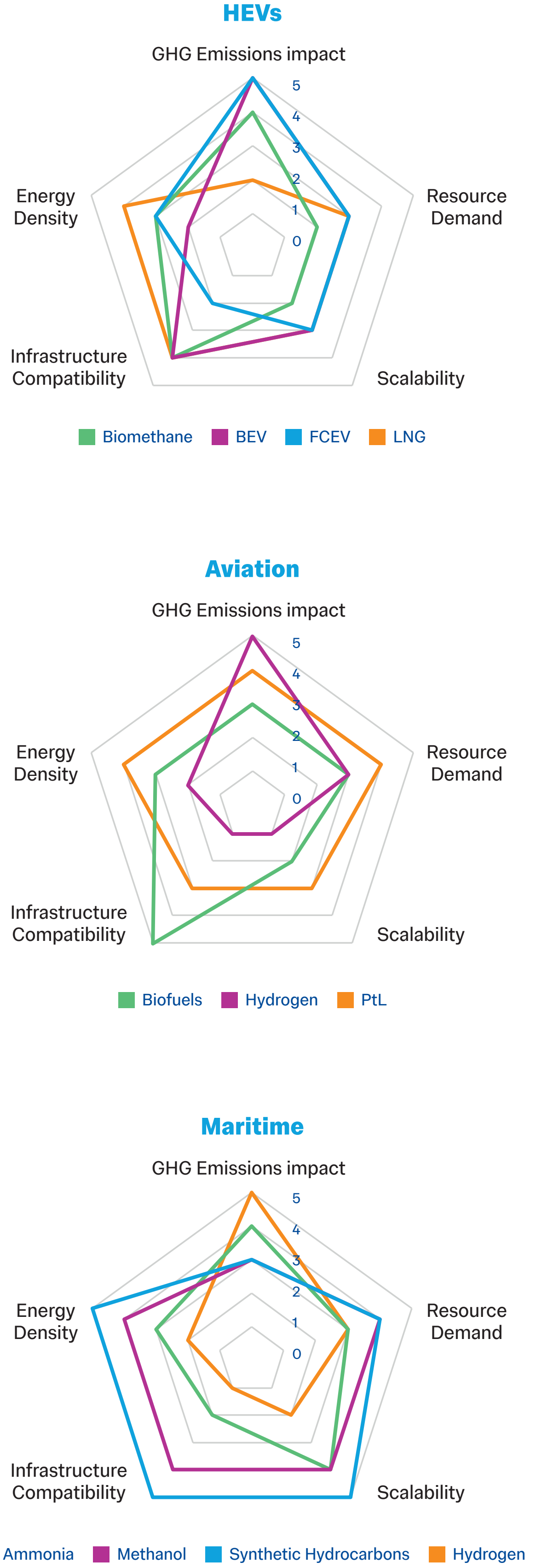


Figure 6. Comparative evaluation of low-carbon fuel and propulsion technologies for Heavy Good Vehicles (HGVs), aviation and maritime sectors. The radar charts assess different fuel options across five key criteria: GHG emissions impact, energy density, infrastructure compatibility, scalability, and resource demand.

investments. In these pathways, efficiency improvements and fossil fuel with CCS integration (Scenario A) play a central role, reducing the need for aggressive technological overhauls in transport.

In contrast, Scenario B and D, with their higher energy demand and rapid decarbonisation, require substantial innovation deployment to sustain a large-scale shift towards electrification and alternative fuels. These scenarios necessitate major policy support for infrastructure investments, such as widespread charging networks and hydrogen refuelling stations. Scenario D, in particular, represents a high-intensity energy transition, where non-biomass renewables expand aggressively, requiring coordinated policies to manage the scale-up of transport decarbonisation technologies alongside broader energy system transformations.

- **Scenario A:** relies on gradual energy demand reduction through efficiency improvements and behavioural shifts, avoiding large-scale technological overhauls. Fossil fuels remain in use with CCS, meaning transport decarbonisation progresses slowly, with limited electrification or hydrogen adoption. Freight and logistics probably continue relying on conventional fuels, but efficiency policies help curb emissions. The reliance on land-based removals for CDR may limit large-scale biofuel expansion, creating trade-offs between decarbonisation and biodiversity.
- **Scenario B:** follows a high-energy demand pathway, requiring rapid electrification and alternative fuel deployment to phase out fossil fuels early. Hydrogen refuelling and charging infrastructure must be scaled quickly, particularly for heavy-duty transport and freight corridors. Unlike other scenarios, DAC is introduced mid-century, limiting land-based removals and reducing biofuel dependency. This shift enables long-term energy diversification but requires extensive upfront investments in infrastructure and policy support.
- **Scenario C:** has the lowest energy demand, relying on aggressive fossil fuel phase-out and deep efficiency measures to achieve emissions reductions. This implies that transport would be primarily electrified, while freight and logistics shift toward multimodal efficiency improvements. BECCS becomes the dominant removal strategy rather than land-based removals, reducing land competition leaving more room for bioenergy supply chains.
- **Scenario D:** sees the highest energy demand, requiring large-scale alternative fuel deployment alongside continued fossil fuel use. This scenario struggles with fossil fuel phase-out, making decarbonisation highly reliant on large-scale removals. The transport industry probably decarbonises under a portfolio of various options including electrification and maintaining the status quo in some instances. Unlike Scenario B, DAC is not deployed, meaning land-based removals and BECCS must scale aggressively, raising concerns over land availability, biodiversity loss, and food security.

3.3 Addressing Residual Emissions through Carbon Dioxide Removal

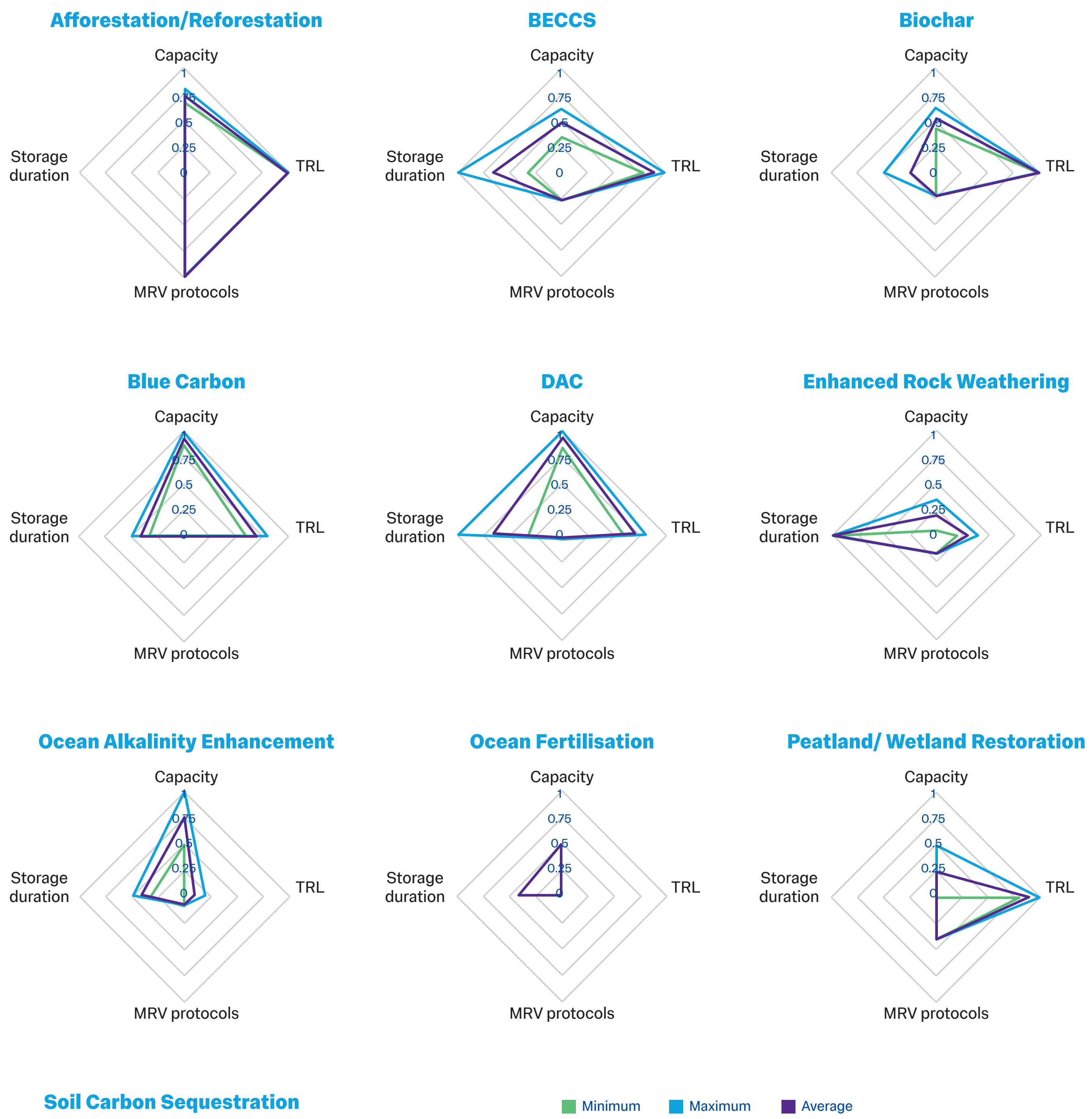
Achieving net zero requires a combination of emissions reductions and Carbon Dioxide Removal (CDR) to help offset residual emissions that are hard-to-abate. This applies at a country level and for individual companies. Existing CDR methods can be broadly categorized into nature-based solutions (NBS) and engineered solutions, each with distinct advantages, limitations, and roles within a net-zero strategy.

NBS solutions include afforestation/reforestation (AR), biochar, enhanced rock weathering (EW), peatland and wetland restoration, soil carbon sequestration (SCS), ocean alkalinity enhancement, blue carbon and ocean fertilization. Engineered solutions include Direct Air Carbon Capture and Storage (DAC) and Bioenergy with Carbon Capture and Storage (BECCS).

In all scenarios presented above, CDR is a necessary component, even in those with the lowest energy demand and a complete phase-out of fossil fuels. This is because certain emissions, such as those from agriculture, industrial processes, and legacy carbon already in the atmosphere, cannot be fully mitigated through mitigation options alone. Despite differences in energy system transformation across scenarios, they all rely on varying levels and types of CDR, whether through land-based removals referring to AR, BECCS and DAC.

It is important to recognize that the scenarios explored here are based on the IPCC's AR6 scenarios, which do not fully capture the full suite of CDR technologies. Since AR6 was published, our understanding of the feasibility, scalability, and trade-offs of other CDR approaches has improved significantly, particularly regarding emerging methods such as blue carbon and different types of DAC including electrochemical DAC. Therefore, to effectively leverage all the different CDR technologies, it is essential to understand how these methods operate individually and complement one another. This section evaluates all the existing CDR options (NBS and engineered) across technological, environmental, and economic dimensions to highlight their feasibility and integration potential in tailored, region-specific carbon management strategies.

The technological dimension helps us understand the maturity, capacity and permanence of the different CDR approaches. Data was gathered across different metrics including Technology Readiness Level (TRL), global estimated CO_2 removal capacity, storage duration and number of existing Monitoring, Reporting and Verification (MRV) protocols. Figure 7 presents a comparative analysis of the parameters included in the technological dimension, the larger the area of the radar chart the better the technology scores in this dimension.



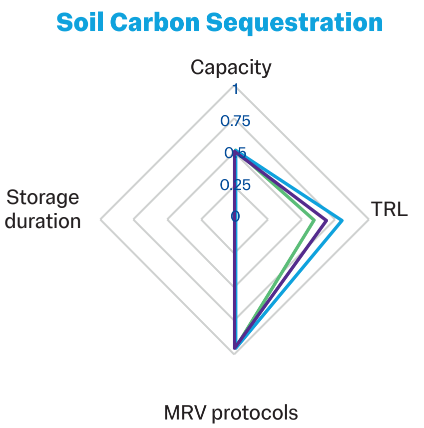


Figure 7. Comparative analysis of Carbon Dioxide Removal (CDR) approaches across the technological dimension including, capacity, storage duration, technology readiness level and number of Monitoring Reporting and Verification (MRV) protocols related metrics. Where available, minimum, maximum and average values are plotted. The larger the extension of the chart the better the technology scores in the areas evaluated.

From a technological perspective, fundamental contrasts between NBS and engineered carbon removal solutions can be observed in Figure 7. NBS like AR, peatland and wetland restoration, and SCS all show relatively high TRLs, with well-developed protocols for MRV. MRV is crucial for ensuring that carbon removal claims are credible, quantifiable and durable over time, particularly for nature-based approaches where carbon fluxes are dynamic and affected by external factors such as climate change and land-use changes. While NBS solutions can be valuable for near-term, region-specific carbon removal and ecosystem restoration purposes. Given the uncertainty around their carbon removal efficiency, NBS are better suited for smaller-scale applications and can provide essential co-benefits beyond carbon sequestration [1, 3, 4]. However, due to their storage vulnerability, and dependency on stable ecosystems, these solutions alone are insufficient to achieve large-scale, long-term carbon removal targets.

Engineered solutions on the other hand, offer higher theoretical capacities for carbon removal and longer storage duration compared to NBS, with DAC having the potential to sequester vast amounts of carbon if deployed at scale. Nevertheless, engineered solutions require substantial investment and technological development to scale-up, which poses a near-term challenge [5]. Given the urgency of climate mitigation, it is essential to deploy currently available approaches, such as NBS, while simultaneously accelerating the development and deployment of engineered solutions. A phased approach that leverages NBS for immediate action while scaling up engineered removals in parallel can ensure both near-term impact and long-term stability in carbon removal efforts. Rather than waiting for one solution to mature, integrating both approaches strategically can create a resilient and scalable CDR portfolio.

Hence, it is important to note that nature-based and engineered solutions are complementary rather than competitive. A successful carbon removal strategy must balance NBS and engineered solutions. Where NBS are maximized for immediate, localized impact and engineered solutions receive financing for long term development and large-scale deployment.

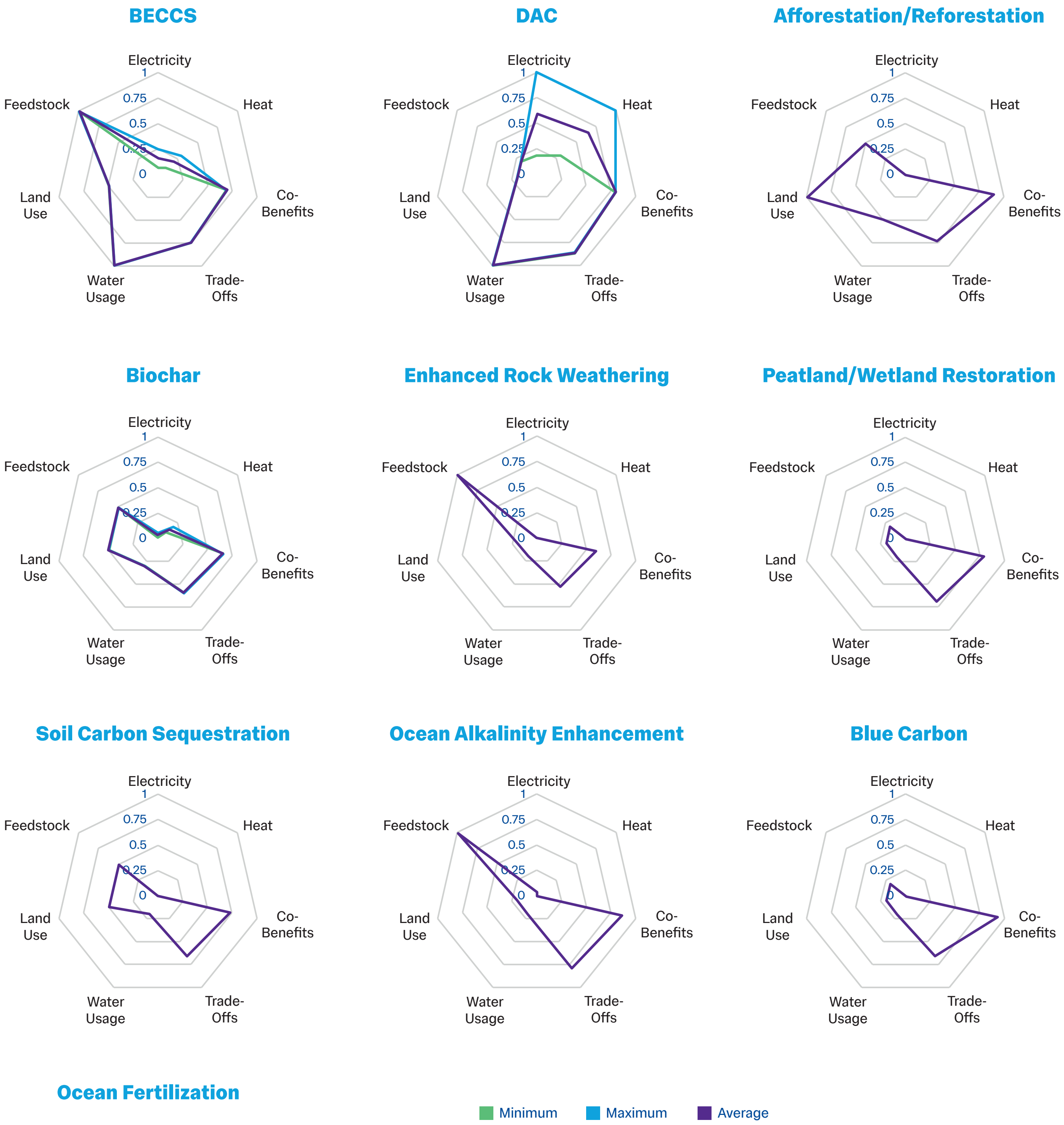
The comparison across CDR technologies for the environmental impact dimension is shown in Figure 8. The key metrics in this dimension included electricity demand, heat demand, feedstock intensity, water intensity, land usage, and number of co-benefits and trade-offs. Having an extension towards electricity, heat, feedstock, water, land usage, and trade-offs represents a “cost” to the environment, the lower the extension the better the technologies perform in the environmental impact dimension. Nevertheless, higher values for co-benefits are positive, this value was not inverted to observe the behaviour between co-benefits and trade-offs.

Engineered solutions like DAC and BECCS generally require substantial energy inputs, especially in electricity and heat. This high energy demand limits their scalability in regions without abundant, affordable renewable energy. Feedstock requirements vary widely, with technologies like BECCS and biochar depending heavily on biomass. This dependency can lead to resource competition with food production and other land uses [5-7]. Engineered solutions have minimal feedstock needs. Water usage is another critical factor; some types of DAC and BECCS are water-intensive, posing challenges in arid regions, whereas most nature-based solutions have low or moderate water demands.

NBS provide a range of co-benefits beyond carbon storage, such as increased biodiversity, which supports critical ecosystem services like pollination, water purification, and climate resilience [16, 17, 18]. These solutions also have significant socio-economic advantages, such as the potential to generate local jobs in ecosystem restoration, land management, and monitoring activities. Engineered solutions, on the other hand, while highly efficient at capturing CO_2, generally lack the ecological benefits. Their primary co-benefit lies in the potential to create jobs in the construction, operation, and maintenance of facilities. However, they often come with trade-offs such as high energy and resource demands and may have localized environmental impacts (e.g., water use or habitat disturbance) [19, 20].

Currently, there is no standardized numerical unit of comparison for evaluating the co-benefits and trade-offs between NBS and engineered solutions for carbon dioxide removal. This lack of a unified framework makes it challenging to directly compare these approaches in terms of their broader impacts beyond carbon sequestration. Given that NBS and engineered solutions should be viewed as complementary rather than competitive, developing methodologies to quantify and assess these aspects is essential. Quantifying these co-benefits and trade-offs requires new frameworks that can account for diverse metrics like biodiversity enhancement, ecosystem services, and socio-economic contributions. Such frameworks would help decision-makers design integrated strategies that maximize the synergies between NBS and engineered solutions.

Nature-based and engineered solutions are complimentary rather than competitive.



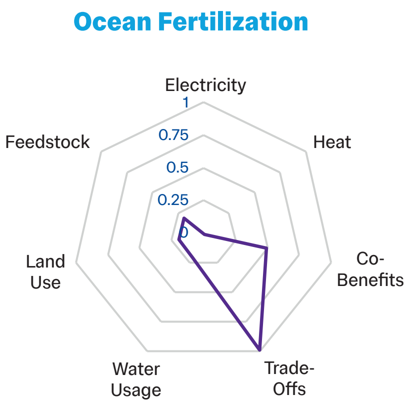


Figure 8. Comparative analysis of Carbon Dioxide Removal (CDR) approaches across the environmental dimension including, electricity demand, heat demand, feedstock intensity, water intensity, land usage, and number of co-benefits and trade-offs. Having an extension towards electricity, heat, feedstock, water, land usage, and trade-offs represents a "cost" to the environment, the lower the extension the better the technologies perform in the environmental impact dimension. Nevertheless, higher values for co-benefits are positive, this value was not inverted to observe the behaviour between co-benefits and trade-offs. For electricity and heat use normalized averages, minimums, and maximums were considered where available.

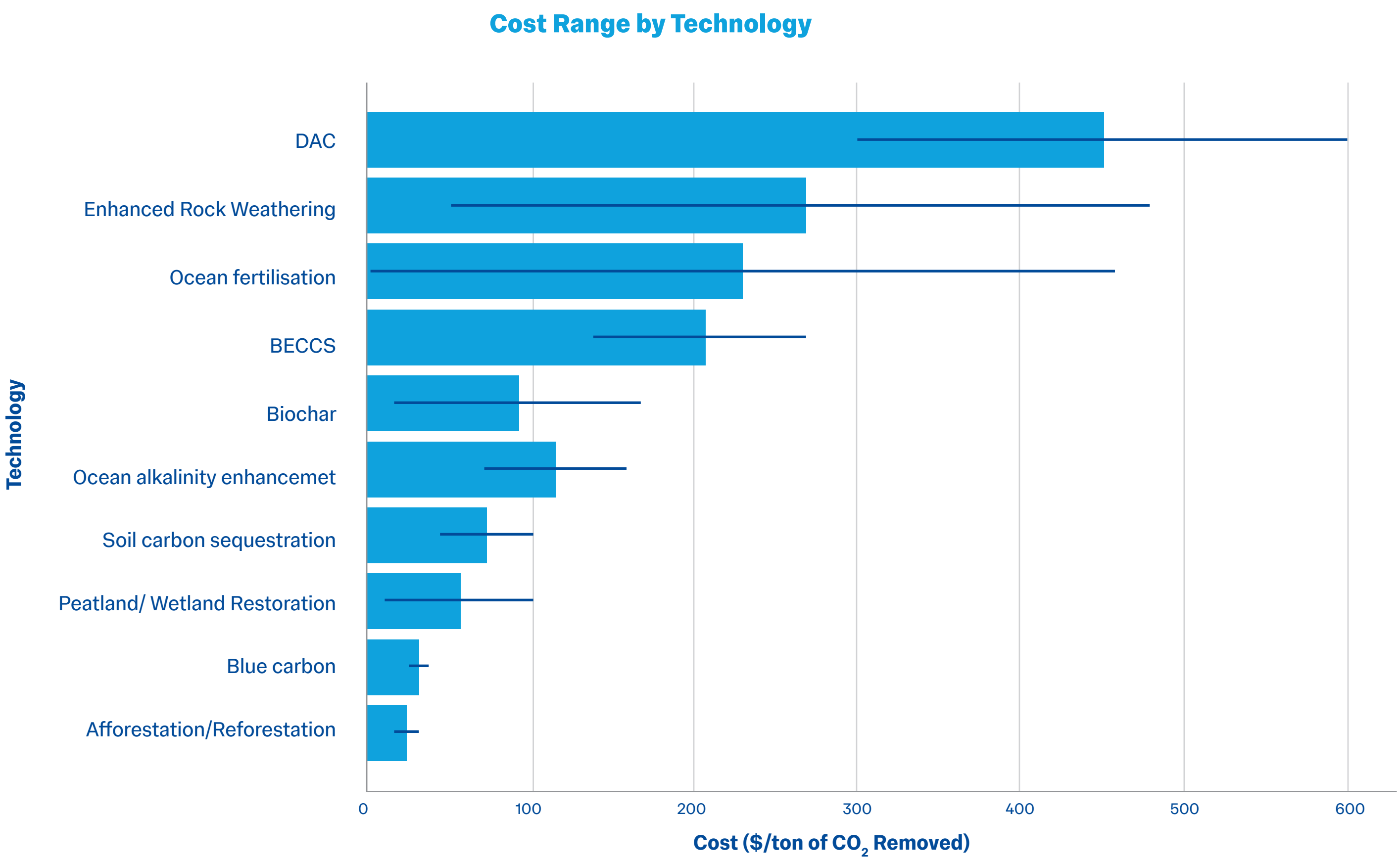


Figure 9. Current costs of different CDR approaches

There is a pronounced disparity between NBS and engineered solutions in terms of cost. (Figure 9). NBS, such as AR and blue carbon, stand out as the most cost-effective, with costs predominantly below $50 per ton of CO_2 removed. In contrast, engineered solutions like DAC and EW while offering high permanence, are significantly more expensive, with costs ranging from $250 to over $500 per ton for DAC. Intermediate options such as biochar and SCS strike a balance, presenting moderate costs with tangible benefits in certain contexts.

This cost disparity continues to highlight the need for a complementary approach to CDR deployment. NBS with their affordability and co-benefits, should play a central role in near-term climate action, especially in regions where they can be implemented at scale. Engineered solutions, despite their high costs, will be critical for achieving the deeper carbon reductions necessary for net-zero and beyond.

3.3.1 Scenario-specific deployment of CDR

Each scenario deploys carbon dioxide removal (CDR) in varying proportions, reflecting different assumptions about energy demand, mitigation strategies, and technological reliance. The differences in CDR deployment percentages are crucial, as they shape the land-use footprint, infrastructure requirements, and the feasibility of long-term carbon neutrality. Some scenarios (e.g., Scenario A and C) prioritize land-based CDR, whereas others (e.g., Scenario B and D) incorporate a mix of engineered and nature-based solutions, each with distinct trade-offs.

- **Scenario A:** Deploys the lowest overall energy demand and relies heavily on land-based removals, with approximately 75% of its total CDR coming from afforestation and soil carbon sequestration. The remaining CDR comes from BECCS (~25%), and notably, DAC is not deployed. This reflects a pathway that prioritizes lower economic and resource costs but maintains some level of fossil fuel use with CCS, which still requires balancing through removals. The strong reliance on land-based removals raises concerns about long-term sequestration stability, especially under climate-induced stressors such as drought or deforestation.

Box 2: Comparing Nature-Based and Engineered Carbon Removal Solutions

Nature-Based Solutions (NBS):

- Examples: Afforestation and Reforestation (AR), Peatland Restoration, Soil Carbon Sequestration (SCS), and Blue Carbon.
- **Strengths:**
  - Effective for near-term, localized carbon removal.
  - Provide substantial co-benefits, such as biodiversity enhancement, improved soil health, water regulation, and ecosystem restoration.
- **Limitations:**
  - Capacity constraints: Limited scalability to meet long-term carbon removal needs.
  - Vulnerability: Storage is susceptible to environmental factors like drought, deforestation, or soil degradation.
  - Land Use: Requires large land areas, creating competition with agriculture or urban development.

Engineered Solutions:

- Examples: DAC, BECCS, Ocean Alkalinity Enhancement, and Biochar.
- **Strengths:**
  - Scalability: Can sequester vast amounts of carbon if deployed at scale.
  - Storage Stability: Provide durable carbon sequestration options, often over geological timescales.
  - Land Efficiency: Minimal land requirements make these technologies adaptable for urban or industrial areas.
- **Limitations:**
  - High Energy Demand: Substantial electricity and heat inputs are required, posing scalability challenges in regions with limited renewable energy.
  - Costs and Trade-Offs: High operational costs, resource competition, and water demands limit accessibility in certain regions.
  - Fewer Co-Benefits: DAC and BECCS typically have lower ecological co-benefits.

- **Scenario B:** Represents a relatively high-energy demand future with a transition away from fossil fuels towards a renewable-dominated system. While DAC is introduced in the second half of the century, it still only contributes ~20% of total removals by 2100. Instead, BECCS and biomass-based removals dominate, which presents risks of land-use pressure and resource competition. Unlike Scenario A, land-based removals remain limited, meaning this scenario relies on large-scale energy transformation but not necessarily on aggressive technological diversification for CDR.
- **Scenario C:** Features the lowest energy demand of all scenarios, with an aggressive fossil fuel phase-out. However, even with minimal fossil fuel use, removals are still required due to residual emissions from sectors like agriculture. Unlike Scenario A, which prioritizes land-based removals, Scenario C relies predominantly on BECCS for CDR, with minimal land-based removals. This shift reflects the trade-off between land competition and energy system efficiency, as lower energy demand reduces the reliance on extensive land-based solutions while maintaining a technological role for BECCS.
- **Scenario D:** Has the highest energy demand and the highest overall CDR deployment, reaching over 18 $GtCO_2$ per year by 2100. Initially, land-based removals and BECCS are deployed in nearly equal measures (~50% each by mid-century). However, post-2050, BECCS scales aggressively, reaching 14 $GtCO_2$ per year, while land-based removals level off at ~4 $GtCO_2$ per year. Notably, DAC is not deployed in this scenario, meaning it relies entirely on large-scale land-dependent removals. This raises concerns about land availability, biodiversity impacts, and food security. Scenario D represents the most extreme reliance on negative emissions, which could pose significant feasibility challenges if BECCS deployment is constrained by biomass supply, land use conflicts, or infrastructure limitations.

The varying shares of CDR across scenarios highlight key trade-offs:

- **Land-Use vs. Technological Deployment:** Scenarios that prioritise land-based removals (A and D) may face challenges in scaling due to biodiversity constraints and land competition. By contrast, scenarios that integrate BECCS (B and C) shift the burden toward sustainable bioenergy supply and infrastructure development.
- **Delayed Deployment Risks:** Scenarios that introduce DAC later (e.g., B) or omit it entirely (A and D) may struggle with long-term climate stabilisation, particularly if land-based removals fail to deliver the necessary sequestration due to climate variability or land-use constraints.
- **Residual Emissions Challenge:** Even in scenarios with low fossil fuel use (e.g., C), residual emissions from non-energy sectors (e.g., agriculture, industrial processes) still necessitate large-scale removals, reinforcing the necessity of robust CDR strategies regardless of the energy mix.

3.3.2 Evolving CDR Deployment in future IPCC Scenarios

The IPCC scenarios presented in Section are expected to be updated in future assessments, reflecting advancements in CDR technologies, land-use modelling and policy considerations. These updates are likely to result in several key shifts:

- **Greater Diversification of CDR Approaches:** Current scenarios rely heavily on land-based removals, BECCS, and DAC, because these methods are among the most developed and widely modelled carbon removal approaches. However, future iterations are expected to incorporate a broader range of technologies, including enhanced rock weathering, ocean-based removals, and hybrid land/engineered approaches.
- **Refined Land-Use Assumptions:** Future assessments may better account for land competition trade-offs and the feasibility of large-scale afforestation, leading to scenarios that emphasize alternative removals rather than over-reliance on land-based methods.
- **Improved Energy System Integration:** The interplay between energy demand and CDR will be modelled with higher granularity, potentially leading to scenarios where DAC is deployed earlier due to declining renewable energy costs, rather than being treated as a late-stage intervention.
- **Policy and Socioeconomic Considerations:** Existing scenarios primarily focused on technological feasibility, but future updates are expected to integrate policy, governance, and socio-economic dynamics more explicitly, recognizing that deployment scales will be shaped by regional policies, financing structures, and equity considerations.

The differences in CDR deployment across scenarios underscore that there is no one-size-fits-all solution to achieving net zero. While some pathways emphasise minimising energy demand and relying on land-based removals, others lean on BECCS and DAC to offset higher energy use. The challenge moving forward is to balance technological feasibility, land-use sustainability, and socio-economic factors in a way that ensures long-term carbon neutrality. As future IPCC scenario updates refine these pathways, a more nuanced understanding of CDR's role in net-zero strategies will emerge, likely expanding the portfolio of removal methods and optimising their integration with broader climate mitigation efforts.

All scenarios require CDR to manage residual emissions. A portfolio approach combining near-term deployment of nature-based solutions with longer-term scale-up of engineered CDR is essential.

4. Wider Ecosystem Services

As nations and industries pursue decarbonisation through a combination of mitigation technologies, carbon removal strategies, and energy system transformations, it is essential to consider the wider ecological consequences of these efforts since, maintaining high biodiversity is essential for ecosystem functioning (Tilman et al., 2014). While the previous sections have explored pathways to reduce and remove emissions, these strategies do not operate in isolation from natural systems. The way in which energy demand is met, land is allocated, and resources are extracted will ultimately shape biodiversity, ecosystem resilience and the ability of natural systems to continue providing essential services. Different species perform distinct roles, supporting processes such as carbon sequestration, nutrient cycling, food provision, and water purification, all of which are vital to ecosystem stability and human health [21, 22, 23, 24].

In other words, achieving net-zero emissions is not just a technical or economic challenge – it is also an ecological one. Some decarbonisation strategies, if deployed at scale, may place additional pressures on land, water, and biodiversity, potentially undermining long-term sustainability. This section explores the critical links between decarbonisation and ecosystem health, examining how different energy transitions, land-use changes, and pollution pathways influence biodiversity and natural carbon sinks. Understanding these interactions is crucial for designing net-zero strategies that enhance, rather than compromise, the planet's ecological stability.

As the world transitions towards net-zero emissions, it is crucial to recognise the interconnectedness of decarbonisation strategies across sectors and their impact on ecosystem health because actions in one sector can create ripple effects across others, influencing emissions, resource availability, and environmental trade-offs. Healthy ecosystems provide services that humans depend upon (e.g., clean air, clean water, and food). While mitigation efforts such as electrification, alternative fuels, and renewable energy deployment are central to reducing emissions, they must also be assessed for their broader ecological impacts. The extent to which these pressures materialize varies across future scenarios, as different energy demand levels and carbon removal strategies lead to distinct land-use and resource allocation trade-offs. This section explores the intricate relationship between biodiversity, decarbonisation, while also considering how different pathways shape ecosystem services.

Like many industry sectors, the transport sector can significantly impact ecosystems. Large areas of land are required for the development of mobility infrastructure, including power plants, transmission lines, roads, railways, and airports. These projects can significantly impact ecosystems, causing habitat loss and fragmentation, resulting in reduced biodiversity and diminished ecosystem health [25, 26, 27]. This is cause for concern, especially as previous research has shown that diverse ecosystems contribute to greater oceanic and terrestrial carbon sequestration, thus serving as an effective nature-based solution for decarbonisation (Figure 10). Land use changes that reduce biodiversity consequently diminish the capacity of ecosystems to provide this service, making the protection and restoration of biodiversity central to enhance decarbonisation efforts.

The benefit of encouraging high biodiversity also extends to the wider ecosystem. Enhanced biodiversity not only improves carbon sequestration but also supports other essential services that humanity depends on, such as energy, materials and food provisioning (Figure 10). Ecosystems with greater biodiversity are also better able to withstand disturbances, as diverse communities are more likely to include species that enhance ecosystem resilience [28, 29]. This is essential, as the transport sector is a major source of pollution that can degrade species and habitats, reducing biodiversity and its benefits. Tyre wear from vehicle use, for example, produces particles that release microplastics and toxic chemicals into the air and water systems [30]. These pollutants disrupt aquatic habitats and accumulate in the food web, affecting individual species and overall ecosystem health [31]. To address these challenges, better regulation and mitigation of the various impacts associated with the transport sector are essential. Encouraging biodiversity can not only help ecosystems recover from disturbances but also support broader environmental health by enhancing pollutant processing and ecosystem resilience.

The land-use implications of different decarbonisation scenarios play a crucial role in determining their overall impact on biodiversity and ecosystem resilience. High-energy demand scenarios (e.g., Scenario D) require extensive land conversion for renewables and biofuels, which could place pressure on existing ecosystems and lead to habitat loss. Scenarios with aggressive electrification may reduce direct fossil fuel reliance, indirectly benefiting biodiversity, but could simultaneously increase demand for rare earth minerals needed for battery production and grid expansion and so drive habitat loss. Meanwhile, slower transition scenarios risk prolonged fossil fuel dependency, increasing cumulative biodiversity loss over time.

Biodiversity is not just a passive co-benefit of decarbonisation but an active contributor to climate resilience. Scenarios that rely heavily on biofuels and BECCS must account for potential ecosystem disruptions, as large-scale monoculture plantations could degrade soil health and reduce overall carbon sequestration efficiency. On the other hand, maintaining

Figure 10. Key figure from Moffett et al. (2023) showing the comparison of how each ecosystem function category responds to increasing biodiversity. From Moffett et al. (2023), the effect sizes (Fishers Z-score, Zr) of how ecosystem function responds to increasing biodiversity. Higher values indicate a greater increase in function in comparison with other functions. Carbon sequestration was found to have a high response to increasing biodiversity, along with other ecosystem functions such as Energy and Learning and Inspiration.

diverse and healthy ecosystems strengthens resilience to climate disruptions such as floods and droughts, reducing long-term risks to both human and natural systems. This highlights the importance of designing decarbonisation strategies that integrate biodiversity protection into land-use planning, ensuring that climate and ecological goals are pursued in tandem.

The role of diverse ecosystems in mitigating risk and enhancing resilience is increasingly recognized as a key rationale for promoting economic incentives in environmental protection initiatives [32]. This is important not only for broader societal benefits but also for the private sector, especially industries such as power and mobility that rely on large, fixed assets where infrastructure is costly to replace and repair. For example, safeguarding these assets requires fostering ecosystem health, which can improve water resources [33] and reduce risks from natural disasters such as floods and wildfires [34, 35, 36]. In this context, maintaining biodiverse and healthy ecosystems around critical infrastructure emerges as a proactive and cost-effective solution [35, 37]. Beyond protecting assets, biodiverse ecosystems also contribute to pollutant processing and water regulation, making them particularly relevant when evaluating supply chain locations and their environmental impacts [38, 39]. Ultimately, integrating ecosystem health into business practices not only enhances resilience and reduces risks but also promotes a more sustainable, collaborative approach to environmental protection, benefiting both the private and public sectors in ways that extend beyond carbon sequestration.

Although all industry sectors have environmental impacts, supporting biodiversity can help to mitigate some of the effects. This can be through nature-based decarbonisation strategies as well as regulating water and air quality, potentially counteracting some of the sector's negative impacts. Furthermore, biodiversity provides a wide array of essential ecosystem services that extend beyond those related to the power and mobility sectors, playing a crucial role in supporting human well-being. Adopting sustainable practices and greener technologies that promote biodiversity conservation is therefore essential, and integrating biodiversity considerations into policy and planning can lead to more resilient ecosystems and long-term environmental benefits.

> Adopting sustainable practices and greener technologies that promote biodiversity conservation is essential.

4.1.1 Scenario-Specific Impacts on Ecosystem Services

The balance between decarbonisation and biodiversity preservation varies across future scenarios, reflecting different levels of land-use change, renewable energy deployment, and carbon removal strategies. Each scenario presents distinct trade-offs between emissions reduction and ecosystem health, highlighting the importance of integrated policy approaches that mitigate environmental risks while promoting sustainable development.

- **Scenario A:** Features a moderate energy demand reduction and a reliance on fossil fuels with CCS, which results in a relatively lower land-use footprint than high-renewable scenarios. However, this scenario relies heavily on land-based removals (75%), raising concerns about land-use change, biodiversity loss, and soil degradation (with implications for broader concerns such as agriculture). While lower total energy demand mitigates some pressures, long-term ecosystem health (and so human health and wellbeing) remains dependent on how effectively land-based CDR is managed.
- **Scenario B:** Represents a high-energy demand future with a renewable-dominated energy system. This scenario introduces a significant expansion of non-biomass renewables, which by 2100 make up 65% of the primary energy mix. While reducing fossil fuel dependency is a critical step for climate mitigation, large-scale deployment of solar and wind infrastructure may introduce land-use conflicts and biodiversity risks (potentially higher than those in Scenario A). The scenario also sees increased biomass-based removals, contributing to forest cover changes and potential ecosystem disruptions. However, with DAC deployment beginning mid-century, some of the land-use burden is alleviated, as engineered removals reduce the need for further land-intensive approaches.
- **Scenario C:** Characterised by the lowest energy demand and the most aggressive fossil fuel phase-out, this scenario minimizes ecosystem disruption associated with energy expansion. However, even with a low-energy pathway, ecosystem services remain a critical consideration, as BECCS plays a dominant role in removals. While BECCS is less land-intensive than afforestation, its reliance on biomass introduces potential risks, such as competition with food production and impacts on forest ecosystems. Compared to other scenarios, Scenario C provides a more balanced approach, where energy efficiency and sustainable land use reduce the overall environmental burden.

- **Scenario D:** Exhibits the most extreme land-use pressure due to its high-energy demand and large-scale CDR deployment. The expansion of non-biomass renewables quadruples between 2020 and 2040, requiring vast amounts of land for wind and solar infrastructure. Biomass use more than triples by 2100, increasing land stress and biodiversity concerns. Unlike other scenarios, which integrate carbon capture as part of fossil fuel mitigation, this scenario relies heavily on BECCS and land-based removals to counterbalance unabated fossil fuel emissions. By 2100, more than 18 $GtCO_2$ per year is removed through these methods, placing immense pressure on ecosystems, water resources, and land availability. This raises significant sustainability concerns, as high land conversion rates could undermine the very carbon sequestration benefits these removals are intended to achieve.

The insights drawn from these scenarios offer valuable considerations for shaping future scenario modelling and climate mitigation strategies. Our analysis adds further depth by highlighting the diverse trade-offs that must be considered when integrating biodiversity and ecosystem services into decarbonisation strategies. Understanding how land-use pressures, carbon removal strategies, and renewable energy expansion interact with ecosystem health is crucial for refining future scenario development.

Biodiversity and ecosystem services must be central considerations in net-zero pathways, as the long-term success of decarbonisation efforts depends on the stability of natural systems. The trade-offs between emissions reduction and ecosystem health vary significantly across scenarios, highlighting the need for integrated approaches that minimise land-use conflicts and prioritise sustainable development. As IPCC scenarios refine our understanding of climate mitigation strategies, future scenarios will need to account for the growing body of research on ecosystem resilience, biodiversity conservation, and the co-benefits of nature-based solutions. Achieving net-zero in a way that safeguards ecosystems will require balancing energy transition goals with biodiversity preservation, ensuring that climate action supports, not undermines, the natural processes that sustain life on Earth.

> A robust decarbonisation strategy for nations and corporates relies on effective measurement, financial mechanisms, and policy support.

5. Measuring and Financing Decarbonisation

As nations and corporations work towards net-zero emissions, ensuring environmental sustainability goes beyond emissions reductions and carbon removal – measuring progress and mobilizing financial resources are equally critical. The previous sections have explored the technological, ecological, and systemic considerations of decarbonisation strategies, emphasizing how land use, biodiversity, and carbon removal pathways interact with energy demand and mitigation efforts. However, the effectiveness of these strategies ultimately depends on how emissions are accounted for, how financial mechanisms incentivise decarbonisation, and how policy frameworks enable long-term transitions.

A robust decarbonisation strategy for nations and corporates relies on effective measurement, financial mechanisms, and policy support to drive emissions reductions across sectors. Carbon accounting methodologies play a pivotal role in providing transparency and accountability, enabling industries to track their progress towards net zero. At the same time, regulatory frameworks such as the EU Emissions Trading System (EU ETS) and financial instruments like the Carbon Border Adjustment Mechanism (CBAM) create economic incentives for businesses to decarbonise. The role of multinational corporations (MNCs) is particularly crucial, as they operate across diverse geographies and supply chains, making them both significant sources of emissions and key enablers of global climate action.

The necessity of decarbonisation spans across all modelled scenarios, yet the pathways and financial mechanisms required to achieve emissions reductions vary significantly. Scenarios with high energy demand, such as Scenario D, underscore the importance of stringent carbon pricing mechanisms and large-scale investments in low-carbon infrastructure to mitigate emissions effectively. In contrast, lower-energy demand pathways, like Scenario C, highlight how strategic efficiency improvements can reduce the reliance on heavy financial interventions while still necessitating targeted carbon removal investments. Moreover, scenarios differ in their dependency on carbon removal solutions, influencing how financing mechanisms for CDR are structured – whether through direct subsidies, market-based incentives, or integration into cap-and-trade systems.

This section explores the methodologies, policies, and financial frameworks that enable decarbonisation, illustrating how scenario-driven insights can shape future regulatory and investment strategies. By understanding the diverse financial and policy levers at play, businesses, policymakers, and investors can better align their decarbonisation strategies with emerging climate goals. The following analysis builds on these foundations to

Box 3: Carbon Accounting and Scopes

Carbon accounting methodologies classify emissions into three primary categories under the Greenhouse Gas Protocol (GHGP): Scope 1, Scope 2, and Scope 3 emissions. Each scope provides a framework for understanding and quantifying an organisation's carbon footprint based on its direct and indirect emissions.

1. **Scope 1 Emissions:** Direct Emissions: These originate from sources owned or controlled by the organisation. Examples include on-site fuel combustion in boilers, furnaces, and generators, as well as emissions from company-owned vehicles and industrial processes. Methods for calculating Scope 1 emissions involve tracking fuel usage and applying appropriate emissions factors to estimate greenhouse gas (GHG) emissions.

2. **Scope 2 Emissions:** Indirect Energy Emissions: Indirect emissions arise from the consumption of purchased electricity, heating, or cooling. These are measured using two main approaches:

a. Location-Based Method: Reflects the average emissions intensity of the grid in the region where the energy is consumed.

b. Market-Based Method: Accounts for the specific characteristics of the purchased electricity, such as renewable energy certificates (RECs) or power purchase agreements (PPAs), which reflect the environmental impact of an organisation's energy procurement strategy.

3. **Scope 3 Emissions:** Value Chain Emissions: Scope 3 represents indirect emissions resulting from activities across the value chain, including upstream activities (e.g., purchased goods, transportation, and supplier emissions) and downstream activities (e.g., product use, waste disposal). Measuring Scope 3 emissions requires extensive data collection and collaboration with supply chain partners.

Table 5: assessment of carbon accounting methods across various factors. Green denotes methods exhibiting strong performance, Yellow signifies moderate performance and red indicates methods with significant limitations.

	Spend-based	Activity-based	Hybrid	Supplier-specific	Physical unit	Production-based	Value-added/income based
Data intensive	Red	Yellow	Yellow	Red	Green	Green	Yellow
Third-party dependent	Yellow	Yellow	Yellow	Red	Green	Green	Yellow
Accounts emissions in the value	Green	Yellow	Green	Yellow	Red	Red	Red
Considers end-of-life use	Green	Red	Yellow	Red	Red	Red	Red
Operational efficiency	Red	Green	Yellow	Yellow	Green	Green	Green

assess the tools and mechanisms necessary to achieve emissions reductions while ensuring economic viability and sectoral resilience.

Carbon accounting encompasses various methods and approaches, each designed to capture different aspects of greenhouse gas (GHG) emissions. One prevalent distinction lies between spend-based, activity-based, and hybrid methods. Spend-based accounting, also known as consumption-based accounting, delves into the emissions embedded in the entire lifecycle of products, evaluating financial transactions associated with goods and services. Activity-based approaches, also known as the physical-unit method, concentrate on direct emissions from an organization's activities, often measured in relation to physical units of output. Supplier-specific methods focus on the emissions linked to individual suppliers in the supply chain, providing insights into their contributions. Hybrid methods combine elements of spend-based and activity-based approaches, offering a comprehensive perspective on both consumption-related and operation-related emissions. Other approaches include production-based accounting, which assesses direct emissions within organizational boundaries, and value-added or income-based approaches, which consider emissions in relation to economic value or income generated. Each of these methods contributes to an understanding of an organisation's carbon footprint, enabling tailored strategies for emissions reduction and sustainability.

Each method comes with its own set of advantages and challenges, and the choice depends on an organization's specific goals, data availability, and the aspects of emissions it wishes to address. Organizations often use a combination of methods to gain a more comprehensive understanding of their carbon footprint. An assessment using the traffic light system highlighting green as having strong performance in that aspect and red meaning it has significant limitations in that aspect (Table 5).

Another key consideration involves physical and financial accounting. Physical accounting measures emissions in actual quantities, such as metric tons of CO_2, while financial accounting assesses the monetary costs associated with emissions. Beyond these distinctions, additional concepts like carbon intensity, carbon offsetting, and life cycle assessment contribute to a holistic understanding of emissions. Carbon intensity evaluates the amount of CO_2 emitted per unit of economic output. Carbon offsetting involves investing in projects to offset emissions, contributing to carbon neutrality. Life cycle assessment provides a comprehensive view by evaluating the environmental impacts of a product or service throughout its entire life cycle.

Furthermore, the choice between location-based and market-based reporting in Scope 2 emissions accounting is significant. Location-based reporting considers the average emissions intensity of the grid where the facility is located, while market-based reporting allows organizations to account for emissions based on the characteristics of the electricity they purchase.

These diverse methodologies offer flexibility for organizations based on their goals, industry standards, and regulatory requirements. The array of carbon accounting methods, spanning spend-based, activity-based, hybrid, supplier-specific, physical-unit, production-based, and value-added or income-based approaches, primarily centre on evaluating both Scope 1 and Scope 2 emissions. These methods comprehensively address the direct emissions from sources owned or controlled by an organization (Scope 1), as well as the indirect emissions associated with purchased electricity (Scope 2). For example, spend-based approaches consider financial transactions related to electricity consumption, and activity-based methods may assess indirect emissions linked to energy use in production processes.

The effectiveness of carbon accounting methodologies will depend on the level of ambition in a given decarbonisation scenario. High-ambition scenarios, such as Scenario C, necessitate highly precise accounting frameworks to track decarbonisation progress, with an increased role for digital MRV technologies and standardized reporting. Conversely, slower transition pathways (Scenario A) may rely more on spend-based accounting due to weaker regulation and slower policy intervention. As new mitigation technologies emerge—such as synthetic fuels and hydrogen – ensuring accurate lifecycle emissions tracking will be essential for determining their real carbon savings.

However, the distinctive nature of Scope 3 emissions, which comprise indirect emissions throughout the value chain, necessitates nuanced considerations. Scope 3 encompasses various categories, including purchased goods and services, transportation, and waste generation, extending beyond an organization's direct operational control. While spend-based, activity-based, and production-based methods are foundational to Scopes 1 and 2, organizations can adapt and tailor these approaches to gain insights into specific aspects of Scope 3 emissions. For instance, spend-based methods extend their focus to understanding the emissions embedded in the entire lifecycle of purchased goods and services within Scope 3. Improving Scope 3 estimates also requires greater data sharing and transparency between companies within the same value chain, enabling more accurate tracking of upstream and downstream emissions.

Recognizing the diversity and indirect nature of Scope 3 emissions, organizations often employ a combination of methods to ensure a comprehensive understanding of their broader environmental impact throughout the value chain. This holistic approach allows for a nuanced examination of both direct and indirect emissions, supporting organizations in their efforts to develop effective carbon reduction strategies and contribute to broader sustainability goals.

5.1 Best Practices and Tools for Carbon Accounting

Advancements in carbon accounting tools and frameworks have made it possible to achieve more precise and actionable insights into emissions. Key methodologies include:

1. **Life Cycle Assessments (LCA):** LCA evaluates the environmental impact of a product or service throughout its lifecycle, from raw material extraction to disposal. This comprehensive approach enables organisations to identify emissions hotspots and develop targeted mitigation strategies.

2. **Emissions Inventories:** Organisations compile emissions inventories to quantify emissions across Scope 1, 2, and 3. Data is standardised using emissions factors derived from established environmental agencies and inventories.

3. **Data-Driven Approaches:** Software solutions like Persefoni, Watershed, and Tableau enhance emissions tracking through real-time data integration, predictive analytics, and automated reporting. IoT sensors and blockchain technology further enable granular data collection and validation.

4. **Hybrid Methods:** Combining spend-based, and activity-based approaches offers a more holistic view of emissions across operational and consumption-related activities. For example, spend-based methods analyse financial transactions to estimate emissions, while activity-based methods focus on direct emissions linked to specific organisational processes.

These tools and practices allow organisations to enhance transparency, improve reporting accuracy, and align their carbon accounting efforts with international standards.

5.2 Policy, Regulation, and Commercial Drivers for Decarbonisation

Achieving decarbonisation at scale relies heavily on effective policies, regulatory frameworks, and commercial incentives that align global industries with climate goals. A key regulatory tool is carbon pricing, either through a carbon tax or market. The European Union Emissions Trading System (EU ETS) represents one of the most advanced cap-and-trade systems globally, regulating over 15,000 installations and accounting for approximately 40% of the EU's GHG emissions. By setting a cap on emissions and allowing tradeable allowances, the EU ETS creates a robust carbon pricing mechanism that incentivises industries to invest in low-carbon technologies. Recent reforms include steeper annual reductions in emission caps and the introduction of the Market Stability Reserve (MSR) to ensure allowance scarcity. These updates align the EU ETS with the European Green Deal and net-zero ambitions, creating a stronger framework for industries to transition to sustainable practices.

To address the risk of firms relocating their emissions to non-regulated regions, the introduction of the Carbon Border Adjustment Mechanism (CBAM) will seek to prevent carbon leakage by levying a carbon price on imports from regions with less stringent climate policies. A CBAM ensures that imported goods bear a cost reflective of their carbon footprint, incentivising industries to adopt lower-carbon practices across supply chains. For example, sectors such as steel, cement, and aluminium are particularly impacted, as they are currently high-emission industries with substantial global trade flows. By driving supply chain and industrial decarbonisation, The CBAM will aim to level the playing field for domestic producers adhering to stricter environmental regulations.

International cooperation further supports decarbonisation through mechanisms such as Article 6 of the Paris Agreement, which enables countries to trade carbon credits. This framework facilitates cost-effective emissions reductions across borders, encouraging nations to collaborate in achieving their climate targets. By allowing the exchange of credits generated from carbon removal or avoidance projects, Article 6 promotes investment in climate solutions that benefit the global community.

Financial incentives and subsidies can also play a role in advancing decarbonisation technologies. Governments worldwide have implemented initiatives such as tax credits, grants, and targeted funding to accelerate the deployment of renewable energy, energy storage, and green hydrogen production. For example, the U.S. Inflation Reduction Act (IRA) allocated substantial funding for renewable energy projects, aiming to bolster investment in clean energy technologies. Similarly, the UK's Contracts for Difference (CfD) scheme has driven down the costs of renewable energy projects like offshore wind, ensuring their commercial viability.

Lastly, growing consumer demand for sustainable products and increasing investor pressure for transparent environmental, social, and governance (ESG) compliance have emerged as powerful commercial drivers. Institutional investors now prioritise companies that demonstrate robust sustainability strategies, compelling organisations to integrate decarbonisation into their operations and value chains. These combined forces create a conducive environment for industries to adopt and scale low-carbon solutions, aligning their business models with a sustainable, net-zero future.

Robust carbon accounting methodologies, advanced tools, and supportive policy frameworks are vital for fostering meaningful progress in global decarbonisation efforts. By leveraging insights from regulatory mechanisms like the EU ETS, coupled with advanced carbon accounting practices such as LCA and hybrid methods, organisations can develop more effective strategies for reducing emissions. In parallel, commercial drivers and international agreements can provide the necessary financial and operational incentives to transition to a sustainable, low-carbon economy. This integrated approach ensures alignment with climate goals while addressing the complexities of emissions measurement and mitigation.

5.3 Scenario-Driven Pathways for decarbonisation financing and policy

The financial and regulatory landscape for decarbonisation is shaped by the scale and urgency of emissions reductions required under different scenarios. Scenario A, which emphasises energy efficiency and continued use of fossil fuels with CCS, suggests a world where policy mechanisms focus on making CCS cost-competitive while maintaining some level of fossil fuel reliance. In this case, financial mechanisms such as tax credits for CCS deployment and

performance-based subsidies could be central to ensuring the feasibility of continued fossil fuel use within a net-zero framework. The presence of nuclear power in 2100 within this scenario also implies a need for long-term financing strategies to sustain nuclear investments alongside other low-carbon energy sources.

Scenario B, with its high renewable energy penetration and aggressive fossil fuel phase-out, presents a contrasting financial landscape. The shift towards non-biomass renewables making up 65% of primary energy by 2100 highlights the importance of financing mechanisms that support large-scale renewable deployment, such as feed-in tariffs, green bonds, and direct subsidies for wind and solar expansion. This scenario also sees DAC emerging as a key CDR method from mid-century onwards, necessitating market-driven carbon removal mechanisms like Article 6 carbon credit trading to scale direct air capture operations.

In Scenario C, the lowest energy demand scenario, financial mechanisms would potentially prioritise efficiency-driven policies and incentives that reduce energy consumption rather than large-scale infrastructure transformations. The aggressive fossil fuel phase-out in this pathway implies that stringent carbon pricing, through mechanisms like the EU ETS and CBAM, plays a critical role in ensuring a cost-effective transition. Moreover, this scenario relies primarily on BECCS for removals, suggesting a need for targeted financing of bioenergy supply chains, alongside policies that regulate land-use pressures to balance biomass demand with food security and biodiversity protection.

Scenario D represents the most capital-intensive pathway, requiring significant financial and policy interventions to manage both high energy demand and extreme reliance on carbon removals. This scenario sees rapid expansion of renewables, tripling biomass use, and achieving more than 18 Gt of CDR per year by 2100. The scale of investment required implies a future where international carbon markets, large-scale green infrastructure funds, and public-private partnerships drive decarbonisation efforts. The reliance on BECCS as the dominant removal method necessitates financial models that integrate CDR into compliance carbon markets, ensuring stable revenue streams for large-scale removal projects. Additionally, the pressure on land use in this scenario underscores the importance of integrating biodiversity valuation into carbon financing to mitigate negative environmental trade-offs.

Across all scenarios, the evolution of carbon accounting, regulatory frameworks, and financial incentives will shape the pace and feasibility of decarbonisation. Future policy design must consider not only emissions reductions but also the economic, social, and environmental implications of different mitigation pathways. By aligning carbon accounting methodologies with sector-specific needs and refining financial tools to support both mitigation and removals, scenario-driven insights can enhance the effectiveness of global decarbonisation efforts, ensuring a just and sustainable transition to net zero.

6. Conclusion & Policy Recommendations

There are multiple pathways to achieving global net zero, each shaped by different combinations of emission reduction strategies, energy system transitions, and carbon removal approaches. The choice of technologies – whether for mitigation, energy production, or removals – will define the trade-offs in land use, infrastructure needs, and economic feasibility. As highlighted in this analysis, no single aspect of decarbonisation can be addressed in isolation; energy demand influences the scale of required mitigation measures, carbon removal depends on residual emissions left by sectoral decarbonisation, and land-use decisions for renewables and bioenergy directly impact biodiversity and ecosystem services. A siloed approach to policymaking, technology deployment, or financial planning risks inefficiencies, unintended environmental consequences, and missed opportunities for integration.

In this paper, we use mobility and transport as a case study to illustrate these interconnections, showing how decarbonisation strategies in one sector influence energy demand, infrastructure needs, and carbon removal requirements. However, this type of systems thinking must extend beyond transport – similar approaches are needed across all industries, from power and heavy industry to agriculture and urban planning. Each sector requires granular, scenario-based strategies that align regional energy needs, emission profiles, and technological capabilities while ensuring policy flexibility as economic and technological landscapes evolve.

To ensure effective and resilient decarbonisation strategies, a more sector-specific approach is necessary – one that accounts for regional energy needs, sectoral emission profiles, and the evolving technological landscape. This includes aligning carbon accounting frameworks with realistic CDR deployment timelines, ensuring biodiversity safeguards in large-scale removals and renewables expansion, and designing policies that can pivot as technologies and economic conditions evolve. Scenario-driven insights underscore that flexibility and adaptability in decision-making are critical; net-zero plans must be robust yet responsive, ensuring that mitigation and removal pathways remain scalable, financially viable, and environmentally sustainable.
The success of global decarbonisation efforts and the development of effective policies and strategies needed hinge on the ability to recognize interdependencies, integrate diverse mitigation strategies, and create policy environments that enable sustainable, technology-diverse, and socially equitable transitions to net zero.

The findings in our research centre demonstrate that there is no single path to net zero, but rather multiple potential pathways, each with different trade-offs, technology dependencies, and policy requirements. To ensure that decarbonisation strategies remain effective, adaptable, and resilient, policymakers, industries, and financial institutions must embrace a flexible and iterative approach – one that enables course corrections as technological progress, economic constraints, and environmental considerations evolve.

The following policy recommendations focus on ensuring granularity in net-zero plans, integrating robust carbon accounting, incorporating biodiversity safeguards, and developing standardized MRV frameworks. These measures will de-risk investment, enhance policy certainty, and enable effective scaling of decarbonisation solutions.

1) More granular net-zero plans with flexible technology portfolios

- Policies must support a diversified technology portfolio rather than single-solution approaches to ensure adaptability across different regions, industries, and energy systems. This enables greater resilience against uncertainties in cost, scalability, and deployment feasibility, allowing for course corrections if certain solutions become unviable.
- Sector-specific pathways for power, transport, industry, and carbon removal (CDR) should remain flexible and regionally tailored to accommodate technological advancements, market shifts, and resource availability. This enables dynamic net-zero strategies that can evolve based on real-world learnings rather than rigid commitments.
- Granular regional and sectoral data collection should be expanded to better inform net-zero implementation strategies and optimise resource allocation. This enables more precise planning and investment decisions, preventing inefficiencies in mitigation and removal deployment.
- Policies must differentiate between nature-based and engineered removals while recognising the commonalities in mitigation strategies (e.g., renewables, electrification) and differences in enabling infrastructure (e.g., CCS, nuclear, hydrogen). This enables a more balanced and pragmatic approach that acknowledges trade-offs while maximising synergies.
- The ability to pivot between mitigation strategies must be embedded in policy design, ensuring that decarbonisation pathways remain viable under changing technological, economic, or geopolitical conditions. This enables greater long-term stability and confidence in net-zero strategies, de-risking large-scale infrastructure investments.
- Granular regional and sectoral data collection should be expanded to better inform net-zero implementation strategies and optimise resource allocation. This enables more precise planning and investment decisions, prevents inefficiencies in mitigation and removal deployment, and allows for time-phased interventions. This is important to align short-term action with long-term goals.

2) Integration of strengthened carbon accounting and residual emissions into sectoral decarbonisation plans

- Residual emissions must be clearly defined and understood across different sectors, with transparent methodologies to assess what qualifies as "residual". This enables more accurate net-zero strategies that do not over-rely on removals.
- Policies should require the disclosure of Scope 3 emissions to prevent carbon leakage. This enables a more accurate representation of corporate emissions.
- Industry-wide disclosure of emissions data should be encouraged across supply chains to facilitate the development of allocation models and financing mechanisms for decarbonisation.
- Seamless and sector-specific carbon accounting methodologies should be standardised to improve consistency across industries and policy frameworks. This enables better alignment between planned emissions reductions and actual outcomes, reducing the risk of underestimating removal needs and ensuring that mitigation targets remain achievable.

3) Ensuring biodiversity considerations in net-zero strategies

- Mandatory biodiversity risk assessments should be required for all large-scale decarbonisation projects, including for example, nature- and engineering- removal technologies as well as land-intensive renewable developments. This enables a better balance between climate mitigation and ecosystem protection, ensuring that emission reductions and removals do not create unintended environmental trade-offs.
- Carbon markets and corporate offsetting programs must incorporate biodiversity impact assessments, integrating scoring mechanisms that account for ecosystem effects. This enables more informed investment in removals that contribute to climate goals without undermining biodiversity conservation.
- Irreversible ecosystem damage must be explicitly prohibited within carbon reduction and removal projects, ensuring that climate solutions do not result in long-term environmental degradation. This enables a more sustainable carbon market where reductions and removals contribute positively to both net-zero strategies and ecological resilience.
- Improved modelling of long-term biodiversity impacts should be integrated into climate policy and scenario modelling, ensuring that large-scale reductions and removals do not disrupt ecosystem stability. This enables more comprehensive environmental assessments that guide better policy decisions.
- Research into the effects of overshooting emissions targets on biodiversity should be expanded, recognising that some climate impacts may be irreversible. This enables stronger safeguards in climate and land-use planning, ensuring that net-zero strategies account for ecological thresholds.

Table 6. Key policy area, actions and ideal stakeholder involvement.

Policy Area	Policy Actions	Key Stakeholders Responsible
Net-Zero Planning & Technology Flexibility	Develop policies that support multiple technology pathways, improve regional & sectoral data collection, and allow for dynamic adaptation.	National governments, research institutions, energy regulators, Industry leaders
Carbon Accounting & Residual Emissions	Standardize residual emissions definitions and mandate standardised, sector-specific carbon accounting include Scope 3 emissions.	Intergovernmental bodies (e.g., UNFCCC, IPCC, WRI), national policymakers, carbon market operators
Biodiversity & Land Use	Require biodiversity risk assessments, regulate land use for large-scale removals, and integrate biodiversity co-benefits into carbon markets.	National environmental agencies, conservation organizations, carbon market regulators
MRV & Investment De-Risking	Invest in digital MRV, provide long-term policy clarity for carbon credits and subsidies, and structure financial incentives for early-stage climate tech.	Governments, carbon registries, private sector, international finance institutions (e.g., IMF, World Bank, Green Climate Fund)

4) Developing standardised MRV and clear policy signals to de-risk investments

- Governments must invest in MRV innovation, including digital MRV systems and AI-driven monitoring, to improve the accuracy and transparency of carbon accounting. This enables better regulatory oversight, stronger investor confidence, and more reliable emissions tracking.
- Long-term policy signals for CDR investments must be clarified to ensure that eligibility for carbon credits, subsidies, and emissions reporting standards remain stable across political cycles. This enables greater certainty for industries and financial institutions investing in removals, reducing volatility in carbon markets.
- A demand-response-based policy approach should be implemented, recognising that steep energy demand reductions require different policy interventions than high-demand scenarios. This enables better-aligned mitigation strategies that reflect real-world energy consumption patterns.
- Historical analysis of past policy effectiveness should be expanded to better understand which interventions have successfully driven decarbonisation. This enables more evidence-based policymaking.
- Financial incentives should be structured to encourage early deployment of decarbonisation technologies, ensuring that capital-intensive solutions (e.g., hydrogen, DAC, CCS) receive adequate support for scale-up. This enables a faster transition to net zero by reducing investment risk in emerging climate technologies.

Coordinated action that aligns mitigation, removal, biodiversity, and societal goals is required. The path to net zero is not only a technical endeavour, but also a governance and systems transformation challenge.

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