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A Practical Guide to 1.5°C Scenarios for Financial Users

A deep-dive into the IPCC-assessed 1.5°C scenarios with no or limited overshoot

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Abbreviations

AD	Anaerobic Digestion
AFOLU	Agriculture, Forestry and other Land Use
AR6	The sixth Assessment Report
BECCS	Bioenergy with Carbon Capture and Storage
BOE	Barrel of oil equivalent
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture & Storage
CDR	Carbon Dioxide Removal
CH_4	Methane
CO_2	Carbon dioxide
CO_2eq	Carbon Dioxide equivalent
CPI	Climate Policy Initiative
CSP	Concentrating Solar Power
Cur-Pol	Current policies
DAC	Direct Air Capture
DACCS	Direct Air Carbon Capture & Storage
DRI	direct reduced iron
EAF	Electric Arc Furnace
EDF	Enviro defense fund
EJ	ExaJoules
EOR	Enhanced Oil Recovery
EPA	Environmental Protection Agency
ETS	Emissions Trading Scheme
EU	European Union
EVs	Electric Vehicles
F-gases	Fluorinated gases
FSB	Financial Stability Board
GCAM	Global Change Assessment Model
GDP	Gross Domestic Product
GFANZ	Glasgow Financial Alliance on Net Zero

GHG	Greenhouse gases
GS	Gradual Strengthening
Gt	Gigatonnes
$GtCO_2$	Gigatonnes of Carbon Dioxide
HFCs	hydrofluorocarbons
HVAC	Heating, Ventilation and Air Conditioning
IAMs	Integrated assessment Models
ICCT	International Council on Clean Transportation
ICE	Internal Combustion Engine
ICEVS	Internal Combustion Engine Vehicles
IEA	International Energy Agency
IFRS	International Financial Reporting Standards
IGCC	Investor Group on Climate Change
IIASA	International Institute for Applied Systems Analysis
IIGCC	Institutional Investors on Climate Change
IMF	International Monetary fund
IMPs	Illustrative Mitigation Pathways
IPCC	International Panel on Climate Change
IPCC AR6 WG	IPCC Sixth Assessment Report Working Group
LCOE	Levelised Cost of Electricity
LD	Low Demand
LNG	Liquefied Natural Gas
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
Mha	Million hectares
Mod-Act	Moderate Action
$MtCO_2$	Megatonnes of Carbon Dioxide
N_2O	Nitrous Oxide
NDCs	Nationally Determined Contribution
Neg	Negative Emissions
NGFS	Network for Greening the Financial System
NIESR	National Institute of Economic and Social Research
NZAM	Net Zero Asset Managers Initiative
NZAOA	Net-Zero Asset Owner Alliance
NZBA	Net-Zero Banking Alliance
NZE	Net Zero Emissions Scenario
NZFSPA	Net Zero Financial Service Providers Alliance

NZICI	Net Zero Investment Consultants Initiative
PAII	Paris Aligned Investment Initiative
PFCs	Perfluorocarbons
PV	Photovoltaic
Ren	Renewables
REMIND	Regional Model of Investments and Development
SAF	Sustainable Aviation Fuel
SF6	Sulphur hexafluoride
SP	Shifting Pathways
SR15	Special Report on Global Warming of 1.5 degrees
SSPs	Shared Socio-economic Pathways
TCFD	Taskforce for Climate Related Financial Disclosures
UNEP FI	United Nations Environment Programme Finance Initiative
UNFCCC	United Nations Framework Convention of Climate Change
United Kingdom	The United Kingdom of Great Britain and Northern Ireland
USA	United States of America
WG III	Working Group III
WRI	World Resource Institute

Contents

Summary for policymakers

Purpose of this report

This report by the United Nations Environment Programme Finance Initiative (UNEP FI) serves as a practitioner's guide to understanding the key attributes of IPCC-assessed scenario pathways that limit temperature rise to 1.5°C with no or limited overshoot. In addition, it highlights the required actions that arise from these scenario pathways for different sectors as well as considering how these climate scenarios can be used in practice. These scenarios comprise a combination of mitigation actions and are useful in identifying robust features for a 1.5˚C pathway that have reached a consensus in the scientific community. This report aims to achieve the following key objectives:

- Enhancing the interpretability of climate scenarios for users.
- Identifying common milestones in the path to decarbonisation in climate scenarios.
- Improving the understanding of how policymakers and financial users should effectively use climate scenarios, along with clarification of their inherent limitations.

The report is structured around distinct themes that explore the implications of these scenario pathways for emissions, carbon dioxide removal, energy demand across sectors, financing needs, and socioeconomic assumptions. These chapters are designed to take on questions related to the scenarios, including:

- What are the attributes on which climate models agree and disagree?
- What are the uncertainties among scenarios for specific variables?
- How does the data shown in the scenario pathways compare to current progress?
- How does the IPCC-assessed scenario data set compare to commonly used scenarios by the Network for Greening the Financial System (NGFS) and the International Energy Agency (IEA)?
- What information can be obtained from scenarios?
- What are the gaps and drawbacks of climate scenarios?

This document is **intended to equip readers with insights to enhance their knowledge on 1.5°C scenarios with no or limited overshoot.** The end goal is to enable them to better leverage climate scenarios for scenario analysis. Use cases for the report have been described in the table below.

Table 1: Summary of key use cases of the report

Use cases of the report	How to use the report
Build expertise on the mitigation actions needed to reach 1.5°C	The report summarises key mitigation actions needed to reach net zero by 2050 and to limit warming to 1.5°C. These mitigation actions are compared to the current progress being made.
Build knowledge on the key attributes of 1.5°C pathways with no or limited overshoot	Each chapter details the key attributes of the IPCC-assessed 1.5°C scenarios with no or limited overshoot, including the median data and the interquartile range for specific variables.
Determine appropriate scenarios to use for scenario analysis	The report provides data on the IPCC-assessed scenario dataset, including showing the median, lower and upper quartile values for certain variables. Users can compare specific scenarios to these values to determine whether those scenarios are more or less optimistic than the scenario dataset. This can be used by users to then infer whether the scenario is appropriate to use for scenario analysis.
Understand the key assumptions of commonly used scenarios	Each chapter provides a comparison of the IPCC-assessed scenario dataset with commonly used scenarios by the NGFS and the IEA for specific variables. The comparisons can be used by users to understand the key features of these scenarios and how similar or different they are to other 1.5°C scenarios with no or limited overshoot.
Validate the key assumptions of your scenario analysis	The report analysis the key attributes of the IPCC-assessed scenario dataset. Users can compare the assumptions of a selected scenario to the median values and interquartile range of the IPCC-assessed scenarios for certain variables to determine whether the particular scenario is in line with the attributes of 1.5°C pathways that have reached consensus by the modelling community. The analysis can be used to determine where the robustness lies in scenario assumptions.
Determine the type of scenario enhancements needed for use	The report analyses the available variables, coverage, and granularity of the IPCC-assessed scenarios. On top of this, the report explains the limitations of climate scenarios. This information can then assist users to determine the type of scenario enhancements that they need to perform internally when conducting scenario analysis.
Understand how to use the outputs of a scenario analysis	The report examines the benefits and drawbacks of climate scenarios. By understanding these, users can determine how to best use the information provided by climate scenarios.

Structure of the report:

The report is divided into eight main chapters, with a description for each of the chapters provided below.

- **Chapters 1 and 2** provide an in-depth exploration of concepts such as limiting warming to 1.5°C, no or limited overshoot and net zero and their relevance for readers.
- **Chapter 3** introduces 1.5°C scenarios with no or limited overshoot that have been assessed by the IPCC, as well as provides an understanding of the IPCC's Assessment Report 6.

The following five chapters deep-dive into the key attributes for 1.5°C pathways with no or limited overshoot, scenario considerations for using scenarios, and uncertainties and limitations among scenarios. Each chapter is focused on a specific thematic topic described below.

- **Chapter 4** focuses on emissions reductions for 1.5°C pathways with no or limited overshoot.
- **Chapter 5** provides an overview of carbon capture and storage and carbon dioxide removal in pathways.
- **Chapter 6** provides an assessment of energy demand across sectors within the 1.5°C pathways with no or limited overshoot.
- **Chapter 7** provides considerations of financing the transition to net zero in scenarios
- **Chapter 8** details socioeconomic considerations to limit warming to 1.5°C.

Emissions reductions for 1.5°C pathways with no or limited overshoot

This chapter provides readers with comprehensive information on the role of emissions reductions in achieving 1.5°C pathways with no or limited overshoot. It examines present and historical trends in emissions, analysing data at both sector-specific and regional levels. Additionally, the chapter offers insights into greenhouse gases (GHGs) such as carbon dioxide, methane, nitrous oxide, and F-gases, discussing their sources and emphasising the importance of reducing them to limit global warming.

A central focus of this chapter is an in-depth exploration of the significance of GHGs in scenario pathways and the consensus reached by the climate modelling community regarding GHG reductions, supported by scenario data from IPCC-assessed scenarios. Specifically, data from scenarios by the NGFS and IEA are also compared to other 1.5°C with no or low overshoot scenarios. This comparison is to aid readers in understanding the emission reduction assumptions commonly used in scenarios and the sequence of GHG phase-out in these scenarios. Readers are also provided with a set of recommended scenario variables to use in relation to GHG emission reductions as part of their scenario analysis.

Finally, the chapter offers recommendations and considerations for actions required to reduce emissions across various sectors, providing insights into potential strategies and actions to address climate change effectively.

Key messages

- To effectively cut down overall GHG emissions in the long term, the priority should be on reducing carbon dioxide (CO_2) emissions first, followed closely by addressing other greenhouse (GHG) emissions.
- In 1.5°C scenarios with no or limited overshoot, **CO_2 emissions decrease by 46% *(median)* from 2020 to 2030**. Firms in all areas of the global economy must take **a comprehensive approach**, including transitioning away from fossil fuels and renewable energy sources, adopting electrification, enhancing energy efficiency, minimising land clearing, using carbon-negative technology for carbon dioxide removal, and implementing carbon taxes.
- Methane (CH_4) emissions are the second-largest driver of global warming, with 1.5°C scenarios with no or limited overshoot **reporting CH_4 emissions decreasing by 31% *(median)* from 2020 to 2030**. Concentrated efforts to reduce emissions need to be **directed towards firms operating in the agriculture and energy sectors**. For example, new approaches are needed for agricultural cultivation and livestock production to reduce emissions and fugitive methane released from oil and gas processes also need to be prevented.
- In 1.5°C scenarios with no or limited overshoot, **nitrous oxide (N_2O) emissions decrease by 18% *(median)* from 2020 to 2030**. Due to the high potency of nitrous oxide (N_2O), it is crucial to implement measures to reduce its emissions. **The agriculture sector is a major source**, particularly through the use of synthetic nitrogen fertiliser, where firms will need to prioritise either improving efficiency or decreasing overall use.
- F-gases have a high global warming potential, with 1.5°C scenarios with no or limited overshoot reporting emissions from **F-gases decreasing by 76%** (median) **from 2020 to 2030**. Reductions will need to be addressed globally through **targeted protocol-based action**.

Suitability considerations of scenarios for exploring emissions

Limited information and detail	Some information and detail	Good information and detail
▪ Contribution of specific sectoral activities & investment and lending activities on emissions in the pathways ▪ Some of the scenarios included in the IPCC's assessment were developed multiple years ago and contain outdated assumptions ▪ Details on the emission reduction potential of various mitigation options are absent ▪ Difference in the historical baseline used in the scenarios as baseline emissions	▪ Sector breakdown to obtain information on emission pathways for sectors such as AFOLU, industrials, transportation and buildings ▪ Regional breakdowns of emission pathways	▪ Levels of emission reductions needed for limiting warming to 1.5°C with no or limited overshoot ▪ Data provided on emission trajectories for various GHGs & Kyoto gases ▪ Which GHGs need to be prioritised in terms of reductions in the near and long term

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Suitability considerations of scenarios for exploring emissions for the energy sector

Overall rating: average to good

Potential areas of greatest suitability: Policy design and analysis

Limited information and detail	Some information and detail	Good information and detail
▪ Breakdown of the contribution of specific energy types, such as fossil fuels, renewables and nuclear, on emissions in the pathways not available ▪ How should specific investment and lending activities contribute to emission pathways ▪ Some of the scenarios included in the IPCC's assessment were developed multiple years ago and contain outdated assumptions ▪ Details on the emission reduction potential of various mitigation options are absent ▪ Difference in the historical baseline used in the scenarios as baseline emissions	▪ Regional breakdowns of emission pathways	▪ Levels of emission reductions needed for limiting warming to 1.5°C with no or limited overshoot ▪ Data provided on emission trajectories for various GHGs & Kyoto gases ▪ Which GHGs need to be prioritised in terms of reductions in the near and long term ▪ Information available on emissions from various types of energy use, such as electricity, heat, and gases

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Suitability considerations of scenarios for exploring emissions for the transportation sector

Overall rating: average to good

Potential areas of greatest suitability: Policy design and analysis

Limited information and detail	Some information and detail	Good information and detail
▪ Contributions of specific sectoral activities & investment and lending activities on emissions in the pathways are not available (e.g. the contribution of ICE vehicles, private jets, commercial airlines, etc.) ▪ Some of the scenarios included in the IPCC's assessment were developed multiple years ago and contain outdated assumptions ▪ Details on the emission reduction potential of various mitigation options are absent ▪ Difference in the historical baseline used in the scenarios as baseline emissions	▪ Regional breakdowns of emission pathways ▪ Breakdown of data for some emission types available at the sub-sector level, such as aviation, maritime, rail and road	▪ Levels of emission reductions needed for limiting warming to 1.5°C with no or limited overshoot ▪ Data provided on emission trajectories for various GHGs & Kyoto gases ▪ Which GHGs need to be prioritised in terms of reductions in the near and long term

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Suitability considerations of scenarios for exploring emissions for the agriculture sector

Overall rating: average to good

Potential areas of greatest suitability: Policy design and analysis

Limited information and detail	Some information and detail	Good information and detail
▪ Contribution of specific sectoral activities and investment and lending activities on emissions in the pathways is not available (e.g. fertiliser use) ▪ Some of the scenarios included in the IPCC's assessment were developed multiple years ago and contain outdated assumptions ▪ Details on the emission reduction potential of various mitigation options are absent ▪ Difference in the historical baseline used in the scenarios as baseline emissions	▪ Regional breakdowns of emission pathways ▪ Breakdown of data for some emission types available for different types of land uses, such as manure management and soil management.	▪ Levels of emission reductions needed for limiting warming to 1.5°C with no or limited overshoot ▪ Data provided on emission trajectories for various GHGs & Kyoto gases ▪ Which GHGs need to be prioritised in terms of reductions in the near and long term

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Suitability considerations of scenarios for exploring emissions for the industrials sector

Overall rating: average to good

Potential areas of greatest suitability: Policy design and analysis

Limited information and detail	Some information and detail	Good information and detail
▪ Some of the scenarios included in the IPCC's assessment were developed multiple years ago and contain outdated assumptions ▪ Details on the emission reduction potential of various mitigation options are absent ▪ Difference in the historical baseline used in the scenarios as baseline emissions ▪ Contributions of specific sectoral activities and investment and lending activities on emissions in the pathways are not available	▪ Regional breakdowns of emission pathways ▪ Breakdown of data for some emission types available for some sub-sectors and industrial processes, such as cement, steel and chemicals.	▪ Levels of emission reductions needed for limiting warming to 1.5°C with no or limited overshoot ▪ Data provided on emission trajectories for various GHGs & Kyoto gases ▪ Which GHGs need to be prioritised in terms of reductions in the near and long term

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Suitability considerations of scenarios for exploring emissions for the real estate sector

Overall rating: average to good

Potential areas of greatest suitability: Policy design and analysis

Limited information and detail	Some information and detail	Good information and detail
▪ Information on emissions generated from various energy sources in the sector for a given pathway is not available, and there is no breakdown of different energy uses in buildings, including contributions from appliances, cooling, etc. ▪ Contribution of specific building types & construction activities is not available ▪ How should specific investment and lending activities contribute to emission pathways ▪ Some of the scenarios included in the IPCC's assessment were developed multiple years ago and contain outdated assumptions ▪ Details on the emission reduction potential of various mitigation options are absent ▪ Difference in the historical baseline used in the scenarios as baseline emissions	▪ Regional breakdowns of emission pathways ▪ Breakdown of data for some emission types available at the commercial and residential level	▪ Levels of emission reductions needed for limiting warming to 1.5°C with no or limited overshoot ▪ Data provided on emission trajectories for various GHGs & Kyoto gases ▪ Which GHGs need to be prioritised in terms of reductions in the near and long term

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Considerations for policymakers:

- Does the jurisdiction have policies in place to support emission reductions across sectors?
- Does the jurisdiction provide incentives for emission reductions?
- Have potential opportunities through mitigation actions been identified for the jurisdiction?

General overview of carbon capture and storage/carbon dioxide removal in pathways:

This chapter explores the nature and prevalence of carbon removal assumptions across different 1.5°C scenarios. It provides clear definitions of Carbon Capture and Storage (CCS) and Carbon Dioxide Removal (CDR) and examines their types, current utilisation, and estimated future use. Additionally, the chapter explores the advantages and limitations associated with these technologies.

This chapter examines the critical roles of CCS and CDR in scenario pathways. It also discusses the level of optimism concerning the use of CCS and CDR in models and their implications for other scenario assumptions. Furthermore, the chapter offers insights into the types of CDR methods employed in IPCC-assessed 1.5°C scenarios, providing a detailed examination of CDR methodologies and comparing them with scenarios by the NGFS and IEA to enhance user understanding of commonly used scenario assumptions in relation to carbon removals. Readers are also provided with a set of recommended scenario variables to use in relation to carbon removals as part of their scenario analysis.

Finally, given the carbon removal assumptions in scenario pathways, the chapter assesses the viability of removal technologies as a mitigation measure, taking into account their present development and costs. This also includes a comparison of emissions captured in 2022 to estimates for 2030 and 2050 in 1.5°C scenarios with no or limited overshoot

Key messages

- The deployment of carbon capture and removal technologies could be crucial to countering delays in reducing CO_2 emissions and limiting warming to 1.5°C.

- CDR deployment can **serve various purposes**, such as accelerating the pace of emissions reductions, offsetting residual emissions, and creating the option for net-negative CO_2 emissions.

- Methods for CO_2 removal include Bioenergy with Carbon Dioxide Capture and Storage (BECCS), Direct Air Carbon Dioxide Capture and Storage (DACCS), afforestation, and soil carbon sequestration.

- Significant scale-up of CDR will likely be needed in 2030 onwards; for example, 1.5°C scenarios with no or limited overshoot show **BECCS and DACCS increasing by almost 12-fold and 10-fold between 2030 and 2050**.

- BECCS, DACCS, Land Use and Afforestation are the most common methods considered in the scenarios.
- These methodologies vary in terms of maturity, removal process, storage potential, storage duration, technological readiness, mitigation potential, cost, benefits, adverse impacts, and governance requirements.
- The diverse applications for CO_2 emissions need to be considered, such as capturing, storing, and utilising carbon.
- Similar to renewable technologies, CCS costs are expected to decrease with technological advancements and economies of scale; however, **economic incentives, such as carbon taxation, are needed to promote the scale-up** of carbon capture and removal technologies.

Suitability considerations of scenarios for exploring CDR

Limited information and detail	Some information and detail	Good information and detail
▪ If technological developments do not occur at the rate shown in pathways over the coming years, the scenarios will need to be reviewed for their reliance on CDR. ▪ Lack of consideration for socio-political feasibility, which may lead to only a small number of pathways taking into account the limited viability of CDR for certain countries ▪ Lack of information on long term durability and permanence of the CCS & CDR options	▪ Regional granularity ▪ Lack of regional differentiation between pathways with only a small number of pathways taking into account limited viability of CDR for certain countries	▪ Coverage of different types of CDR options and the most common types used in pathways ▪ Timeframe under which CDR is deployed at a large scale is laid out, with a sizeable proportion of pathways reporting a higher reliance on CDR post-2030. ▪ Needed scale of deployment for CDR technologies

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Considerations for policymakers:

- Does the jurisdiction consider CDR technologies as a viable mitigation option in the near, mid and long term?
- Are there any natural sources of CDR available within the jurisdiction?
- Has the jurisdiction implemented any cost incentives for CDR technologies?

Energy demand across sectors

This chapter explores the wide range of decarbonisation efforts outlined in the IPCC-assessed 1.5°C scenarios with no or limited overshoot across five key sectors: energy, transportation, agriculture, industrials, and real estate. It examines changes in energy demand within each sector across the scenario dataset and discusses their implications. Strategies and challenges for decarbonisation for each sector are also addressed.

Within the energy sector, the chapter examines the phase-out of fossil fuels (coal, oil and natural gas) in the scenarios, exploring both areas where consensus has been reached within the modelling community and where uncertainties persist. Additionally, this chapter deep-dives into the alternatives for fossil fuel for primary energy, with a primary focus on the scale-up of renewables, especially wind and solar, including their drivers for expansion and potential challenges. Variations in reduction and scale-up rates across sectors and regions are explored, alongside the importance of energy efficiency in decarbonisation efforts. A comparison is made between the phase-out and scale-up of primary energy types reported in the scenarios and the latest global data on primary energy use to assess near-term progress in comparison to 1.5°C pathways.

In the transportation sector, the chapter delves into the role of electrification in decarbonising the sector within scenario pathways, discussing factors influencing the expansion of electric vehicles and the related challenges. It also examines the importance of energy efficiency and alternative fuels, considering available data in scenarios.

The chapter also explores the need to decarbonise the agriculture sector in the coming years amidst rising food demand and changing food diets, which bring with them additional challenges for mitigating the sector. This sub-section considers various mitigation options for the sector.

Three subsectors of the industrial sector are explored: steel, cement, and ammonia. In relation to the steel and cement subsectors, this chapter investigates the change in carbon intensity required in scenarios to limit warming to 1.5°C with no or limited overshoot and compares it to the current global average carbon intensity. Alternatives and technologies to decarbonise all three subsectors are also explored.

For the real estate sector, key attributes to decarbonising the sector in scenarios are explored, including the role of electrification in pathways and changes in energy consumption for various use cases. The chapter also discusses operational and embodied carbon emissions for the sector and measures to reduce such emissions.

Throughout this chapter, scenario pathways are evaluated to help the reader understand the data available in these pathways for decarbonising the sectors and their real-world implications. Readers are also provided with a set of recommended sector-specific scenario variables to use in relation to energy demand as part of their scenario analysis. The IPCC-assessed scenario dataset is compared to scenarios by the NGFS and IEA to enhance user understanding of sector-specific assumptions of commonly used scenarios. The chapter concludes with an assessment of scenario limitations.

Overview of energy demand in pathways

Suitability considerations of scenarios for exploring energy demand

Limited information and detail	Some information and detail	Good information and detail
▪ Lack of variables covering the direct energy demand and production changes ▪ Limited consideration of socio-politics of energy-mix changes & income distribution ▪ No reflection on how national priorities can differ from projected changes in energy use ▪ Information on security & affordability of national energy sources not provided ▪ Models inherently rely on historical data which puts them at risk of being unable to capture current trends. For example, models are not updated frequently enough to incorporate new trends in the deployment rates of renewable technologies, potentially leading to underestimates in their future use.	▪ Granularity of energy systems at the geographic and temporal scale across scenarios and their underlying models ▪ Simplified information on technological innovations and their respective adoption	▪ Granularity for the energy sector & energy systems across the global economy ▪ Details on change in energy mix, the expansion of electrification across sectors, energy efficiency gains, and alternative fuel types available to limit warming to 1.5°C ▪ Breakdown into different energy types – primary, secondary and final energy ▪ Energy use breakdowns for sectors & regions (e.g. final energy use of passenger vehicles, heating in residential buildings, industrial processes, etc.)

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Energy sector

Strategies for decarbonising	Challenges in decarbonising
Electrification & Efficiency: Firms in the sector should shift towards electrification, renewable energy, and nuclear power, while enhancing energy efficiency and implementing Carbon Capture and Storage (CCS) technologies at fossil fuel power plants, upgrade transmission networks, and encourage lifestyle changes of consumers. Key indicators in 1.5°C scenarios with no or low overshoot: ▪ Primary energy generated from **coal, oil and natural gas decreases by 73%, 10% and 11%** (median), respectively, from 2020 to 2030. ▪ Primary energy generated from **solar and wind increases by 746% and 323%** (median), respectively, from 2020 to 2030. ▪ Primary energy generated from nuclear increases by 35% (median) from 2020 to 2030. ▪ Energy efficiency of electricity generated from coal with CCS ranges from 34% to 36% (median) from 2020 to 2050.	▪ Supply chain shortages of critical minerals, ▪ Persistent subsidies for fossil fuels, ▪ Intermittency issues with renewable sources, ▪ High installation and maintenance costs, ▪ Geographical dependency on renewable sources, ▪ Risk of carbon lock-ins from existing infrastructure, and ▪ Need for significant investments.

Suitability considerations of scenarios for exploring energy demand in the energy sector

Overall rating: good

Potential areas of greatest suitability: Policy design and analysis

Limited information and detail	Some information and detail	Good information and detail
▪ Integration delays in models may lead to under/overestimation of trends in certain pathways, with a risk of missing existing trends or underestimating future trends due to the reliance on historical data or infrequent updates (e.g. deployment rates of renewables) ▪ Limited consideration of socio-politics of energy-mix changes & income distribution ▪ No reflection on how national priorities can differ from projected changes in energy use ▪ Information on security & affordability of national energy sources not provided ▪ Feasibility of grid integration & disruption of current energy systems not addressed	▪ Granularity of energy systems at the geographic and temporal scale across scenarios and their underlying models ▪ Simplified information on technological innovations and their respective adoption	▪ Granularity for the energy sector & energy systems across the global economy ▪ Details on change in energy mix, the expansion of electrification, energy efficiency gains, and alternative fuel types available to limit warming to 1.5°C ▪ Breakdown into different energy types – primary, secondary and final energy

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Considerations for policymakers:

- What alternatives to fossil fuels have been identified as opportunities for the jurisdiction?
- Does the jurisdiction have any policies in place to support the transition from fossil fuels to renewable energy?
- What potential challenges does the jurisdiction face when scaling up primary energy from renewable sources?

Transportation sector

Strategies for decarbonising	Challenges in decarbonising
Electrification & infrastructure: Firms should support widespread electrification, especially for smaller and short-distance vehicles, as well as support enhancements in EV battery performance, development of fast-charging infrastructure, transition to alternative fuels, improve fuel efficiency of aviation and shipping, utilise hydrogen fuel cells for heavy-duty EVs, increase rail network capacity and the implementation of stringent energy efficiency standards. Further actions for decarbonisation include incentivising used EV purchases, redesigning cities to reduce transportation needs, expanding cycling and walking networks, and improving public transportation accessibility. Key indicators in 1.5°C scenarios with no or low overshoot: ▪ **Final energy generated from electricity increases** from 1.8 exajoules per year (EJ/yr) (median) in 2020 to 22.8 EJ/yr (median) in 2050. ▪ Use of hydrogen for energy increases from almost nothing in 2020 to 3.6 EJ/yr (median) in 2050. ▪ Biofuel energy consumed by passenger and freight vehicles increases from 1.3 EJ/yr (1.2 EJ/yr – 4 EJ/yr) in 2020 to 13 EJ/yr (10 EJ/yr – 16 EJ/yr) by 2050. ▪ Scenarios **can consider behavioural change** by implying a shift to public transport, walking and cycling, reduction in per capita car ownership, avoidance of short flights and telework.	▪ Human rights and environmental concerns linked to EVs and alternative fuels, ▪ Regional disparities in charging infrastructure availability, ▪ Supply chain limitations for critical minerals, ▪ Commercial viability concerns of certain technologies and alternative fuels, ▪ Cost challenges, ▪ Need for large fuel storage capacity for long-distance travel, and ▪ Need to repurpose infrastructure for cycling and walking paths and incentivise behaviour change.

Suitability considerations of scenarios for exploring energy demand in the transportation sector

Overall rating: average to good
Potential areas of greatest suitability: Policy design and analysis

Limited information and detail	Some information and detail	Good information and detail
▪ Limited variables covering direct energy demand changes ▪ Limited consideration of socio-politics of energy-mix changes & income distribution ▪ No reflection on how national priorities can differ from projected changes in energy use ▪ Models do not address the feasibility of raw materials availability and infrastructure needs to electrify the sector ▪ Models inherently rely on historical data which puts them at risk of being unable to capture current trends. For example, models are not updated frequently enough to incorporate new trends in the deployment rates and sales of EVs, potentially leading to underestimates in their future use.	▪ Granularity at the geographic and temporal scale across scenarios and their underlying models ▪ Simplified information on technological innovations and their respective adoption ▪ Energy use breakdowns for sub-sectors covered by some pathways (e.g. final energy use of ICE freight vehicles, final energy use for aviation, etc.)	▪ Details available on change in energy mix, the expansion of electrification, and alternative fuel types available to limit warming to 1.5°C

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Considerations for policymakers:

- What alternatives to carbon-intensive modes of transport have been identified as opportunities for the jurisdiction?
- Does the jurisdiction have any policies in place to support the decarbonisation of the transportation sector?
- What potential challenges might the jurisdiction encounter while phasing out carbon-intensive modes of transport?

Agriculture sector

Strategies for decarbonising	Challenges in decarbonising
Alternative practices & behavioural changes: To decarbonise, firms in the sector should consider electrification, agrivoltaics, alternative fuels, digitalisation, conservation practices, smart irrigation, carbon sequestration, innovative carbon reduction technologies, efficiency of fertiliser supply chains, improvements in livestock management, reductions in food loss, dietary shifts, and nature-based solutions. Key indicators in 1.5°C scenarios with no or low overshoot: ▪ Increase in demand for per capita calories from 2,946 kcal per capita per day (kcal/cap/day) (median) to 3,025 (kcal/cap/day) (median) from 2020 to 2050 ▪ **Agriculture demand increases by 69%** (median) from 2020 to 2050. ▪ **Agriculture production increases by 72%** (median) from 2020 to 2050. ▪ Land cover remains constant at 12805 million ha (median) from 2020 to 2050.	▪ Higher costs and initial investments for energy-efficient technologies, net-zero fertiliser production, and certain decarbonisation methods, ▪ Environmental trade-offs, knowledge gaps in animal health, ▪ Capital costs for infrastructure, limited awareness among producers, and ▪ Potential conflicts between production-focused policies and mitigation incentives.

Suitability considerations of scenarios for exploring energy demand in the agriculture sector

Overall rating: limited

Potential areas of greatest suitability: High-level policy planning

Limited information and detail	Some information and detail	Good information and detail
▪ Lack of variables covering direct energy demand changes, including final energy, electrification and change in energy type ▪ Limited consideration of socio-politics of energy-mix changes & income distribution ▪ No reflection on how national priorities can differ from projected changes in energy use ▪ Lack of information on technological innovations and their respective adoption ▪ Models inherently rely on historical data which puts them at risk of being unable to capture current trends. For example, models are not updated frequently enough to incorporate new trends in the deployment rates of renewable technologies, potentially leading to underestimates in their future use.	▪ Granularity at the geographic and temporal scale across scenarios and their underlying models	▪ Details available on changes in agriculture production & demand

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Considerations for policymakers:

- What alternatives to carbon-intensive agricultural practices and diets are identified as opportunities for the jurisdiction?
- Does the jurisdiction have any policies in place to support the decarbonisation of the agriculture sector?
- Does the jurisdiction have any incentives in place to encourage behavioural change?

Industrials sector

Strategies for decarbonising	Challenges in decarbonising
Efficiency & technological innovation: Firms should expand direct electrification, pilot innovative decarbonisation technologies, use CCUS, enhance material efficiency, improve energy efficiency, minimise waste, and supplement materials with low-carbon alternatives. Reduced demand for carbon-intensive products will also be needed. Key indicators in 1.5˚C scenarios with no or low overshoot: ▪ **Carbon intensity of steel decreases by 84%** (median) from 2020 to 2050 ▪ **Carbon intensity of cement decreases by 81%** (median) from 2020 to 2050	▪ Long lifetimes and high capital intensity of facilities, ▪ Extended construction timelines for less carbon-intensive options, ▪ Challenges in meeting safety and quality criteria with reduced carbon content, ▪ Limited local availability of resources and infrastructure, ▪ Substantial initial and ongoing investments, ▪ Costly advanced technology, ▪ Limited commercial deployment, and ▪ Global constraints on sustainably produced biomass (alternative for fuel and feedstock).

Suitability considerations of scenarios for exploring energy demand in the industrials sector

Overall rating: average to limited

Potential areas of greatest suitability: Policy design and analysis

Limited information and detail	**Some information and detail**	**Good information and detail**
▪ Limited variables covering direct energy demand changes ▪ Limited consideration of socio-politics of energy-mix changes & income distribution ▪ Lack of data provided on improving energy efficiency ▪ No reflection on how national priorities can differ from projected changes in energy use ▪ Models are inherently prone to lagging behind current time, which can lead to the underestimation and overestimation of various trends in pathways. For example, models are not updated frequently enough to incorporate new trends in the deployment rates of renewable technologies, potentially leading to underestimates in their future use.	▪ Granularity at the geographic and temporal scale across scenarios and their underlying models ▪ Simplified information on technological innovations and their respective adoption ▪ Carbon intensity of production for sub-sectors covered by some pathways	▪ Details available on the expansion of electrification and alternative fuel types for sub-sectors available to limit warming to 1.5°C

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Considerations for policymakers::

- What alternatives to traditional industrial processes have been identified as opportunities for the jurisdiction?
- Does the jurisdiction have any policies and incentives in place to support the decarbonisation of the industrial sector?
- What potential challenges does the jurisdiction face in decarbonising the sector?

Real Estate sector

Strategies for decarbonising	Challenges in decarbonising
Efficiency, Low-Carbon Materials, & Renewable Integration: Firms in the sector should prioritise building renovations and reuse, incorporate design of lower-carbon concrete mixes, limit carbon-intensive materials and choose low-carbon alternatives, use carbon-sequestering materials, reuse and incorporate high-recycled content materials, maximise structural efficiency, reduce finished materials and minimise waste, enhance green spaces, improve energy efficiency, implement advanced building and energy management systems, integrate renewables, and provide clean energy access. Key indicators in 1.5˚C scenarios with no or low overshoot: ▪ Global final **energy consumption of electricity in residential buildings increase by 38%** (median) from 2020 to 2050. ▪ **Gas consumption for energy in residential buildings decrease by 60%** (median) from 2020 to 2050	▪ Scalability and cost challenges with high upfront costs, ▪ Difficulty in reaching consensus on retrofitting decisions, ▪ Lack of standardisation in terms of technology, ▪ Processes and financing mechanisms across the industry, ▪ Limited awareness of the benefits of retrofits and existing building codes, and ▪ Regulations posing obstacles to retrofitting projects.

Suitability considerations of scenarios for exploring energy demand in the real estate sector

Overall rating: average to limited

Potential areas of greatest suitability: Policy design and analysis

Limited information and detail	Some information and detail	Good information and detail
▪ Limited variables covering direct energy demand changes and by building type ▪ Models inherently rely on historical data, which puts them at risk of being unable to capture current trends. For example, models are not updated frequently enough to incorporate new trends in the deployment rates of renewable technologies, potentially leading to underestimates in their future use. ▪ Information not available on renovation and construction rates ▪ Lack of data provided on improving energy and operational efficiency of buildings ▪ Limited consideration of socio-politics of energy-mix changes & income distribution	▪ Granularity at the geographic and temporal scale across scenarios and their underlying models ▪ Simplified information on technological innovations and their respective adoption ▪ Changes in energy use, such as for cooking, lighting and appliances, covered by some pathways	▪ Details available on the changes in energy mix and the expansion of electrification needed to limit warming to 1.5°C ▪ Energy use breakdown available for residential & commercial buildings covered

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Considerations for policymakers:

- Are there alternatives to traditional building designs available for use in the jurisdiction?
- Does the jurisdiction have any policies and incentives in place to support the decarbonisation of the real estate sector?
- What potential challenges does the jurisdiction face in decarbonising the sector?

Financing the transition to net zero

This chapter provides a comprehensive overview of the financing needed, from both public and private sources, to limit warming to 1.5°C. It delves into climate financing needs across various sectors and regions and breaks down key mechanisms for private financing. For the key five sectors – energy, transportation, agriculture, industrial and real estate, the chapter details opportunities in climate financing and the scale-up in financing required based on the scenarios assessed by the IPCC.

For example, the chapter examines the energy sector, highlighting both the consensus among scenarios for a rapid shift in investments from fossil fuels to renewables and the variations in the pace and scale of investment across scenario pathways. Investments in fuel types in the IPCC-assessed 1.5°C scenarios with no or limited overshoot are also detailed. Additionally, the chapter discusses financing needs in energy efficiency and transmission and distribution. Similarly, for the transportation sector, the chapter explores investment needs in electrification and electric vehicles, infrastructure, improved materials and alternative fuels. It also examines investment data reported by the scenarios for electrification and infrastructure. Along with outlining the opportunities in financing, the chapter also explores the obstacles faced by institutions in financing and scaling up mitigation measures. Where possible, the chapter provides a comparison of the IPCC-assessed scenario dataset with data from the NGFS and IEA scenarios to help the reader understand the key investment assumptions in commonly used scenarios for their scenario analysis.

The chapter includes financing needs for the agriculture, industrial, and real estate sectors, taking into consideration variable granularity and limitations in scenarios for reporting investment data for these sectors due to existing model drawbacks. Adaptation finance needs are also covered. Finally, the chapter provides an overview of the climate financing gap, comparing required financing to current levels for mitigation and adaptation finance and across the five sectors. The chapter concludes with an assessment of scenario limitations in relation to understanding financing needs for limiting warming to 1.5°C.

Key messages

- Policymakers can support the transition through directing public financing. Investments in fossil-generated electricity energy need to rapidly decrease and shift investments from fossil fuels to renewables as shown in the IPCC-assessed 1.5°C scenarios with no or limited overshoot for investments in new power generation:

Energy type	Median 2020 investments	Median 2030 investments
Coal	\$58.2 billion[1]	\$12.7 billion
Oil	\$0.05 billion	\$0.01 billion
Gas	\$59.9 billion	\$30.8 billion
Solar	\$132.7 billion	\$427.5 billion
Wind	\$102.6 billion	\$391.6 billion

- A **substantial increase in investments in non-biomass renewables** like solar, wind, hydro, and geothermal is needed with **opportunities for financing in emerging markets**.

- Significant financing is needed to **upgrade and expand transmission networks and storage capacity** and the digitalisation of energy systems to improve energy efficiency.

- Investments are also needed for **EVs, battery technology, charging infrastructure, and alternative fuel types** to decarbonise the transportation sector.

- Policymakers need to **consider annual public financing in sustainable agricultural practices** and investments that address heightened demand and minimise food waste. This includes exploring financing opportunities in technologies such as those related to disease resistance and sustainable farming practices.

- To decarbonise the industrial sector, investments are required **for less carbon-intensive power generation, green hydrogen production, and specialised equipment**. For example, steel and cement sub-sectors require investments in clean technologies and innovative processes.

- Investment opportunities to decarbonise buildings include **digitalisation, 'green' building materials, renewable energy, low-emissions building design and construction, material efficiency, and retrofits**.

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[1] All dollar symbols are US dollars unless otherwise stated

Suitability considerations of scenarios for exploring financing

Limited information and detail	Some information and detail	Good information and detail
▪ Limited sector granularity to identify investment opportunities for the buildings, AFOLU, and industrials sectors ▪ No information on adaptation finance ▪ No explicit modelling of the financial sector ▪ Breakdown of financing is not reported at the sectoral level (i.e. private or public) nor by institution type ▪ Information on the risks associated with specific investments & the capital and provision needed for investments is not provided ▪ Limited consideration of costs associated with capital spending ▪ The impacts of changing economic conditions on investments & availability of finance are not taken into account ▪ Lack of clear considerations of cost of capital in different regions, rendering the expected financial return from projects unclear.	▪ Information available on investment opportunities for the energy and transportation sector ▪ Some variables are only covered by certain integrated assessment models	▪ Show levels of financing needed and offer a broad view of potential allocations for limiting warming ▪ Able to identify investment opportunities and potential new markets for firms looking to accelerate the transition to a net-zero economy

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Suitability considerations of scenarios for exploring financing in the energy sector

Overall rating: average to good

Potential areas of greatest suitability: Policy design and analysis

Limited information and detail	Some information and detail	Good information and detail
▪ No explicit modelling of the financial sector ▪ Breakdown of financing is not reported at the sectoral level (i.e. private or public) nor by institution type ▪ Information on the risks associated with specific investments and the capital and provision need for investments is not provided ▪ Limited consideration of costs associated with capital spending ▪ The impacts of changing economic conditions on investments & availability of finance are not taken into account ▪ Lack of clear considerations of cost of capital in different regions, rendering the expected financial return from projects unclear.		▪ Show levels of financing needed and offer a broad view of potential allocations for limiting warming ▪ Able to identify investment opportunities and potential new markets for firms looking to accelerate the transition to a net-zero economy

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Suitability considerations of scenarios for exploring financing in the transportation sector

Overall rating: average to limited

Potential areas of greatest suitability: Policy design and analysis

Limited information and detail	**Some information and detail**	**Good information and detail**
▪ Limited view of investments needed for some of the transport sub-sectors, such as aviation and shipping. ▪ Lack of modelling covering the financing needs for alternative fuels ▪ No explicit modelling of the financial sector ▪ Breakdown of financing is not reported at the sectoral level (i.e. private or public) nor by institution type ▪ Information on the risks associated with specific investments & the capital and provision needed for investments is not provided ▪ Limited consideration of costs associated with capital spending ▪ The impacts of changing economic conditions on investments & availability of finance are not taken into account ▪ Lack of clear considerations of cost of capital in different regions, rendering the expected financial return from projects unclear.	▪ Information available on investment opportunities for the transportation sector ▪ Some variables available are only covered by certain integrated assessment models (e.g., investments in infrastructure and EVs)	▪ Offer a broad view of potential allocations of financing for the sector

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Suitability considerations of scenarios for exploring financing in the agriculture sector

Overall rating: limited

Potential areas of greatest suitability: High-level policy planning

Limited information and detail	Some information and detail	Good information and detail
▪ No variables available that directly cover investment for the sector ▪ Sector granularity is highly limited and therefore pathways do not address the financing needs for the sector and cannot be used to be made definitive statements on investment opportunities for financial institutions	▪ Information available on changes in land use, agriculture production and demand which can be used to infer investment needs for the sector to decarbonise	

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Suitability considerations of scenarios for exploring financing in the industrials sector

Overall rating: limited

Potential areas of greatest suitability: High-level policy planning

Limited information and detail	Some information and detail	Good information and detail
▪ No variables available that directly cover investment for the sector ▪ Sector granularity is highly limited and therefore pathways do not address the financing needs for the sector and cannot be used to be made definitive statements on investment opportunities for financial institutions	▪ Information available on changes in energy use for the sector, including carbon intensity and final energy amount of various industrial processes and the use of carbon sequestration. These variables can be used to infer investment needs for the sector to decarbonise	

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Suitability considerations of scenarios for exploring financing in the real estate sector

Overall rating: limited

Potential areas of greatest suitability: High-level policy planning

Limited information and detail	Some information and detail	Good information and detail
▪ No variables available that directly cover investment for the sector ▪ Sector granularity is highly limited and therefore pathways do not address the financing needs for the sector and cannot be used to be made definitive statements on investment opportunities for financial institutions	▪ Information available on changes in energy use for the sector, including electricity, heating and gas use of buildings. For example, energy use of appliances, cooking and cooling. These variables can be used to infer investment needs for the sector to decarbonise	

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Considerations for policymakers

- What actions has the jurisdiction taken to drive the financing required to support the transition to a low-carbon economy?
- Does the jurisdiction have near-, mid-, and long-term plans to meet the decrease in financing required in 1.5°C pathways with no or limited overshoot for fossil fuel-intensive activities?

Socioeconomic considerations to limit warming to 1.5°C

This chapter offers an extensive overview of Shared Socioeconomic Pathways (SSPs) and the socioeconomic drivers present in 1.5°C scenarios, including factors such as GDP, wealth, population growth, diets, and behavioural change. It delves into the drivers behind these socioeconomic factors and explores the implications of socioeconomic assumptions on scenarios. Additionally, the chapter examines the socioeconomic limitations inherent in scenarios, providing valuable insights into the complexities and challenges associated with modelling socioeconomic factors in climate scenarios.

Key messages

- Shared Socioeconomic Pathways (SSPs) consist of a narrative that outlines characteristics of the global future and country-level population, gross domestic product (GDP), and urbanisation projections over the next century.
- Socioeconomic **assumptions can have implications** on emissions and, therefore, mitigation efforts; for example, pathways with assumptions leading to higher energy and food demand will require more mitigation due to persistent demand for existing energy sources, and greater quantities of food and goods needing to be produced.
- The majority of 1.5°C scenarios with no or limited overshoot are aligned with the assumptions of SSP2, where trends broadly follow their historical patterns through the 21st century.
- The IPCC-assessed 1.5°C scenarios with no or limited overshoot assume a population increase from 7.7 billion people (median) in 2020 to 9.2 billion (median) in 2050, **aligning with the population growth estimates from SSP2**.
    - Common data sources for population estimates include the UN Population Prospects and the IMF World Economic Outlook.
- The IPCC-assessed 1.5°C scenarios with no or limited overshoot assume an increase in GDP (PPP) from 112 trillion US$2010/yr ***(median)*** in 2020 to 247 trillion US$2010/yr ***(median)*** in 2050, **aligning with the GDP growth estimates from SSP2**.
    - Common data sources for GDP are the IMF World Economic Outlook and Economic Forecasts by Oxford Economics.
- Behavioural shifts can play a crucial role in emissions reductions in sectors where mitigation options are limited. **Scenarios are taking behavioural changes into consideration through various assumptions**. Examples include changes in energy consumption by consumers in everyday life, for example, and the decrease in the gap in energy use between high-income and low-income countries (IEA, 2023).

Suitability considerations of scenarios for exploring socioeconomic assumptions

Limited information and detail	Some information and detail	Good information and detail
▪ Information on equality, equity, and justice as a result of climate change is not provided ▪ Limited direct variables available on behavioural shifts ▪ Shock events are not incorporated ▪ Information on the impacts of climate change on social aspects, such as climate migration and geopolitical conflict are not available ▪ Most scenarios use the same socioeconomic narrative, in line with the assumptions of SSP2	▪ Scenarios are in line with one of the Shared Socioeconomic Pathways ▪ Consideration is given to socioeconomic factors related to poverty, employment, diets and the risk of hunger, and urbanisation ▪ Readily accessible information on key socio-economic assumptions, such as population and GDP	

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Considerations for policymakers:

- How do the jurisdiction’s socioeconomic projections (for example, GDP and population growth) differ from the assumptions of SSP2?

In order for readers to determine how these scenarios can be applied and the type of information the scenarios provide, the report examines the benefits and drawbacks of climate scenarios. Understanding these is crucial for policymakers and financial institutions to comprehend how to use climate scenarios effectively in their own assessment.

Climate scenario benefits to consider for use:

- Understand the levels of emission reductions that are needed for limiting global warming to 1.5°C with no or limited overshoot.
- Determine near-term and long-term actions for mitigation efforts.
- Identify the lowest cost mitigation options to reach a given global warming target level.
- Understand assumptions for technology deployment across scenario pathways for the coming decades.
- Enable the alignment of financing activities with science-based 1.5°C pathways.
- Determine investment opportunities and markets created by a decarbonising world.
- Shows a broad view of potential allocations.
- High granularity for the energy sector and energy systems across the global economy.

Climate scenario limitations to consider for use:

- Due to the nature of the review and modelling processes, rapid technological developments and other trends may not be captured in climate scenarios, and thus, some scenario assumptions may be out of date by publication.
- Variable scopes and their definitions are inconsistent across the models.
- Instances of inconsistencies exist between model data provided on the AR6 scenario explorer and the source data for the model outputs.
- The socio-political feasibility of the rapid phase-out of fossil fuels among countries lacks consideration.
- Pathway trajectories are influenced by selection bias and compound bias of models.
- Exogenous or semi-exogenous estimates of macroeconomic factors result in these factors not being sensitive to the scenario dynamics.
- Simplified representation of the global economy means shock events are not fully accounted for.
- Representation of other SSPs and their socioeconomic assumptions in pathways are limited.
- Least cost assumptions may lead to financing needs being underestimated.

In order for readers to determine how these scenarios can be applied and the type of information the scenarios provide, the report examines the benefits and drawbacks of climate scenarios. Understanding these is crucial for institutions to comprehend how to use climate scenarios effectively in their own assessment.

Executive summary

Climate-related impacts are already being felt, with global temperatures now more than 1.1°C above pre-industrial times. The best available science states that "with every additional increment of global warming, changes in weather extremes continue to become larger" (IPCC, 2021). Understanding the potential risks posed by a warming planet, 196 Parties agreed in 2015 to **limit global warming** to well below 2°C, **preferably to 1.5°C**, as part of the Paris Agreement. As the projected losses and damages of 2°C warming significantly exceed those of 1.5°C warming, global efforts are focused on limiting global temperature rise to the latter level (IPCC, 2022).

To limit the most catastrophic impacts of climate change on economies and societies, the cumulative amount of carbon dioxide (CO_2) emissions emitted over time cannot exceed the remaining carbon budget for limiting global warming to 1.5°C. One key attribute for staying within the fixed carbon budget is reaching net zero by 2050. The Intergovernmental Panel on Climate Change (IPCC) defines achieving net zero emissions as when **"anthropogenic emissions of greenhouse gases to the atmosphere are balanced by anthropogenic removals over a specified period"** (IPCC, 2018). Since the Paris Agreement, recent documents such as the Glasgow Climate Pact[1] and IPCC's Assessment Report 6 (AR6) and Special Report on Global Warming of 1.5°C refer to net zero CO_2 emissions to limit warming to 1.5°C.

AR6 by the IPCC provided new evidence of global warming exceeding 1.5°C this century unless greenhouse gas (GHG) emissions are significantly reduced. According to the IPCC, this decade is critical in limiting warming to 1.5°C, with actions taken over the next few years critical to get us on track for our climate goals. With the window to restrict emissions quickly closing, financial institutions must take concrete steps to drive decarbonisation across sectors and regions, for which scenario analysis has become a vital tool. The IPCC assessed 97 scenarios pathways for limiting warming to 1.5°C with no or limited overshoot.[2] These scenarios can help financial institutions assess their preparedness against climate risks and transition to a low-carbon pathway.

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[1] Climate pact agreed upon by countries at COP26 in 2021

[2] Period of time in which global warming temporarily exceeds 1.5°C before cooling down.

Purpose of this report

This report by the United Nations Environment Programme Finance Initiative (UNEP FI) serves as a financial practitioner's guide to understanding the key attributes of IPCC-assessed scenario pathways that limit temperature rise to 1.5°C with no or limited overshoot. In addition, it highlights the required actions that arise from these scenario pathways for different sectors as well as considering how these climate scenarios can be used in practice. These scenarios comprise a combination of mitigation actions and are useful in identifying robust features for a 1.5˚C pathway that have reached a consensus in the scientific community. This report aims to achieve the following key objectives:

- Enhancing the interpretability of climate scenarios for financial users.
- Identifying common milestones in the path to decarbonisation in climate scenarios.
- Improving the understanding of how financial institutions should effectively use climate scenarios, along with clarification of their inherent limitations.

The report is structured around distinct themes that explore the implications of these scenario pathways for emissions, carbon dioxide removal, energy demand across sectors, financing needs, and socioeconomic assumptions. These chapters are designed to take on questions related to the scenarios, including:

- What are the attributes on which climate models agree and disagree?
- What are the uncertainties among scenarios for specific variables?
- How does the data shown in the scenario pathways compare to current progress?
- How does the IPCC-assessed scenario data set compare to commonly used scenarios by the Network for Greening the Financial System (NGFS) and the International Energy Agency (IEA)?
- What information can be obtained from scenarios by financial users for climate risk assessment, target setting, and mitigation action?
- What are the gaps and drawbacks of climate scenarios in use by financial institutions?

This document is intended to be a resource for financial institutions, equipping readers with insights to enhance their knowledge on 1.5°C scenarios with no or limited overshoot. The end goal is to enable them to better leverage climate scenarios for scenario analysis within their respective institutions. Use cases for the report have been described in the table below.

Table 1: Summary of key use cases of the report

Use cases of the report	How to use the report
Build expertise on the mitigation actions needed to reach 1.5°C	The report summarises key mitigation actions needed to reach net zero by 2050 and to limit warming to 1.5°C. These mitigation actions are compared to the current progress being made.
Build knowledge on the key attributes of 1.5°C pathways with no or limited overshoot	Each chapter details the key attributes of the IPCC-assessed 1.5°C scenarios with no or limited overshoot, including the median data and the interquartile range for specific variables.
Determine appropriate scenarios to use for scenario analysis	The report provides data on the IPCC-assessed scenario dataset, including showing the median, lower and upper quartile values for certain variables. Users can compare specific scenarios to these values to determine whether those scenarios are more or less optimistic than the scenario dataset. This can be used by financial users to then infer whether the scenario is appropriate to use for scenario analysis.
Understand the key assumptions of commonly used scenarios	Each chapter provides a comparison of the IPCC-assessed scenario dataset with commonly used scenarios by the NGFS and the IEA for specific variables. The comparisons can be used by financial users to understand the key features of these scenarios and how similar or different they are to other 1.5°C scenarios with no or limited overshoot.
Validate the key assumptions of your scenario analysis	The report analysis the key attributes of the IPCC-assessed scenario dataset. Financial users can compare the assumptions of a selected scenario to the median values and interquartile range of the IPCC-assessed scenarios for certain variables to determine whether the particular scenario is in line with the attributes of 1.5°C pathways that have reached consensus by the modelling community. The analysis can be used to determine where the robustness lies in scenario assumptions.
Determine the type of scenario enhancements needed for use	The report analyses the available variables, coverage, and granularity of the IPCC-assessed scenarios. On top of this, the report explains the limitations of climate scenarios. This information can then assist financial users to determine the type of scenario enhancements that they need to perform internally when conducting scenario analysis.
Understand how to use the outputs of a scenario analysis	The report examines the benefits and drawbacks of climate scenarios. By understanding these, financial users can determine how to best use the information provided by climate scenarios.

Key characteristics of the IPCC-assessed 1.5°C scenarios with no or limited overshoot:

Overview of emissions in pathways:

- The IPCC-assessed 1.5°C scenarios with no or limited overshoot report:
    - Deep and rapid cuts in CO_2 by 2030, with other GHG emissions following shortly thereafter.
    - CO_2 emissions decrease by 46% *(median)* from 2020 to 2030, and by 97% *(median)* from 2020 to 2050.
    - Methane (CH_4) emissions decrease by 31% *(median)* from 2020 to 2030, and by 50% *(median)* from 2020 to 2050.
    - Nitrous oxide (N_2O) emissions decrease by 18% *(median)* from 2020 to 2030, and by 27% *(median)* from 2020 to 2050.
    - F-gases emissions decrease by 76% *(median)* from 2020 to 2030, and by 88% *(median)* from 2020 to 2050.
- Key mitigation actions needed to reduce these GHG emissions include, but are not limited to, the transition to clean energy (such as wind and solar), the use of carbon sequestration, improvements to energy efficiency, the introduction of fuel-efficient light-duty vehicles, the adoption of low-carbon land uses, and the restoration of degraded lands.

Overview of carbon dioxide removal (CDR) in pathways:

The IPCC defines carbon capture and storage (CCS) as:

> **"A process in which a relatively pure stream of carbon dioxide (CO_2) from industrial and energy-related sources is separated (captured), conditioned, compressed and transported to a storage location for long-term isolation from the atmosphere."**
>
> IPCC, 2021[3]

- The IPCC-assessed 1.5°C scenarios with no or limited overshoot report an increase in CCS use from 0.04 megatonnes (Mt) CO_2 per year (CO_2/yr) *(median)* in 2020 to 1,095 MtCO_2/yr in 2030 *(median)*, and to 7,287 MtCO_2/yr *(median)* in 2050.

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[3] Note: The IPCC definition of CCS does not specify the different types of CCS considered in 1.5°C scenarios with no or limited overshoot. It is important to consider the various types of CCS, such as industrial and energy CCS.

The IPCC defines CDR as:

> **"Anthropogenic activities removing carbon dioxide (CO_2) from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical CO_2 sinks and direct air carbon dioxide capture and storage (DACCS), but excludes natural CO_2 uptake not directly caused by human activities."**
>
> IPCC, 2021

- CDR includes a variety of methods, such as Bioenergy with Carbon Dioxide Capture and Storage (BECCS), Direct Air Carbon Dioxide Capture and Storage (DACCS), afforestation, and soil carbon sequestration.
- The IPCC-assessed 1.5°C scenarios with no or limited overshoot show:
  - The use of BECCS and DACCS increasing by almost 12-fold and 10-fold *(median)* between 2030 and 2050, respectively.
  - The use of carbon sequestration from land use increasing by 6-fold *(median)* from 2020 to 2030 and 29-fold *(median)* between 2020 and 2050.
- Many obstacles remain in the development and deployment of these technologies, including high costs, the early stage nature of many technologies, risk of leakage, permanence, pollution, transportation of CO_2, high energy and water use, and competition for land use.

Overview of energy demand in pathways:

Energy sector

- The sector covers the total production and supply of energy, including the extraction, manufacturing, refining, and distribution of energy.
- The energy sector, including electricity and heat, accounts for one-third (33%) of global GHG emissions (IPCC, 2022).
- IPCC-assessed 1.5°C scenarios with no or limited overshoot show:
  - A rapid phase-out of fossil fuels in the global energy mix, with a decrease in primary energy generated from coal (73%) *(median)*, oil (10%) *(median)* and natural gas (11%) *(median)* between 2020 and 2030.
  - A massive scale-up in non-biomass renewables, with an increase in primary energy generated from solar by 746% *(median)* and wind by 323% *(median)* from 2020 to 2030.

Transportation sector

- The sector covers motorised land, sea, and air transport, focusing on emissions from manufacturing, use, and related infrastructure.
- The transportation sector accounts for 15% of global GHG emissions (IPCC, 2022).
- Key actions to decarbonise the transportation sector include a switch to electric vehicles (EVs), improvements in the energy efficiency of vehicles, and the adoption of alternative fuels, such as hydrogen and biofuel.

- 1.5°C scenarios with no or limited overshoot show final energy generated from electricity for the transport sector increasing from 1.8 exajoules per year (EJ/yr) *(median)* in 2020 to 22.8 EJ/yr *(median)* in 2050, as well as an increase in the sector's use of hydrogen for energy from almost nothing in 2020 to 3.6 EJ/yr *(median)* in 2050.

Agriculture sector

- The sector covers ecosystems managed for producing and delivering food, obtaining natural resources, and conserving biodiversity.
- The agriculture, forestry, and other land use (AFOLU) sector accounts for 22% of global GHG emissions (IPCC, 2022).
- Key actions to decarbonise the agriculture sector include the electrification of machinery, the use of minimum tillage practices, and the adoption of renewable alternatives.
- The IPCC-assessed 1.5°C scenarios with no or limited overshoot report an increase in demand for per capita calories from 2,946 kilocalories for person per day (kcal/cap/day) *(median)* to 3,025 kcal/cap/day *(median)* from 2020 to 2050.

Industrials sector

- The sector covers the processing and manufacturing of metals, minerals, and chemicals, as well as including direct and indirect emissions from fuel combustion and chemical processes.
- The industrials sector accounts for 24% of global GHG emissions (IPCC, 2022).
- Key actions to decarbonise the industrials sector include the use of CCUS (Carbon Capture, Usage and Storage), electrification and use of renewable alternatives, waste reduction, and supplementation of carbon-intensive materials with low-carbon materials.
- The IPCC-assessed 1.5°C scenarios with no or limited overshoot report a reduction in the carbon intensity of steel by 84% *(median)* and of cement by 81% *(median)* from 2020 to 2050.

Real estate sector

- The real estate sector accounts for 21% of global GHG emissions (including both direct and indirect emissions) (IPCC, 2022).
- The sector covers energy used for construction, heating, cooling, and lighting of buildings, plus the appliances and equipment installed in them (IEA, n.d.).
- Key actions to decarbonise the real estate sector include renovating and reusing buildings, designing lower-carbon concrete mixes, limiting carbon-intensive materials, reusing materials, using carbon-sequestering materials, maximising structural efficiency, and reducing waste.
- 1.5°C scenarios with no or limited overshoot report a global final energy consumption of electricity in residential buildings increase by 38% *(median)* from 2020 to 2050.

Overview of financing and investment levels referenced in pathways:

- The IPCC-assessed 1.5°C scenarios with no or limited overshoot report globally investments in new power generation from:
    - Coal decreasing from 58.2 billion USD 2010/yr *(median)* in 2020 to 12.7 billion USD 2010/yr *(median)* in 2030.
    - Oil decreasing from 0.05 billion USD 2010/yr *(median)* in 2020 to 0.01 billion USD 2010/yr *(median)* in 2030.
    - Gas decreasing from 59.9 billion USD 2010/yr *(median)* in 2020 to 30.8 billion USD 2010/yr *(median)* in 2030.
    - Solar increasing from 132.7 billion USD 2010/yr *(median)* in 2020 to 427.5 billion USD 2010/yr *(median)* in 2030.
    - Wind increasing from 102.6 billion USD 2010/yr *(median)* in 2020 to 391.6 billion USD 2010/yr *(median)* in 2030.
- Decarbonisation of the transport sector will require a shift in investment from Internal combustion engine vehicles (ICEVs) to EVs.
- From 2020 to 2030, the IPCC-assessed 1.5°C scenarios with no or limited overshoot report a reduction in investments in ICEVs from 1.1 billion USD 2010/yr *(median)* to 0.4 billion USD 2010/yr *(median)*.
- The number of models that offer a view for investments in the AFOLU, industrials, and real estate sectors are limited, and those that do exist have limited granularity.

Overview of socioeconomic assumptions in pathways:

- Shared Socioeconomic Pathways (SSPs) consist of a narrative that outlines characteristics of the global future and country-level population, gross domestic product (GDP), and urbanisation projections over the next century.
- Socioeconomic assumptions can have implications on emissions and, therefore, mitigation efforts; for example, pathways with assumptions leading to higher energy and food demand will require more mitigation due to persistent demand for existing energy sources, and greater quantities of food and goods needing to be produced.
- The majority of 1.5°C scenarios with no or limited overshoot are aligned with the assumptions of SSP2, where trends broadly follow their historical patterns through the 21st century.
- The IPCC-assessed 1.5°C scenarios with no or limited overshoot assume population increase from 7.7 billion people *(median)* in 2020 to 9.2 billion *(median)* in 2050, aligning with the population growth estimates from SSP2.
    - Common data sources for population estimates include the UN Population Prospects and the IMF World Economic Outlook.
- The IPCC-assessed 1.5°C scenarios with no or limited overshoot assume a population increase in GDP (PPP) from USD 112 trillion 2010/yr *(median)* in 2020 to USD 247 trillion 2010/yr *(median)* in 2050, aligning with the GDP growth estimates from SSP2.
    - Common data sources for GDP are the IMF World Economic Outlook and Economic Forecasts by Oxford Economics.

- Behavioural shifts can play a crucial role in emissions reductions in sectors where mitigation options are limited. Scenarios are taking behavioural changes into consideration through various assumptions. Examples include changes in energy consumption by consumers in everyday life, for example, and the decrease in the gap in energy use between high-income and low-income countries (IEA, 2023).

In order for readers to determine how these scenarios can be applied and the type of information the scenarios provide, the report examines the benefits and drawbacks of climate scenarios. Understanding these is crucial for financial institutions to comprehend how to use climate scenarios effectively in their own assessment.

Climate scenario benefits to consider for financial use:

- Understand the levels of emission reductions that are needed for limiting global warming to 1.5°C with no or limited overshoot.
- Determine near-term and long-term actions for mitigation efforts.
- Identify the lowest cost mitigation options to reach a given global warming target level.
- Understand assumptions for technology deployment across scenario pathways for the coming decades.
- Enable the alignment of financing activities with science-based 1.5°C pathways.
- Determine investment opportunities and markets created by a decarbonising world.
- Shows a broad view of potential allocations.
- High granularity for the energy sector and energy systems across the global economy.

Climate scenario limitations to consider for financial use:

- Due to the nature of the review and modelling processes, rapid technological developments and other trends may not be captured in climate scenarios, and thus, some scenario assumptions may be out of date by publication.
- Variable scopes and their definitions are inconsistent across the models.
- Instances of inconsistencies exist between model data provided on the AR6 scenario explorer and the source data for the model outputs.
- The socio-political feasibility of the rapid phase-out of fossil fuels among countries lacks consideration.
- Pathway trajectories are influenced by selection bias and compound bias of models.
- Exogenous or semi-exogenous estimates of macroeconomic factors result in these factors not being sensitive to the scenario dynamics.
- Simplified representation of the global economy means shock events are not fully accounted for.
- Representation of other SSPs and their socioeconomic assumptions in pathways are limited.
- Least cost assumptions may lead to financing needs being underestimated.

CHAPTER 1:

Introduction

1.1 Context

2021 was the year that net zero went mainstream. Following the United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP 26) in Glasgow, nearly 90% of global emissions were covered by a net-zero commitment of some form (Climate Action Tracker, 2021). Private-sector institutions have followed suit with their commitments. Following these promising announcements, commitments must be turned into tangible action. If net-zero commitments are the first step towards a low-carbon future, the next step involves the setting of credible targets. A number of financial alliances have developed target setting protocols (e.g., the Net-Zero Asset Owner Alliance, the Net Zero Asset Managers Initiative, and the Net-Zero Banking Alliance) to provide transparency and credibility regarding both final and interim net-zero targets. The UNFCCC's Race to Zero campaign, which accredits these financial alliances, has also provided guidance on defining 'net zero' (UNFCCC, 2021).

The Intergovernmental Panel on Climate Change (IPCC) published its Sixth Assessment Report (AR6) in separate iterations between 2021 and 2022 and a complete synthesis report in 2023. As part of the report, the IPCC assessed 97 scenarios pathways for limiting warming to 1.5 degrees Celsius (˚C) with no or limited overshoot. AR6 is the IPCC's first major report on limiting global warming to 1.5˚C since its Special Report on Global Warming of 1.5°C (SR15) in 2018.[4] AR6 provides new evidence[5] of global warming exceeding 1.5°C this century unless greenhouse gas (GHG) emissions are significantly reduced. According to the IPCC, this decade is critical in limiting warming to 1.5°C, with actions taken over the next few years determining whether global climate goals are met. With the window to restrict emissions quickly closing, financial institutions must take concrete steps to drive decarbonisation across sectors and regions.

However, many technical concepts around decarbonisation remain confusing for financial practitioners entrusted with guiding their organisations to net zero. A similar level of uncertainty pervades assumptions behind the various net-zero scenarios used for target setting. This paper by the United Nations Environment Programme Finance Initiative (UNEP FI) is a practitioner's guide to understanding the decarbonisation pathways assessed by the IPCC. Readers will be provided with a detailed view of scenario pathways that limit temperature rise to 1.5°C with no or limited overshoot. The insights provided aim to help financial institutions understand the key attributes of 1.5°C pathways with no or limited overshoot, the actions needed from these scenario projections and the limitations of using the climate scenarios.

1.2 Scientific consensus behind net zero and its importance

Climate impacts at 1.5°C and 2°C

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[4] For more details on the IPCC reports, see section 3.2.

[5] Further discussed in section 1.2

Climate change demands immediate action as society confronts the consequences of a warming world. Climate-related impacts are already being felt on the planet, with human-induced warming reaching 1.26°C in 2022 (Forster *et al.*, 2023). Climate change has intensified heat waves in South Asia and Europe, wildfires in the United States of America and Canada, and severe storms across Asia-Pacific. The IPCC's recent AR6 report paints a frightening picture of how these unnatural disasters will continue to worsen if climate change is not adequately addressed (IPCC, 2021). The IPCC states that "*the rise in weather and climate extremes has led to some irreversible impacts as natural and human systems are pushed beyond their ability to adapt*"(IPCC, 2022a). As illustrated in Figure 1, climate-related effects harm economies and societies worldwide in diverse ways.

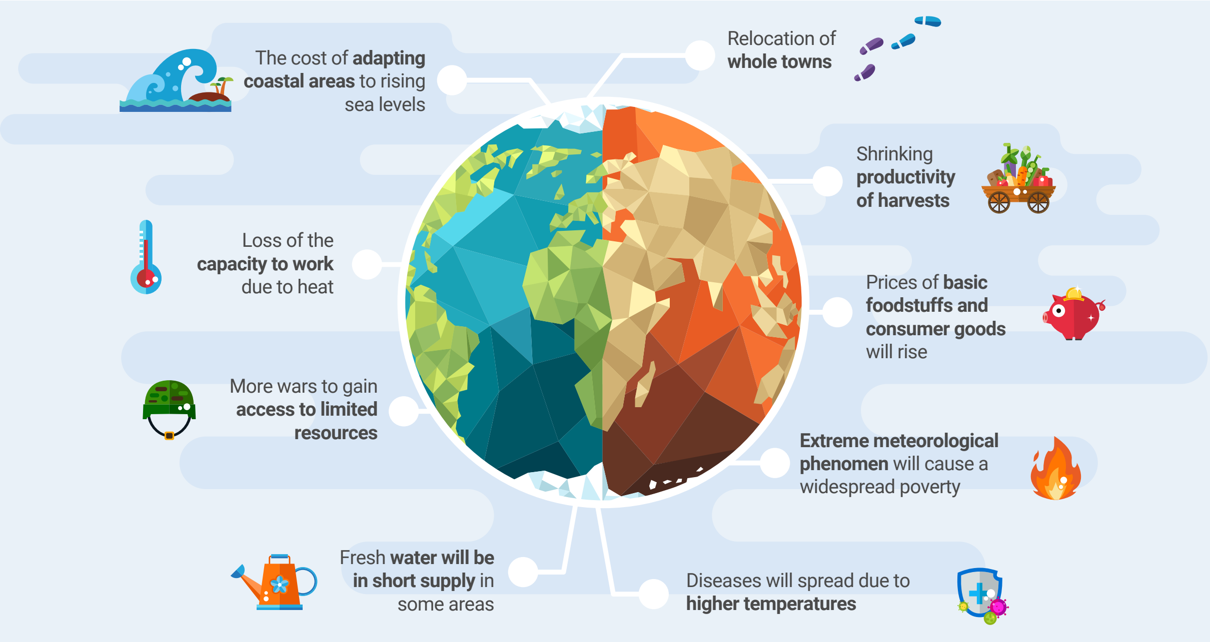
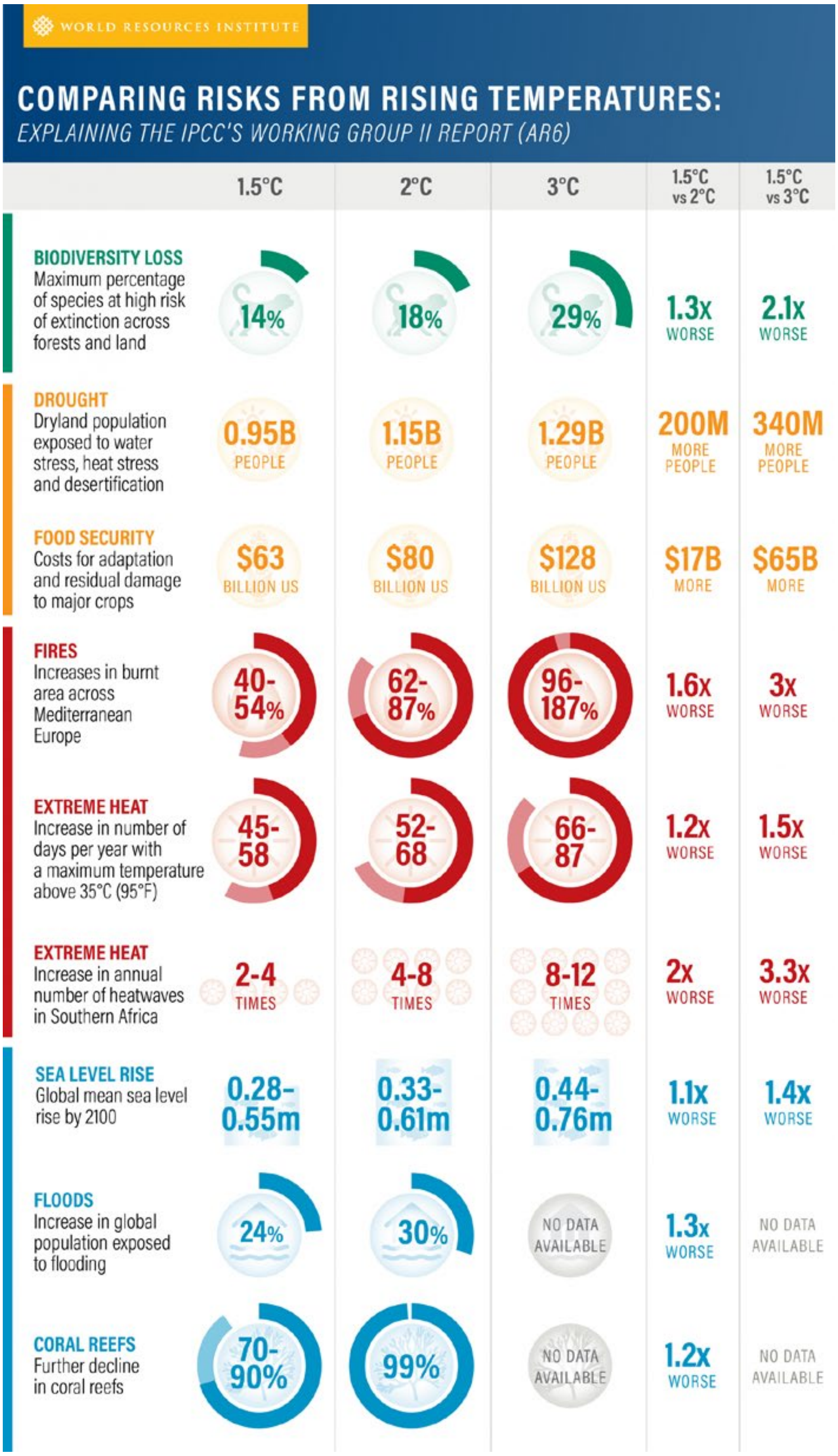


Figure 1: Impacts of climate change (Iberdrola, n.d.)

As climate change exacerbates natural and unnatural disasters, global leaders have become aware of the potential risks posed by a warming planet. At COP 21 in 2015, 196 Parties gathered together and concluded the Paris Agreement, a **legally binding international treaty on climate change** (UNFCCC, 2015). **The Paris Agreement aims to limit global warming** to well below 2°C, **preferably to 1.5°C**, compared to pre-industrial levels:

> **"Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognising that this would significantly reduce the risks and impacts of climate change." (Article 2)**

The impacts of 2°C warming can vary greatly from the impacts of 1.5°C warming. The IPCC has emphasised that "*with every additional increment of global warming, changes in weather extremes continue to become larger*". As a result, every additional 0.5°C rise in global temperature will lead to further increases in the severity and frequencies of heat waves, precipitation, droughts, and other weather events (IPCC, 2021). According to the IPCC's 2022 WGII Assessment Report (IPCC, 2022b), warming exceeding 1.5 degrees, even if only temporary, will lead to irreversible impacts, including stronger storms, increased heat waves, and extreme precipitation (IPCC, 2022b). Figure 2 highlights key differences in risks between a temperature rise of 1.5°C, 2°C, and 3°C (WRI, 2022).



WORLD RESOURCES INSTITUTE

COMPARING RISKS FROM RISING TEMPERATURES:
EXPLAINING THE IPCC'S WORKING GROUP II REPORT (AR6)

	1.5°C	2°C	3°C	1.5°C vs 2°C	1.5°C vs 3°C
BIODIVERSITY LOSS Maximum percentage of species at high risk of extinction across forests and land	14%	18%	29%	1.3x WORSE	2.1x WORSE
DROUGHT Dryland population exposed to water stress, heat stress and desertification	0.95B PEOPLE	1.15B PEOPLE	1.29B PEOPLE	200M MORE PEOPLE	340M MORE PEOPLE
FOOD SECURITY Costs for adaptation and residual damage to major crops	$63 BILLION US	$80 BILLION US	$128 BILLION US	$17B MORE	$65B MORE
FIRES Increases in burnt area across Mediterranean Europe	40-54%	62-87%	96-187%	1.6x WORSE	3x WORSE
EXTREME HEAT Increase in number of days per year with a maximum temperature above 35°C (95°F)	45-58	52-68	66-87	1.2x WORSE	1.5x WORSE
EXTREME HEAT Increase in annual number of heatwaves in Southern Africa	2-4 TIMES	4-8 TIMES	8-12 TIMES	2x WORSE	3.3x WORSE
SEA LEVEL RISE Global mean sea level rise by 2100	0.28-0.55m	0.33-0.61m	0.44-0.76m	1.1x WORSE	1.4x WORSE
FLOODS Increase in global population exposed to flooding	24%	30%	NO DATA AVAILABLE	1.3x WORSE	NO DATA AVAILABLE
CORAL REEFS Further decline in coral reefs	70-90%	99%	NO DATA AVAILABLE	1.2x WORSE	NO DATA AVAILABLE

Figure 2: Comparison between the impacts of 1.5°C to 2°C of warming (WRI, 2022)

In addition, scientific evidence increasingly supports the possible occurrences of a series of climate 'tipping points'—threshold points for nature or climate systems—that cannot be returned to their original state once passed. Tipping points can result in far-reaching and drastic consequences in the long term. Tipping points are likely to occur sooner with the continued rise in GHG emissions. There are a number of identified climate tipping points, including the Amazon rainforest dieback, permafrost loss, and the Atlantic meridional overturning circulation breakdown. Potential biosphere tipping points can trigger abrupt disasters for the environment and human activities. As tipping points can be triggered at low levels of global warming (Lenton *et al.*, 2019), reducing global GHG emissions represents an urgent priority.

Avoiding 1.5°C or 2°C warming

The Paris Agreement additionally calls for a balance in GHG emissions and removals in the second half of this century. Each signatory is requested to:

> **"…undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century…"**
>
> **UNFCCC, 2015**

This text has been essentially operationalised in different IPCC Special or Assessment reports. The IPCC's 2018 report, SR15, found that, on average, 1.5°C pathways with no or limited overshoot (going temporarily past 1.5°C before returning below) require: (i) a reduction of 45% in carbon dioxide (CO_2) emissions from 2010 levels by 2030; and (ii) to reach net zero CO_2 emissions around 2050. In comparison, 2°C pathways require a reduction of 25% of GHG emissions on average in 2030 from 2010 levels, with net zero emissions achieved by 2070 (IPCC, 2018). Similarly, the IPCC Sixth Assessment Report Working Group (IPCC AR6 WG) 1 report, released in 2021, had consistent findings:

> **"From a physical science perspective, limiting human-induced global warming to a specific level requires limiting cumulative CO_2 emissions, reaching at least net zero CO_2 emissions, along with strong reductions in other greenhouse gas emissions."**
>
> **IPCC, 2021a**

This finding has been embedded into the Glasgow Climate Pact, which recognises:

> **“…that limiting global warming to 1.5°C requires rapid, deep and sustained reductions in global greenhouse gas emissions, including reducing global carbon dioxide emissions by 45% by 2030 relative to the 2010 level and to net zero around mid-century, as well as deep reductions in other greenhouse gases.”**
>
> UNFCCC, 2021

The text of the Paris Agreement refers to net zero GHG emissions, while SR15, AR6, and the Glasgow Climate Pact all refer to net zero CO_2 emissions with sufficient reductions in non-CO_2 emissions. Although the understanding of net zero in these latter documents is closer to current physical science (Allen *et al.*, 2022), the implied consequences are the same—namely, that radical reductions are needed in the short term for all GHG emissions. Although reaching 1.5°C in the near term will not eliminate all the effects of climate change, it can significantly reduce the projected losses and damages compared to higher levels of warming (IPCC, 2022b).

National decarbonisation targets currently set by countries to reach net zero are falling short of the 1.5°C goal (UN, 2021). UNEP's Emissions Gap Report (2023) projected that annual emissions need to be 22 gigatonnes (Gt) of CO_2 equivalent (CO_2eq) lower than current unconditional Nationally Determined Contributions (NDCs) by 2030 to reach the 1.5°C goal, with the gap being reduced by 3 GtCO_2eq when considering conditional NDCs. IPCC AR6 WGIII concluded that limiting warming to 1.5°C with limited overshoot will not be possible under current NDCs (IPCC, 2022a).

Nevertheless, there are promising signs of a successful transition to a low-carbon economy. For example, global investment in the low-carbon energy transition totalled USD 1.1 trillion in 2022—a new record and a huge acceleration from the year before—as the energy crisis and policy action drove deployment of clean energy technologies. (BloombergNEF, n.d.). As of July 2022, 75 countries had agreed not to develop new coal power plants or to phase out coal (IEA, 2023a). These promising moves need to be expanded and accelerated across the globe.

Relationship between 1.5˚C and net zero

The IPCC commonly refers to the concept of our "*remaining carbon budget*" for limiting global warming to 1.5°C. The "remaining carbon budget" refers to the estimated cumulative amount of CO_2 emissions that would be permissible over a period of time to successfully limit global warming to a specific level, such as 1.5°C (IPCC, 2018). The carbon budget concept is based on the relationship between CO_2-induced temperature rise and cumulative CO_2 emissions (IPCC, 2018). The IPCC AR6 WG1 estimates that, from the start of 2020, a remaining carbon budget of 500 GtCO_2 would give a 50% probability of staying below 1.5°C, whereas 400 GtCO_2 would provide a 67% probability (IPCC, 2021). Updated to 2023 and using the latest emission estimates, our remaining carbon budget is estimated at 250 GtCO_2 and 150 GtCO_2 to provide a 50% and 67% probability of limiting warming to 1.5°C, respectively (Forster *et al.*, 2023). A study by Lamboll *et al.*, (2023) determined that at the current rate of CO_2 emissions, the remaining carbon budget to limit warming to 1.5°C with a 50% probability is only six years (Lamboll *et al.*, 2023).

The consequence of a fixed carbon budget is that CO_2 emissions need to reach net zero. The IPCC defines achieving net zero emissions as when "**anthropogenic emissions of greenhouse gases to the atmosphere are balanced by anthropogenic removals over a specified period**" (IPCC, 2018). A pathway to net zero can still exceed the carbon budget if short-term reductions are insufficient (4C Carbon Outlook, 2021).

The term 'net zero' is confused with other common, related, but distinct climate terms used. Table 2a and b differentiate net zero from these other terms.

Table 2a: Differentiating 'net zero' from 'absolute zero' and 'carbon neutral' (Race to Zero, 2021)

Net Zero	Absolute Zero	Carbon Neutral
"When anthropogenic emissions of greenhouse gases to the atmosphere are balanced by anthropogenic removals over a specified period."	"When no greenhouse gas emissions are attributable to an actor's activities across all scopes."	"A state in which human activities result in no net effect on the climate system."

Table 2b: Differentiating net zero CO_2 and GHG emissions (IPCC, 2021)

Net Zero CO_2 emissions	Net Zero GHG emissions[6]
"Condition in which anthropogenic carbon dioxide (CO_2) emissions are balanced by anthropogenic CO_2 removals over a specified period."	"Condition in which metric-weighted anthropogenic greenhouse gas (GHG) emissions are balanced by metric-weighted anthropogenic GHG removals over a specified period."

1.3 Net zero in the financial sector

Responding to calls for urgent climate action, many countries, cities, businesses, and financial institutions are pledging to achieve net zero emissions.

Major economies such as the United States of America, the European Union, the United Kingdom, Japan, and Canada have already committed to achieving net zero by 2050. China—currently the world's largest CO_2 emitter—has pledged to achieve net zero carbon emissions by 2060. Additionally, by November 2023, 145 countries had announced or were considering some form of a net-zero goal, with many under discussion or undergoing the legislative process (Climate Action Tracker, 2023). In 2021, the UNFCCC stated that 150 of the 193 Parties to the Paris Agreement submitted new or updated NDC action plans for the next 5–10 years to limit temperature rise to below 1.5°C (UNFCCC, 2021b).

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[6] Net zero GHG emissions is not as clearly defined as net zero CO_2 as metrics are vague and open to debate.

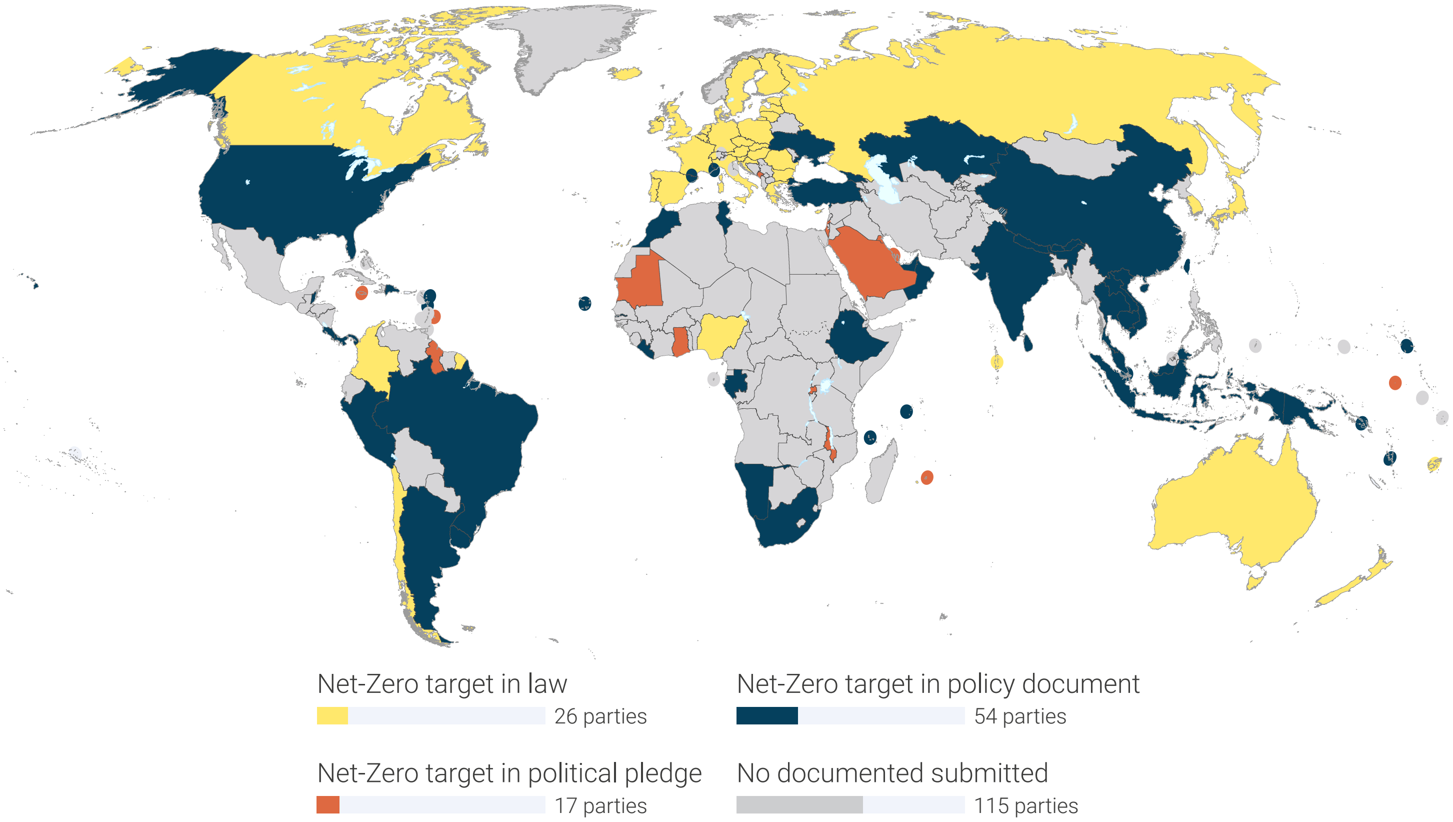


Figure 3: Net-zero commitments status for countries (Net-Zero Tracker, 2023)

By 2021, more than 700 cities in 53 countries committed to halving their emissions by 2030 and reach net zero by 2050 (C40, 2021); more than one-third of the world's 2,000 largest publicly traded companies set net-zero targets, up from one-fifth in 2020. Similarly, by September 2022, over 1,136 cities, 52 states and regions, and 8,307 companies and 595 financial institutions became members of the United Nations' Race to Zero Campaign (UNFCCC, 2022d).

The financial sector plays a critical role in addressing climate change, shouldering the responsibility of financing the transition to a low-carbon economy and thus enabling these wider net-zero commitments. Financial institutions can lead the race to net zero by mobilising capital to decarbonise sectors and industries at the scale needed to achieve net zero emissions. In the past few years, several net-zero initiatives in the financial sector have been established to facilitate the world economy's green transition (Table 3).

Table 3: Leading net-zero initiatives for financial institutions

Initiative	Description
Initiatives by UNEP FI	
Net-Zero Asset Owners Alliance (NZAOA)	▪ The NZAOA currently includes over 86 asset owners representing USD 11 trillion Assets under Management. ▪ This alliance unites investors under the common goal of transitioning their investment portfolios to achieve net zero GHG emissions by 2050. ▪ In January 2023, the Third edition of the Target-Setting Protocol was published, setting out a pathway to reduce portfolio emissions for major institutional investors worldwide.
Net-Zero Banking Alliance (NZBA)	▪ The NZBA comprises a group of 132 banks representing over USD 74 trillion in global banking assets that commit to transition to net zero by 2050 or sooner. ▪ Signatories agree to set a 2030 and 2050 target within 18 months of signing. ▪ Participating banks are expected to set intermediary targets every five years after 2030. ▪ Signatories must publish annual absolute emissions, emissions intensity, and progress against a board-reviewed climate strategy.
Other initiatives	
Net Zero Asset Managers initiative (NZAM)	▪ The NZAM includes 301 asset manager signatories that collectively manage USD 59 trillion in assets. ▪ Signatories have committed to working with their asset-owner clients to move towards net zero emissions by 2050. ▪ Member organisations formally commit to consider portfolio Scope 1 and 2 emissions, while also setting respective emissions reduction targets for 2030. ▪ Members are also expected to engage in relevant policy advocacy, publish disclosures annually in line with the recommendation of the Task Force on Climate-Related Financial Disclosures (TCFD), and submit these to the Investor Agenda.
Paris Aligned Investment Initiative (PAII)	▪ The PAII represents 56 asset owners managing USD 33 trillion in assets, all of which commit to aligning their investment portfolios with the goals of the Paris Agreement. ▪ It is supported by four regional investor networks: the Asia Investor Group on Climate Change, Ceres (North America), Institutional Investors Group on Climate Change (Europe), and Investor Group on Climate Change (Australasia).

Net Zero Financial Service Providers Alliance (NZFSPA)	- The NZFSPA was launched by 17 founding organisations: BDO, Bloomberg, Campbell Lutyens, Deloitte, De Vere, EY, Grant Thornton, KPMG, London Stock Exchange Group, Minerva Analytics, Moody's Corporation, Morningstar, MSCI, PwC, Singapore Exchange, Solactive, and S&P Global. - This alliance includes investment advisors, rating agencies, auditors, exchanges, index providers, ESG research and data providers, and proxy research providers. - Members have committed to aligning their services and products to achieving net zero GHG emissions by 2050. - It is supported by the Principles for Responsible Investment, known as the 'PRI', and the Sustainable Stock Exchanges Initiative.
Net Zero Investment Consultants Initiative (NZICI)	- The NZICI's founding members, with assets exceeding USD 10 trillion, are Barnett Waddingham, bfinance, Cambridge Associates, Cardano, Frontier, Hymans Robertson, JANA, LCP, Meketa, Redington, Willis Towers Watson, and Wilshire. - The initiative has set out nine actions for investment consultants to support the global goal of net zero emissions by 2050.

The link between the net-zero alliances is further strengthened by the United Nations (UN) Race to Zero campaign, whose scope includes financial institutions with real economy businesses, cities, and regions. The short-term goal of the Race to Zero is to halve global emissions by 2030—something that all signatories must commit to do on joining the campaign. Further, within 12 months, they must explain the actions that they will take going forward to achieve this. Each is also required to publish an annual progress report. Targets must include Scope 1, 2, and 3 emissions, with offsets not included in the emission calculations.

1.4 Actions to mitigate climate change

Reaching net zero by 2050 needs a rapid and sustained transition to clean energy, reduction of emissions from industrial processes, increased use of sustainable and efficient agricultural practices, and greater uptake of nature-based solutions to reduce vegetation loss and restore degraded lands (WRI, 2020; WRI, 2023). Scenarios reaching net zero by 2050 often include these vital activities in various ways and to different extents. Until now, however, limited progress has been made in meeting the emission reduction targets needed to reach net zero by 2050 (WRI, 2020). Figure 4 shows ten key actions to reduce GHG emissions.

Figure 4: Key actions to reduce GHG emissions (WRI, 2023)

According to the UNEP's Emission Gap Report 2023, current existing policies will lead to a 3°C temperature increase. Achieving all unconditional and conditional NDC pledges by 2030 will lead to a global temperature rise of 2.5°C, and meeting all announced net-zero pledges would limit global warming to 2°C. Current greenhouse gas emissions will need to be reduced by 42% by 2030 to achieve the goal of limiting global warming to 1.5°C (UNEP, 2023a). According to UNEP's Production Gap Report (2023), governments intend to produce about 110% more fossil fuels in 2030 than those consistent with the 1.5°C pathway. Current government plans and projections will lead to 460% more coal, 29% more oil, and 82% more gas by 2030 than the levels needed to limit the global temperature rise to 1.5°C, as illustrated in Figure 5 (UNEP, 2023b).

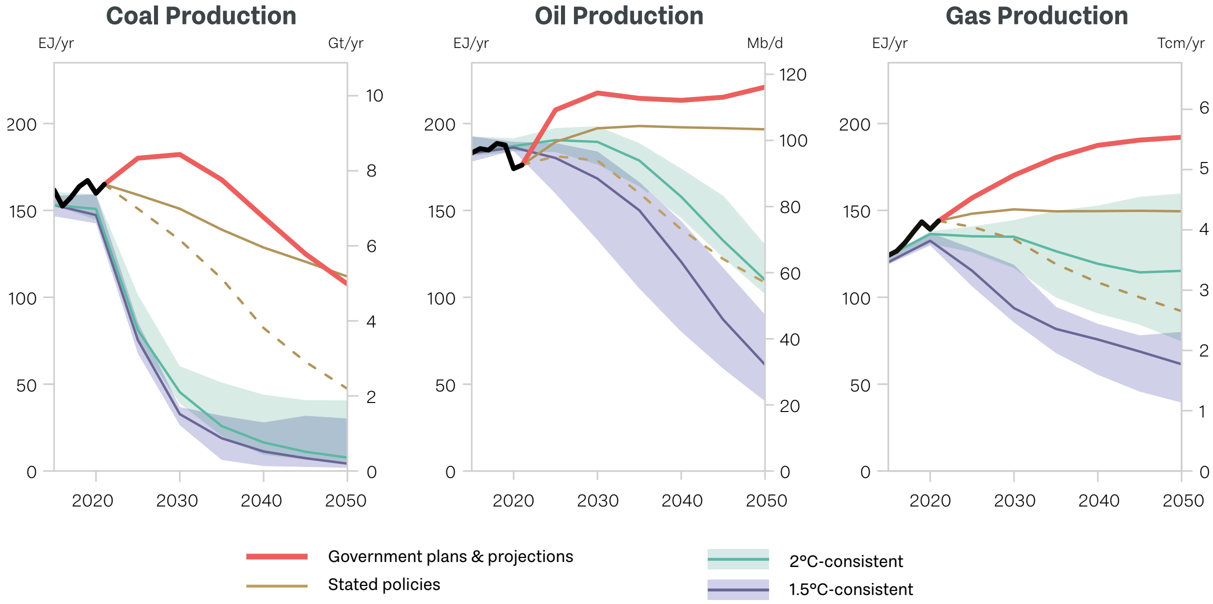


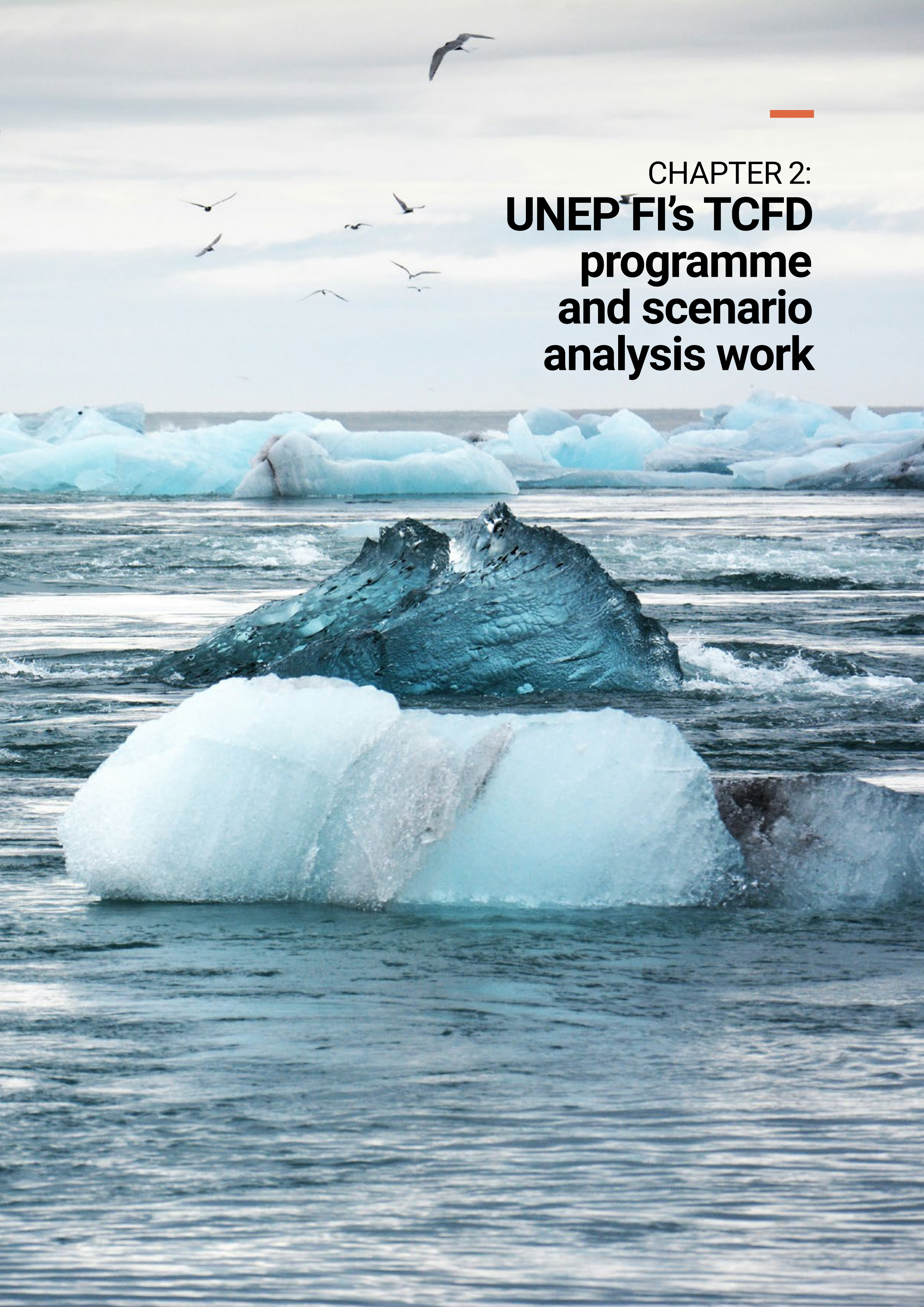
Figure 5: Projected fossil-fuel production for 1.5°C and 2°C warming (UNEP, 2023b)

Globally, financial institutions need to take a leading role to help accelerate GHG emissions reduction as they will be responsible for directing large-scale financing towards activities that will help economies reach net zero by 2050. Apart from reducing their operational carbon footprints, firms will also need to decarbonise their lending and investment portfolios. Financial firms will need to take urgent actions, including measuring and disclosing financed emissions, setting targets, developing strategies to reduce emissions using scenario analysis for support, and implementing mitigation measures (Guidehouse Insights, 2021).

One of the biggest priorities of the global economy is the rapid decarbonisation of the energy sector. This will require shifts across policy, behaviour, and technology. The International Energy Agency (IEA) has described this transition as "*nothing less than a complete transformation of how we produce, transport, and consume energy*" (IEA, 2021). The IEA has further found in its 1.5°C energy transition pathway that there is no need for investments in new coal, oil, or gas fields and estimates that 70% of electricity production must come from wind and solar by 2050 (IEA, 2023b; Tollefson, 2023). The IPCC puts the estimated need for investment in the electricity sector at USD 2.3 trillion annually from 2023 to 2050 in order to achieve 1.5°C model pathways with no or limited overshoot (IPCC, 2022). Fortunately, most of the technology needed for renewable energy at this scale is widely available and cost-effective (WRI, 2019). For example, in 2020, solar and onshore wind power became the cheapest sources of electricity for two-thirds of the world's population (Bloomberg, 2020).

While significant reductions in gross emissions characterise 1.5°C pathways, it is likely that carbon dioxide removal (CDR) will be needed to offset emissions in hard-to-mitigate sectors, such as parts of the industrial sector and long-distance transport. This will require large amounts of funding from financial institutions. While various methods can be implemented, such as the use of land-based methods and technologies (WRI, 2019), many of the latter are not yet available at any meaningful scale. As a result, there is significant uncertainty about the credibility and consistency of the technology needed to be relied upon in the coming decades for successful global-scale CDR (Carbon Brief, 2019).

Achieving net zero by 2050 is a vast task that requires huge sums of financing and large-scale transformations. Countries, cities, financial institutions, and corporations must, therefore, act as soon as possible to limit global warming to 1.5°C and reduce the negative impacts of climate change.



CHAPTER 2:

UNEP FI’s TCFD programme and scenario analysis work

The work in this report was carried out as part of UNEP FI's Climate Risk and TCFD programme. Since the publication of the Financial Stability Board's TCFD recommendations in 2017, UNEP FI has run a series of pilot programmes to assist its financial institution members to explore physical and transition risks and to develop practical approaches for evaluating these risks using climate scenario analyses. Over 100 financial institutions (banks, investors, and insurers) from around the world have participated in these pilots. Participating institutions have been supported by more than a dozen technical partners, including climate modellers and climate risk experts.

This report follows previous publications by the programme on climate scenario analysis. UNEP FI partnered with CICERO, a leading research institute on climate scenarios, to release a guide to help financial sector practitioners better understand climate models and how climate scenarios work in a financial context. Entitled 'Pathways to Paris', this report delved into integrated assessment models (IAMs) and their mechanisms for producing scenarios. With the support of the global consulting firm Oliver Wyman, UNEP FI also released a report titled 'Decarbonisation and Disruption', which explored the use of climate scenarios in understanding the financial risks of a disorderly transition. UNEP FI also worked with Oliver Wyman to develop Transition Check, a user-friendly web tool to assess transition risks across various geographies, economic sectors, and climate scenarios. In 2021, the programme also released a detailed user guide on effectively executing climate stress tests, titled 'UNEP FI's Comprehensive Good Practice Guide to Climate Stress Testing'. In 2022, UNEP FI partnered with the National Institute of Economic and Social Research (NIESR) to develop three climate-drive macroeconomic shock scenarios and subsequently published a report titled 'Economic Impacts of Climate Change: Exploring short-term climate-related shocks with macroeconomic models'.

CHAPTER 3:

Understanding 1.5˚C scenarios

3.1 Growing importance of 1.5˚C scenarios for financial actors

The financial sector needs to prepare for different futures and make decisions under the uncertainty of future outcomes, and scenario analysis has become a vital tool in meeting this goal. Since the 1970s, corporations and governments have been adopting scenario planning in their strategy-making processes to prepare for future uncertainties. The consequences of the Global Financial Crisis greatly intensified the use of scenario analysis by financial institutions. The crisis resulted from financial institutions inadequately measuring and managing their exposure to risk. In turn, this caused severe economic turmoil, with numerous banks running out of capital and requiring government bailouts. Given the lack of preparedness against major risks, scenario analysis took on new importance for financial institutions. Now, many large firms have over a decade of scenario analysis experience due to supervisory and internal stress-test requirements designed to assess resiliency and performance under adverse financial and economic conditions. With the increasing recognition that climate change poses significant financial risks, climate scenarios are becoming an essential tool among financial institutions to manage climate risks.

1.5°C scenarios have wide applications (Figure 6), with growing importance in climate-related risk analysis, disclosure, and stress testing. As global economies shift to a low-carbon future, the inclusion of net-zero scenarios in scenario analysis and climate stress testing for financial institutions is increasing. As such, the need for firms to assess the potential impact of a net-zero future on their business models is becoming more relevant. It is crucial for financial institutions to understand the methodology, assumptions, and implications of these scenarios.

Figure 6: Applications of 1.5°C scenarios in the financial sector

Below we detail four key use cases of climate scenarios for the financial sector.

1. **Risk analysis**
   Scenario analysis is a valuable tool to model forward-looking climate risks for risk analysis over various time horizons (NGFS, 2020). A range of scenarios can be used to conduct a scenario-based climate risk analysis to explore a set of future projections against a financial institution's business strategy. Exploring alternative assumptions to the business-as-usual pathway can allow firms to assess climate risks and opportunities, while also permitting the financial institution in question to determine its resilience to climate change.

2. **Climate risk analysis within disclosures**
   The G20's Financial Stability Board (FSB) launched the TCFD in 2015. With over 2,000 supporting organisations, the TCFD has become the financial sector's global standard for climate risk disclosures. In 2017, the TCFD secretariat released its climate disclosure framework, which described climate scenario analysis as an:

> **"important and useful tool … for understanding strategic implications of climate-related risks and opportunities and for informing stakeholders about how the organisation is positioning itself in light of these risks and opportunities."**
>
> TCFD, 2017

In recent years, regulators around the world have endorsed the TCFD recommendations with expectations that firms use scenario analysis to assess and disclose climate risks, as highlighted in Figure 7. In 2024, the International Financial Reporting Standards (IFRS) Foundation took over the monitoring of the TCFD from the FSB.

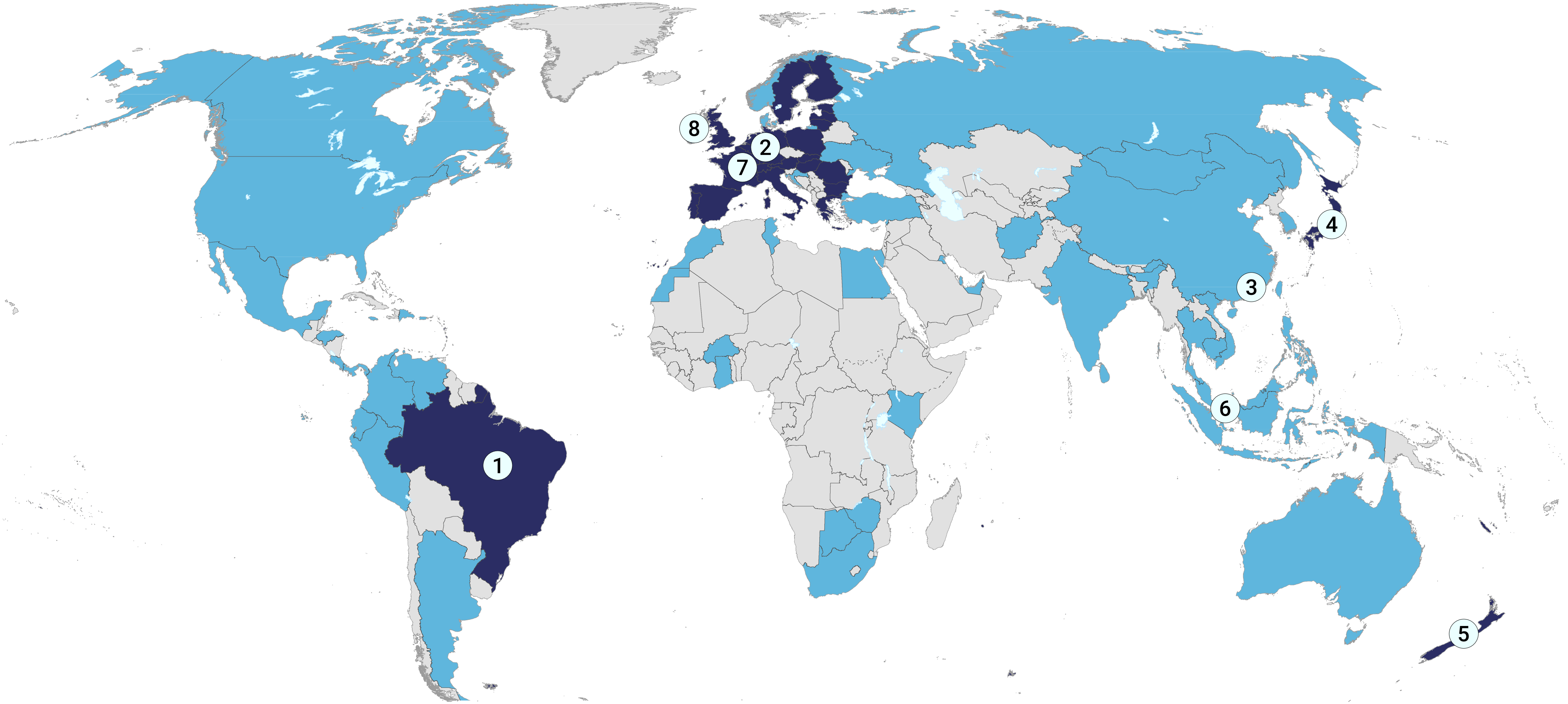


Figure 7: Countries supporting TCFD disclosures (FSB, 2021)

Note: 1–8 are countries with TCFD-aligned official reporting requirements (Brazil, European Union, Hong Kong, Japan, New Zealand, Singapore, Switzerland, and the United Kingdom)

Along with the TCFD, a worldwide group of central banks and supervisors launched the Network for Greening the Financial System (NGFS) in 2017. The NGFS developed easily accessible and globally available reference scenarios to examine different climate futures, including pathways for limiting the global temperature rise to 1.5°C. A growing number of financial institutions are using the NGFS scenarios as well as other reference scenarios to conduct climate risk analysis for their climate risk disclosures.

3. Climate stress tests

Central banks and regulators are increasingly adapting methodologies to better understand the nature and scale of climate risks to the financial system. A growing number of supervisory authorities are designing climate stress tests with reference scenarios. Identifying and quantifying exposure to climate risks using these stress tests further supports firms in disclosing climate risks in their TCFD reports. Table 4 highlights a selection of supervisors using the scenarios for climate stress testing.

Table 4: Selection of supervisors using scenarios for their climate stress tests

Supervisory authority	Exercise	Scenarios overview
Australian Prudential Regulatory Authority	Climate Vulnerability Assessment	Adopted two different climate scenarios developed by NGFS (Disorderly Transition Scenario and Current Policy Scenario) (APRA, 2022).
Hong Kong Monetary Authority	Pilot Banking Sector Climate Risk Stress Test	Published its Guidelines for Banking Sector Climate Risk Stress Test in 2023, focusing on both short- and long-term scenarios, the later took into account the NGFS Orderly, Disorderly and Current Policy scenarios (HKMA, 2022).
Monetary Authority of Singapore	Pilot climate stress test	Stated that it "*will reference climate scenarios developed by the NGFS*" in its climate stress test (MAS, 2021).
Autorité de Contrôle Prudentiel et de Résolution (ACPR) and the Banque de France	Climate pilot exercise	Used the NGFS Phase I reference scenarios as a starting point for its baseline orderly scenario and two disorderly scenarios (ACPR, 2020).
Bank of England (BOE) and the Prudential Regulation Authority	Climate Biennial Exploratory Scenario	Published the results of the 2021 Climate Biennial Exploratory Scenario (CBES) which adopted the NGFS Phase II scenarios (Late Action and Early Action) (Bank of England, 2022).
European Central Bank	Supervisory bottom-up climate stress test	Deployed short and long-term (orderly, disorderly, hot house world) transition risk scenarios as well as two physical risk scenarios, largely based on the NGFS Phase II scenarios. (European Central Bank, 2022).

Other supervisors are looking at some of the exercises above to guide their future assessment requirements.

4. **Target setting and informing net-zero strategy**
   For financial institutions, applications of scenario analysis extend well beyond regulatory requirements. Transition risks for the financial sector are already beginning to materialise as climate policies aiming for a 1.5°C pathway starting to take shape. A growing number of countries have committed to net-zero targets or are implementing net-zero legislation. These commitments now cover 88% of global emissions, 92% of global GDP, and 89% of the global population (Net Zero Tracker, 2023), with over 8,307 companies, 595 financial institutions, 1,136 cities, 52 states and regions having made net-zero commitments as part of the UN's Race to Zero (UNFCCC, 2023). In the financial sector, an increasing number of firms have committed to reaching net zero emissions by 2050 through initiatives like the NZAOA and NZBA.

   Achieving net zero emissions will require implementing government policies and deploying new technologies. These are likely to impact market dynamics in a range of sectors. Indeed, industries with business models that are incompatible with a net-zero future may cease to exist. As a result, financial institutions need to take active measures in assessing the potential systematic risk of aligning their portfolios to net zero.

As reaching net zero emissions by 2050 gains political momentum, there is a growing need for financial institutions to assess the impact of 1.5°C pathways. Achieving this goal requires the implementation of mitigation measures that need to be explored using scenario pathways. In the Climate Risk Landscape report (UNEP FI, 2023), UNEP FI surveyed scenario analysis methodologies and found that nearly all methodologies now include a 1.5°C or a below 2°C scenario. Many modellers are beginning to develop net-zero pathways that limit global warming to 1.5°C. Scenario analysis of net-zero pathways is critical to understanding the global risk of transforming to a net-zero economy and understanding the potential impacts of a firm's own net-zero strategy.

3.2 The IPCC's assessment of 1.5°C scenarios

A rapid reduction in CO_2 and other GHGs is required across all sectors to achieve all 1.5°C pathways. When developing 1.5°C scenarios with no or limited overshoot, modellers must make assumptions related to future projections for population, economic growth, behaviour, technology, and policies. Scenario assumptions are linked to drivers of climate change and lead to outcomes such as changing GHG emissions levels. While the pathways to 1.5°C with no or limited overshoot may be narrow, there are still a variety of assumptions that can lead there. Understanding these assumptions and trade-offs is critical when making risk assessments.

IPCC AR6 (2022)

Along with its Special Reports, the IPCC publishes detailed Assessment Reports on climate change, its causes, potential impacts, and mitigation and adaptation options. The IPCC published AR6 from 2021 to 2023 and consists of publications from three Working Groups:

- Working Group I (2021)—The Physical Science Basis
- Working Group II (2022)—Impacts, Adaptation and Vulnerability
- Working Group III (2022)—Mitigation of Climate Change
- AR6 Synthesis Report (2023)

In April 2022, the IPCC released its report from Working Group III (WG III) on mitigating climate change. WG III received submissions of over 2,500 scenarios, including an assessment of 97 scenarios for limiting warming to 1.5°C with no or limited overshoot. All scenarios assessed as part of AR6 have also been compiled into a database hosted by the International Institute for Applied Systems Analysis (IIASA), and 80% of the scenarios contained in the database are new scenarios developed since SR15. NGFS and IEA models are also included as part of the assessment. The WG III assessment showed that global GHG emissions decrease by 43% from 2019 levels by 2030 and 84% by 2050 for scenarios that limit warming to below 1.5°C with no or limited overshoot. Under the same scenarios, CO_2 emissions fall by 48% by 2030 and reach net zero in the 2050s.

IPCC SR15 Report (2018)

AR6 is IPCC's first major report since SR15 that assesses limiting global warming to 1.5°C. SR15 explored the possibilities of keeping within 1.5°C, the potential requirements to meet this climate target, and the consequences of failed efforts. AR6 provided new evidence, which strengthened the conclusions from SR15.

For many years, limiting global warming to below 2°C above pre-industrial levels was the de-facto climate target for policymakers. However, in 2015, a UN report concluded that limiting the global temperature rise to 2°C would not be sufficient to reduce the severe impacts of climate change. The report recommended that efforts should be made to reduce warming to 1.5°C. As a result, 195 countries supported the agreement to limit global warming to below 2°C and "*pursue efforts towards 1.5˚C*". As part of the Paris Agreement, the UNFCCC invited the IPCC to publish a special report on the impacts of a global temperature rise of 1.5°C. In 2018, the IPCC released its Special Report on Global Warming of 1.5°C (SR15). Ninety-one scientists and policy experts authored the report (Carbon Brief, 2018). The report concluded that meeting a 1.5˚C climate target was possible but would require significant actions for emissions reductions.

Of the 90 scenarios selected for SR15, 18 included a net zero carbon emissions by 2050 pathway. The scenarios are hosted by IIASA. The ensemble contains emission pathways with distinct features related to socio-economic development, energy-system transformations, and land-use changes until 2100. The models were also used in the IPCC's Special Report on Climate Change and Land (IIASA, 2022). The NGFS models are also included as part of the assessment.

Summary of updates in IPCC's AR6 in comparison to SR15

Below, we explore the main updates in AR6 compared to SR15 (Table 5).

Table 5: Key updates in IPCC's AR6 compared to SR15

Key updates	AR6	SR15
More scenarios	97 pathways that limit warming to 1.5°C with no or limited overshoot. All of the 97 pathways reach net zero carbon emissions by the median year of 2050–2055.	90 pathways that limit warming to 1.5°C with no or limited overshoot. Of these, 18 pathways reach net zero carbon emissions by 2050.
New illustrative mitigation pathways	Eight distinct scenario categories (C1–C8). Seven illustrative mitigation pathways for the scenarios assessed.	Four illustrative model pathways: P1, P2, P3, and P4.
Increased carbon budget	360 $GtCO_2$ for a 66% chance of limiting warming to 1.5°C.[7]	295 $GtCO_2$ for a 66% chance of limiting warming to 1.5°C.
Increased CO_2 emissions	GHG emissions are estimated to be reduced by 37% in 2030, relative to 2010. Higher likelihood of temperature temporarily exceeding 1.5°C.	GHG emissions are estimated to be reduced by 45% in 2030, relative to 2010. Lower likelihood of temperature temporarily exceeding 1.5°C.
Delay in achieving net zero emissions	Net zero CO_2 reached between 2050–2055.	Net-zero CO_2 reached between 2040–2055.
Greater focus on decarbonisation pathways for sectors	Assesses specific mitigation options at the sectoral level with sector-specific chapters on energy, transport, buildings, industrials, and agriculture.	Limited assessment at the sectoral level; no sector-specific chapters.
Focus on demand-side measures	Focus on low-demand scenarios.	No focus on low-demand scenarios.
Decreased reliance on CDR and net-negative emissions	364 $GtCO_2$ removed in 1.5°C with low or no overshoot; scenario pathways from Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Carbon Capture (DACCS).	480 $GtCO_2$ carbon dioxide removed in 1.5°C with low or no overshoot scenario pathways from BECCS and DACCS.

Detailed comparison of SR 15 and AR6 across key areas

Updated illustrative mitigation pathways

The IPCC's SR15 introduced the concept of illustrative pathways to identify a group of assessed scenarios with distinguished characteristics. The pathways are differentiated in terms of strategies, ambitions, and mitigation options for achieving climate goals (IPCC, 2022a).

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[7] AR6 has an increased budget due to a narrower estimate for warming per tonne of CO_2, called the transient climate response to cumulative carbon emissions (TCRE).

The report describes four illustrative model pathways to limit global warming to 1.5°C: P1, P2, P3, and P4. Three of the pathways show different emissions-reduction mitigation strategies for limiting global warming to 1.5°C with no or limited overshoot, with one showing a higher overshoot. While all of the pathways rely on the use of CDR, the extent of the reliance on such technology varies between them. Below, we briefly describe the illustrative model pathways presented in SR15.

No or limited overshoot pathways

- **P1:** In this pathway, social, business, and technological innovations decrease energy demand until 2050, and living standards rise globally. Rapid decarbonisation of the energy supply occurs. Carbon capture and sequestration (CCS) and BECCS are not used. Only afforestation is used for CDR.

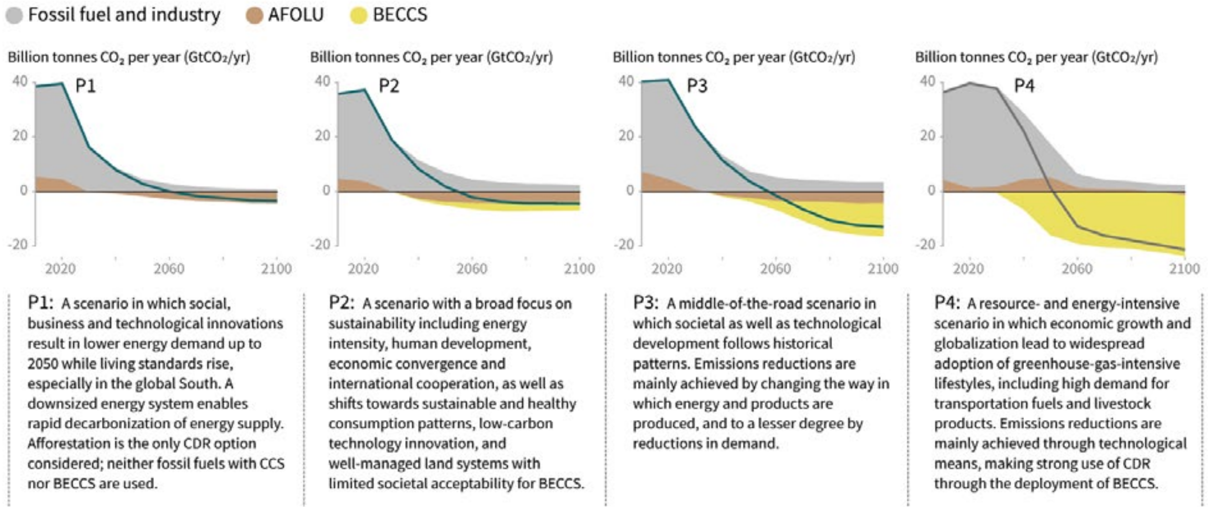
- **P2:** In this pathway, the economy shifts towards more sustainable practices, including reductions in energy intensity, innovative low-carbon technology, and changes in consumption patterns. Land systems are well-managed, with limited acceptance across society for BECCS.

- **P3:** In this pathway, social and technological developments follow historical patterns. Emissions are reduced by changing the way energy and products are produced and, to some extent, by shrinking the size of energy demand.

Higher overshoot pathways

- **P4:** In this pathway, economic growth occurs in a resource and energy-intensive manner with carbon-intensive lifestyles. Emissions reduction is achieved using CDR through the deployment of BECCS.

Breakdown of contributions to global net CO_2 emissions in four illustrative model pathways



P1: A scenario in which social, business and technological innovations result in lower energy demand up to 2050 while living standards rise, especially in the global South. A downsized energy system enables rapid decarbonization of energy supply. Afforestation is the only CDR option considered; neither fossil fuels with CCS nor BECCS are used.

P2: A scenario with a broad focus on sustainability including energy intensity, human development, economic convergence and international cooperation, as well as shifts towards sustainable and healthy consumption patterns, low-carbon technology innovation, and well-managed land systems with limited societal acceptability for BECCS.

P3: A middle-of-the-road scenario in which societal as well as technological development follows historical patterns. Emissions reductions are mainly achieved by changing the way in which energy and products are produced, and to a lesser degree by reductions in demand.

P4: A resource- and energy-intensive scenario in which economic growth and globalization lead to widespread adoption of greenhouse-gas-intensive lifestyles, including high demand for transportation fuels and livestock products. Emissions reductions are mainly achieved through technological means, making strong use of CDR through the deployment of BECCS.

Figure 8: Breakdown of global, net CO_2 emissions in the P1–P4 illustrative model pathways (IPCC, 2022b)

Shifting away from the P1–P4 pathways described in SR15, AR6 divides scenarios into eight climate categories with distinct temperature outcomes, ranging from C1 to C8 (Table 6, Figure 10). Table 6 describes each of the categories.

Table 6: Summary of the eight climate categories in AR6

Scenario category	Temperature outcome	CO_2 emissions assumptions
C1	Warming is limited to below 1.5°C with limited overshoot, with a probability of 50%.	CO_2 emissions peak before 2025. Net zero CO_2 emissions are reached between 2035–2070.
C2	Warming is limited to below 1.5°C with a high overshoot.	CO_2 emissions peak before 2030. Net zero CO_2 emissions are reached between 2045–2070.
C3	Warming is limited to likely below 2°C (>67%).	CO_2 emissions peak before 2030. Net zero CO_2 emissions are reached from 2055 to after 2100.
C4	Warming is limited to below 2°C (>50%).	CO_2 emissions peak before 2030. Net zero CO_2 emissions are reached from 2065 to after 2100.
C5	Warming is limited to below 2.5°C.	CO_2 emissions peak before 2030. Net zero CO_2 emissions are reached from 2080 to after 2100.
C6	Warming is limited to below 3°C.	Net zero CO_2 emissions are achieved before 2090. Net zero CO_2 emissions not achieved.
C7	Warming is limited to below 4°C.	Peak CO_2 emissions for some of the scenarios in this category are reached after 2100. Net zero CO_2 emissions not achieved.
C8	Warming exceeds 4°C.	Peak CO_2 emissions for some scenarios are reached after 2100. Net zero CO_2 emissions not achieved.

Table 7: Mapping SR15 scenarios and illustrative pathways to AR6 WGIII scenario categories

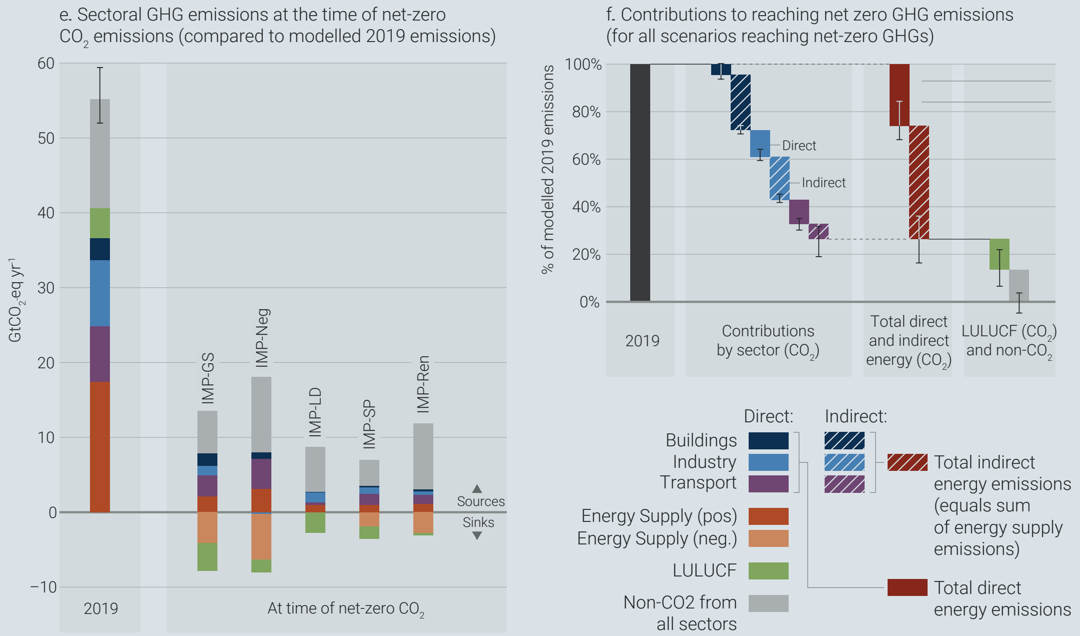
SR15: scenarios and illustrative pathways	AR6 WGIII: scenario categories
▪ P1 and P2 pathways ▪ Below 1.5°C and 1.5°C with low overshoot	C1
▪ P3 and P4 ▪ 1.5°C with high overshoot	C2
▪ Below 2°C	C3
▪ Higher than 2°C	C4

Box 1: Illustrative pathways of AR6

AR6 has also created seven illustrative mitigation pathways (IMPs) for the scenarios assessed (Figure 9). These pathways highlight key themes of the WG III assessment: namely, keeping current policies in place; meeting commitments of 2030 with limited new policies implemented; and combining different mitigation strategies that limit global warming. Below, we briefly describe each illustrative pathway and its mitigation strategy.

- **Current Policies (Cur-Pol):** Implementation of current policies, including NDCs. This does not include climate goals and targets that have been announced by governments but have not been implemented. The pathway assumes there will be a gradual strengthening of policies after 2030.
    - Scenarios of this pathway are a part of the C7 category (Figure 10)
- **Moderate Action (Mod-Act):** Current policies are implemented and NDCs for 2030 are achieved. Policies (including NDCs) are further strengthened after 2030.
    - Scenarios of this pathway are a part of the C6 category (Figure 10)
- **Gradual Strengthening (GS):** Current NDCs are implemented for 2030. Following this, universal coordinated action is taken to decarbonise rapidly. Global temperatures are likely to be limited to 2˚C. Global emissions decline by 14% by 2030, compared to 2020 levels. CO_2 emissions are halved in the 2040s, and net zero emissions are achieved in the early 2070s. Fossil fuels are slowly phased out and renewables meet future energy demand. A significant amount of CDR is deployed later in the century (Carbon Brief, 2022).
    - Scenarios of this pathway are a part of the C3 category (Figure 10)
- **Net-Negative Emissions (Neg):** Emissions are reduced below Mod-Act and GS pathways due to international climate policies implemented by 2030 to achieve a long-term temperature goal. After 2030, negative emissions (described as the removal of CO_2 through CDR processes) rise on a large scale. sectors are decarbonised due to a considerable reliance on negative emissions. Fossil fuels are slowly phased out with high dependence on biomass and BECCS for CDR. Net global negative emissions after 2050 meet the 1.5˚C-temperature goal with high overshoot.
    - Scenarios of this pathway are a part of the C2 category (Figure 10)
- **Renewables (Ren):** Immediate policy action and incentives to favour renewable energy are implemented with a smaller focus on negative emissions technologies. International policies allow for vast deployment and innovation of renewables and electrification of energy systems. As a result, fossil fuels are rapidly phased out. Global temperature is limited to between 1.5˚C or below 2˚C.
    - Scenarios of this pathway are a part of the C1 category (Figure 10)

- **Low Demand (LD):** International climate policies are implemented with immediate action on the demand side. Policies and incentives are put in place to reduce demand to lower emissions, which can decrease the need for large decarbonisation efforts on the supply side. Fossil fuels are rapidly phased out and future energy demand is decreased. Limited negative emissions are used, apart from land use. Global temperature is limited to 1.5˚C or below 2˚C.
    - ▫ Scenarios of this pathway are a part of the C1 category (Figure 10)
- **Shifting Pathways (SP):** International climate policies aiming to achieve sustainable development goals are implemented. These policies aim to reduce poverty and environmental protection and result in a major shift towards sustainability and equality and a reduction in GHG emissions. Fossil fuels are rapidly phased out with a significant decrease in future energy demand. Global temperature is limited to 1.5˚C or below 2˚C.
    - ▫ Scenarios of this pathway are a part of the C1 category (Figure 10)



e. Sectoral GHG emissions at the time of net-zero CO_2 emissions (compared to modelled 2019 emissions)

f. Contributions to reaching net zero GHG emissions (for all scenarios reaching net-zero GHGs)

Figure 9: Net zero CO_2 and GHG emissions estimates across different modelled mitigation pathways (IPCC, 2022a)

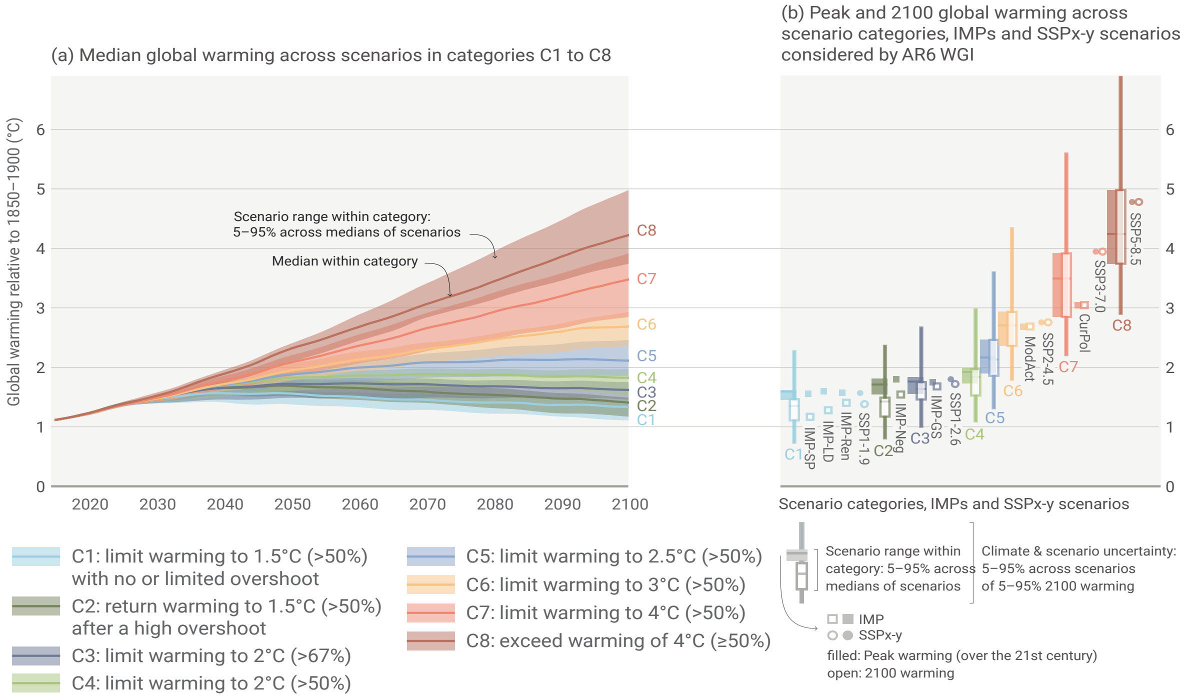


Figure 10: Projected global warming across scenarios in categories C1 to C8 and IMPs

Increased carbon budget

SR15 and AR6 suggest a remaining carbon budget of 460 $GtCO_2$ for a 50% chance to limit global temperature rise to 1.5˚C. AR6 suggests a remaining carbon budget of 360 $GtCO_2$ for a 66% chance of limiting warming to 1.5˚C. This is an increase from SR15, which reported a 66% chance carbon budget of 295 $GtCO_2$ (Figure 11). The increased budget is due to AR6's narrower estimate for warming per tonne of CO_2, also known as the transient climate response to cumulative carbon emissions (TCRE). TCRE is the global average surface temperature change ratio per unit of CO_2 emitted. For example, AR6 assumes a TCRE value of 1.0˚C to 2.3˚C per 1,000 $GtCO_2$, whereas SR15 assumes a lower TCRE value of 0.8˚C to 2.5˚C per 1,000 $GtCO_2$. As a result, the narrower estimate of climate sensitivity in AR6 causes increased projections (Carbon Brief, 2021).

Another difference in the methodology of the two reports was the consideration of various earth system feedbacks, such as the impacts of carbon released from thawing permafrost and other climate change-triggered atmospheric events. This assumption was not included in the remaining carbon budget estimates of SR15 but was included in the AR6 estimates.

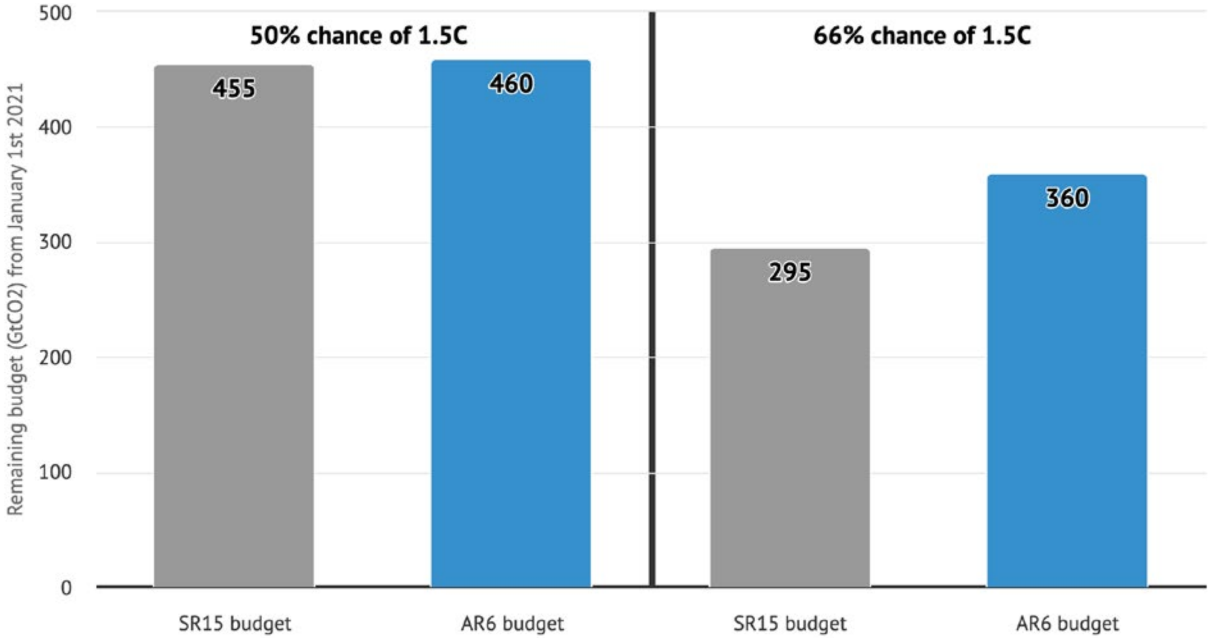


Figure 11: Carbon budget estimates from AR6 and SR15 (Carbon Brief, 2021)

Increased CO_2 emissions

Global emissions have continued to rise since the release of SR15. In AR6, emissions reductions are calculated relative to the 2019-modelled emissions level. For SR15, the baseline level is 2010. As emissions have risen between 2010 and 2019, GHG emissions in 2030 for scenarios limiting warming to 1.5˚C with no or limited overshoot are estimated to be higher in AR6 (31 $GtCO_2e$) than in SR15 (28 $GtCO_2e$). In AR6, GHG emissions are estimated to be reduced by 37% in 2030 relative to 2010. For SR15, the estimated reduction is larger, at 45%. Despite the rate of decline of GHG emissions by 2030 for 1.5°C scenarios with no or limited overshoot being similar in AR6 and SR15, absolute GHG emissions in AR6 are higher in 2030 than in SR15 due to the higher level of starting emissions in 2020.

Since SR15 was released, higher emissions have decreased the likelihood of reaching net zero and limiting warming to 1.5°C with no or limited overshoot. The reduced probability was taken into account by the IPCC in AR6. To reflect this continuous emissions growth, 1.5°C scenarios assessed in AR6 have higher total emissions projections in 2019 than those assessed in SR15. 1.5°C scenarios with low or no overshoot in AR6 have, on average, a higher median peak warming than scenarios in the same category in SR15. The likelihood of limiting warming to below 1.5°C with no or limited overshoot in pathways with stringent mitigation measures has decreased in AR6 compared to SR15. This is due to higher near-term emissions and a delay in reaching net zero CO_2 emissions.

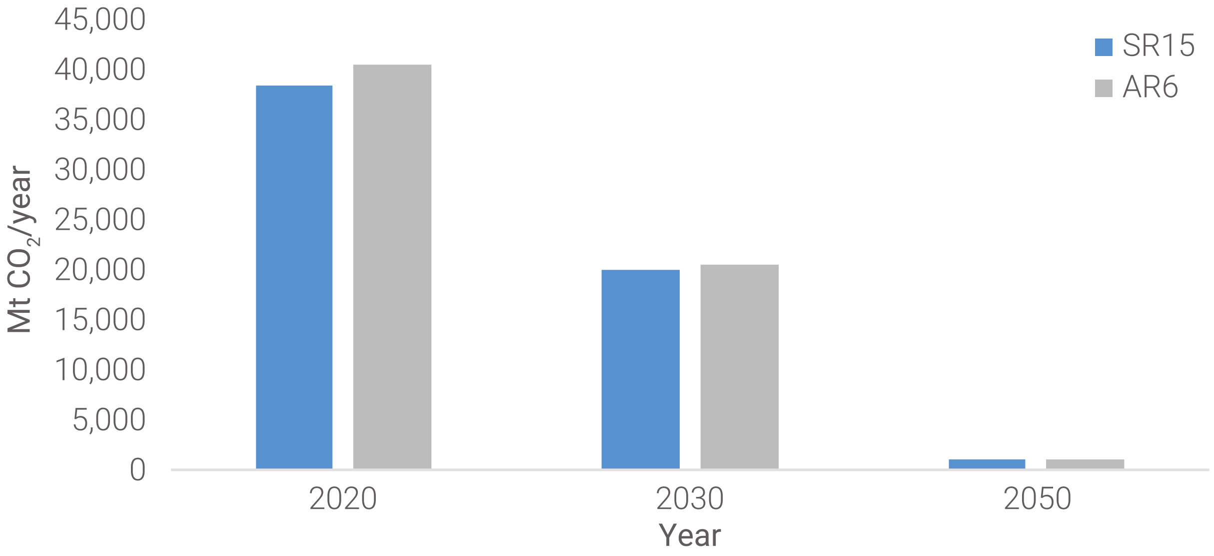


Figure 12: Mean CO_2 emissions projections in SR15 and AR6 from 2020 to 2050

AR6 also acknowledges that CO_2 emissions temporarily decreased in the first half of 2020 due to the COVID-19 pandemic. Though emissions later rebounded, the annual average CO_2 emissions in 2020 were 5.8% lower than in 2019. As a result, COVID-19 has created uncertainty in the range of projections in post-pandemic literature. The share of investments for reducing emissions is negligible in most recovery packages for the pandemic, and no structural shifts have been observed in climate policies. For long-term emissions, most of the scenarios analysed in AR6 do not include the reduction caused by the Covid-19 pandemic. The assessment of climate mitigation pathways for long-term goals assumes a fast recovery. However, the impacts of COVID-19, coupled with subsequent economic recovery measures by governments, could significantly impact emissions under current policy scenarios until 2030.

Delay in achieving net zero emissions

Many scenario pathways in AR6 show CO_2 emissions halving from 2020 to 2030, followed by reaching net zero CO_2 emissions after 2050 in order to limit warming to 1.5°C with no or limited overshoot. Scenario literature now includes a larger number of these pathways, which were not available during the publication of SR15. In AR6, 97 pathways of 1.5°C with no or limited overshoot were assessed, more than half (50) of which reach net zero GHG emissions. In comparison, SR15 included 90 distinct scenarios with at least a 50% chance of keeping warming to 1.5°C by 2100. Of these, only one fifth (18) projected net zero CO_2 emissions by 2050.

As GHG emissions have increased since 2017, many pathways in AR6 project later dates for reaching net zero CO_2 emissions compared to SR15. For 1.5°C pathways with no or limited overshoot, the median value of reaching net zero ranges from 2050–2055, with wider estimates of 2035–2070 (5th and 95th percentile). The SR15 median value of reaching net zero is 2050, which is close to the middle of the range of projections provided by AR6 WG III. AR6 1.5°C scenarios with no or limited overshoot also reach net zero GHG emissions later in the century than SR15 scenarios. A larger number of pathways included in AR6 have been designed to limit temperature overshoot and reliance on net-negative CO_2 emissions. About half of the pathways do not reach net zero GHG emissions by 2100.

Demand-side measures

AR6's WG III assessment focuses on low-demand scenarios, which SR15 does not. Pathways include decoupling material and energy demands from economic growth, achieved through increases in energy efficiency and a shift away from energy-intensive lifestyles. AR6 recognises the potential of demand-side actions, which can complement supply-side interventions to reduce emissions.

These demand-side measures are achieved through socio-cultural, infrastructure, and technological changes, such as: shifts in dietary choices and the avoidance of excessive food consumption; reductions in the frequency of long-haul flights; increased transportation by train and public transport; improvements in waste management and recycling infrastructure; increased access to energy-efficient and CO_2-neutral materials; greater adoption of electric vehicles and efficient technologies; and rapid uptake of renewable energy.

Use of CDR and net-negative emissions

AR6 assesses scenarios that rely on negative CO_2 emissions to a smaller extent than in SR15. Critics were sceptical of the feasibility of SR15 scenarios reliant on CDR technologies that have not yet been deployed at a large scale for commercial use. As a result, AR6-assessed scenarios reduced this reliance on CDR to limit temperature rise, choosing instead to increase their dependence on behaviour change and reduction in energy demand to decrease CO_2 emissions. Figure 13 below illustrates the difference in deployment of BECCS and DACCS in the WG III C1–C3 scenarios and their SR15 equivalents (Carbon Brief, 2022).

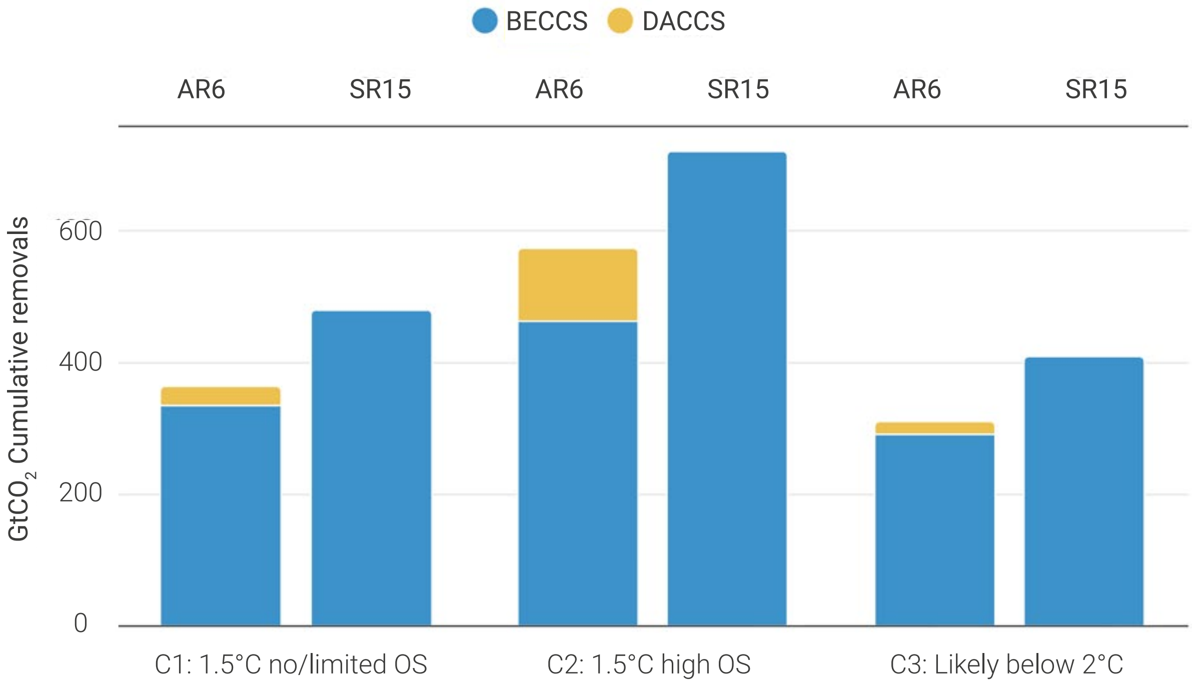


Figure 13: Reliance on CDR in the AR6 WGIII and SR15 (Carbon Brief, 2022)

In the SR15 and AR6 reports, the IPCC presented a range of 1.5°C scenarios with no or limited overshoot. These scenarios comprise a combination of mitigation actions, such as decarbonisation of global energy, transport, industry, buildings, and construction sectors, large-scale scale-up of CDR technologies, a transformation of agricultural and land-use practices, changes in consumer behaviour, and reduction of non-CO_2 GHG emissions (Warszawkski *et al.*, 2021). Although 1.5°C scenarios with no or limited overshoot vary in their assumptions, they are nearly always an *"all of the above"* approach to climate action. While some scenarios can get to 1.5°C without certain technologies, like CCS, they require more effort in other areas, such as greater reductions in energy demand. The scenarios submitted to the IPCC are useful in identifying robust features for a 1.5°C pathway that have reached a consensus in the scientific community.

Sections 4–8 outline key characteristics and limitations that financial users should consider for 1.5°C scenarios using data from the 97 1.5°C scenarios with no or limited overshoot reviewed in IPCC's AR6 Report.[8] It is important to take note that the scenario assessed by the IPCC were developed prior to the submission deadline of between August 2019 and October 2020 to be assessed by the AR6 WGIII (IAM Consortium, 2019).[9]

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[8] The number of 1.5°C scenarios with no or limited overshoot is dependent on the model used. The temperature categories for the AR6 scenarios were determined using MAGICC. If FaIR were used to categorise the scenarios, there would be 203 1.5°C scenarios with no or limited overshoot due to the different temperature sensitivities of models (CICERO, n.d.).

[9] As a result, the data available on the IIASA AR6 scenario database for the NGFS and IEA scenarios are for the previous iterations. The Phase 2 vintage of the NGFS scenarios and the IEA's 2021 World Energy Model are covered in this report.

CHAPTER 4:

Emissions reduction for 1.5°C pathway with no or limited overshoot

Key insights into emissions reduction

- To effectively cut down overall GHG emissions in the long term, the priority should be on reducing carbon dioxide (CO_2) emissions first, followed closely by addressing other greenhouse (GHG) emissions.
- In 1.5°C scenarios with no or limited overshoot, CO_2 emissions decrease by 46% (median) from 2020 to 2030. Firms in all areas of the global economy must take a comprehensive approach, including transitioning away from fossil fuels and renewable energy sources, adopting electrification, enhancing energy efficiency, minimising land clearing, using carbon-negative technology for carbon dioxide removal, and implementing carbon taxes.
- Methane (CH_4) emissions are the second-largest driver of global warming, with 1.5°C scenarios with no or limited overshoot reporting CH_4 emissions decreasing by 31% (median) from 2020 to 2030. Concentrated efforts to reduce emissions need to be directed towards firms operating in the agriculture and energy sectors. For example, new approaches are needed for agricultural cultivation and livestock production to reduce emissions and fugitive methane released from oil and gas processes also need to be prevented.
- In 1.5°C scenarios with no or limited overshoot, nitrous oxide (N_2O) emissions decrease by 18% (median) from 2020 to 2030. Due to the high potency of nitrous oxide (N_2O), it is crucial to implement measures to reduce its emissions. The agriculture sector is a major source, particularly through the use of synthetic nitrogen fertiliser, where firms will need to prioritise either improving efficiency or decreasing overall use.
- F-gases have a high global warming potential, with 1.5°C scenarios with no or limited overshoot reporting emissions from F-gases decreasing by 76% (median) from 2020 to 2030. Reductions will need to be addressed globally through targeted protocol-based action.

Suitability considerations of scenarios for exploring emissions

Limited information and detail	Some information and detail	Good information and detail
▪ Contribution of specific sectoral activities & investment and lending activities on emissions in the pathways ▪ Some of the scenarios included in the IPCC's assessment were developed multiple years ago and contain outdated assumptions ▪ Details on the emission reduction potential of various mitigation options are absent ▪ Difference in the historical baseline used in the scenarios as baseline emissions	▪ Sector breakdown to obtain information on emission pathways for sectors such as AFOLU, industrials, transportation and buildings ▪ Regional breakdowns of emission pathways	▪ Levels of emission reductions needed for limiting warming to 1.5°C with no or limited overshoot ▪ Data provided on emission trajectories for various GHGs & Kyoto gases ▪ Which GHGs need to be prioritised in terms of reductions in the near and long term

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Suitability considerations of scenarios for exploring emissions for the energy sector

Overall rating: average to good

Potential areas of greatest suitability: Risk analysis and stress testing, sensitivity analysis, client engagement, opportunity assessment, benchmark for target setting, internal strategy setting

Limited information and detail	Some information and detail	Good information and detail
▪ Breakdown of the contribution of specific energy types, such as fossil fuels, renewables and nuclear, on emissions in the pathways not available ▪ How should specific investment and lending activities contribute to emission pathways ▪ Some of the scenarios included in the IPCC's assessment were developed multiple years ago and contain outdated assumptions ▪ Details on the emission reduction potential of various mitigation options are absent ▪ Difference in the historical baseline used in the scenarios as baseline emissions	▪ Regional breakdowns of emission pathways	▪ Levels of emission reductions needed for limiting warming to 1.5°C with no or limited overshoot ▪ Data provided on emission trajectories for various GHGs & Kyoto gases ▪ Which GHGs need to be prioritised in terms of reductions in the near and long term ▪ Information available on emissions from various types of energy use, such as electricity, heat, and gases

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Suitability considerations of scenarios for exploring emissions for the transportation sector

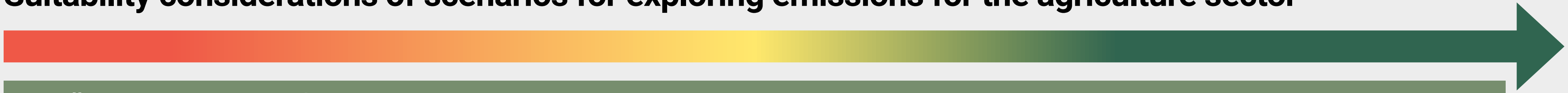
Overall rating: average to good

Potential areas of greatest suitability: Risk analysis and stress testing, sensitivity analysis, client engagement, opportunity assessment, benchmark for target setting, internal strategy setting

Limited information and detail	Some information and detail	Good information and detail
▪ Contributions of specific sectoral activities & investment and lending activities on emissions in the pathways are not available (e.g. the contribution of ICE vehicles, private jets, commercial airlines, etc.) ▪ Some of the scenarios included in the IPCC's assessment were developed multiple years ago and contain outdated assumptions ▪ Details on the emission reduction potential of various mitigation options are absent ▪ Difference in the historical baseline used in the scenarios as baseline emissions	▪ Regional breakdowns of emission pathways ▪ Breakdown of data for some emission types available at the sub-sector level, such as aviation, maritime, rail and road	▪ Levels of emission reductions needed for limiting warming to 1.5°C with no or limited overshoot ▪ Data provided on emission trajectories for various GHGs & Kyoto gases ▪ Which GHGs need to be prioritised in terms of reductions in the near and long term

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Suitability considerations of scenarios for exploring emissions for the agriculture sector



Overall rating: average to good

Potential areas of greatest suitability: Risk analysis and stress testing, sensitivity analysis, client engagement, opportunity assessment, benchmark for target setting, internal strategy setting

Limited information and detail	Some information and detail	Good information and detail
▪ Contribution of specific sectoral activities and investment and lending activities on emissions in the pathways is not available (e.g. fertiliser use) ▪ Some of the scenarios included in the IPCC's assessment were developed multiple years ago and contain outdated assumptions ▪ Details on the emission reduction potential of various mitigation options are absent ▪ Difference in the historical baseline used in the scenarios as baseline emissions	▪ Regional breakdowns of emission pathways ▪ Breakdown of data for some emission types available for different types of land uses, such as manure management and soil management.	▪ Levels of emission reductions needed for limiting warming to 1.5°C with no or limited overshoot ▪ Data provided on emission trajectories for various GHGs & Kyoto gases ▪ Which GHGs need to be prioritised in terms of reductions in the near and long term

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity

Suitability considerations of scenarios for exploring emissions for the real estate sector

Overall rating: average to good

Potential areas of greatest suitability: Risk analysis and stress testing, sensitivity analysis, client engagement, opportunity assessment, benchmark for target setting, internal strategy setting

Limited information and detail	Some information and detail	Good information and detail
▪ Information on emissions generated from various energy sources in the sector for a given pathway is not available, and there is no breakdown of different energy uses in buildings, including contributions from appliances, cooling, etc. ▪ Contribution of specific building types & construction activities is not available ▪ How should specific investment and lending activities contribute to emission pathways ▪ Some of the scenarios included in the IPCC's assessment were developed multiple years ago and contain outdated assumptions ▪ Details on the emission reduction potential of various mitigation options are absent ▪ Difference in the historical baseline used in the scenarios as baseline emissions	▪ Regional breakdowns of emission pathways ▪ Breakdown of data for some emission types available at the commercial and residential level	▪ Levels of emission reductions needed for limiting warming to 1.5°C with no or limited overshoot ▪ Data provided on emission trajectories for various GHGs & Kyoto gases ▪ Which GHGs need to be prioritised in terms of reductions in the near and long term

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Suitability considerations of scenarios for exploring emissions for the industrials sector

Overall rating: average to good

Potential areas of greatest suitability: Risk analysis and stress testing, sensitivity analysis, client engagement, opportunity assessment, benchmark for target setting, internal strategy setting

Limited information and detail	Some information and detail	Good information and detail
▪ Some of the scenarios included in the IPCC's assessment were developed multiple years ago and contain outdated assumptions ▪ Details on the emission reduction potential of various mitigation options are absent ▪ Difference in the historical baseline used in the scenarios as baseline emissions ▪ Contributions of specific sectoral activities and investment and lending activities on emissions in the pathways are not available.	▪ Regional breakdowns of emission pathways ▪ Breakdown of data for some emission types available for some sub-sectors and industrial processes, such as cement, steel and chemicals.	▪ Levels of emission reductions needed for limiting warming to 1.5°C with no or limited overshoot ▪ Data provided on emission trajectories for various GHGs & Kyoto gases ▪ Which GHGs need to be prioritised in terms of reductions in the near and long term

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Primary anthropogenic greenhouse gases (GHGs) found in the atmosphere are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (F-gases). F-gases consist of hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF6).[10] Targets for the first commitment period of the Kyoto Protocol cover emissions of these six main GHGs (UNFCC, n.d.). A significant increase in the atmospheric concentrations of these GHGs due to human activities is driving global warming and climate change. Carbon dioxide accounts for 75% of global emissions, followed by methane at around 18%. Nitrous oxide and fluorinated gases account for 4% and 2% of global emissions, respectively (IPCC, 2022a) (Figure 14).

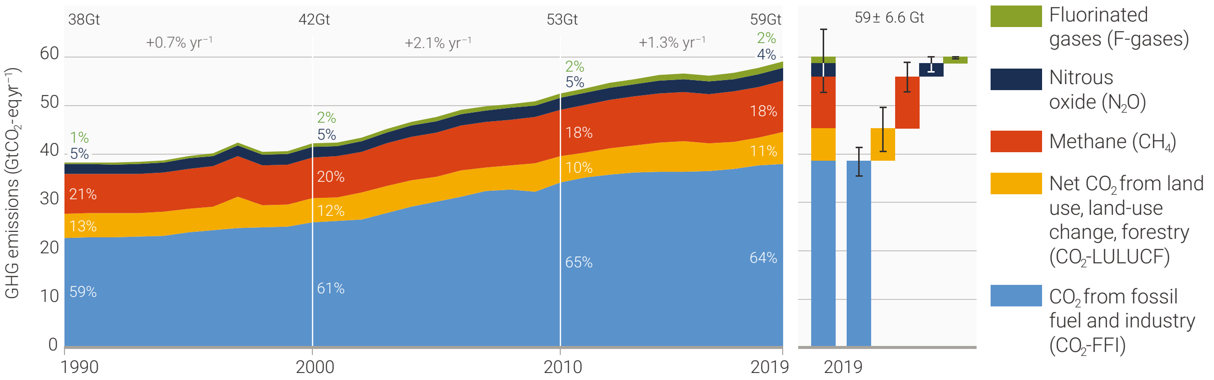


Figure 14: Breakdown of anthropogenic GHG emissions by gas from 1990–2019 (IPCC, 2022a)

> **"Global net anthropogenic GHG emissions during the decade (2010–2019) were higher than any previous time in human history."**
>
> **Working Group III (IPCC, 2022b)**

Since the 1990s, human activities have led to emissions growth across all the major GHGs (Figure 15). Emissions of all these GHGs were at higher levels during the last decade than at any time observed in human history. Carbon dioxide emissions have increased the most from fossil fuel use and industrial processes, followed by methane emissions. F-gases have experienced the highest relative growth compared to 1990 levels. Over the same time period (1990–2019), CO_2 emissions from fossil fuel use and industry have increased by 67%, CH_4 by 29%, N_2O by 33%, and F-gases by 250% (IPCC, 2022b).

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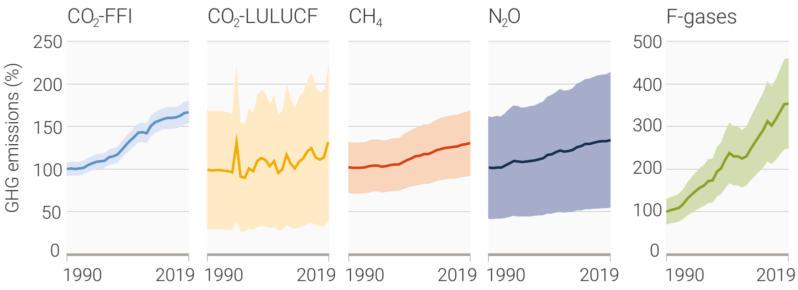
[10] F-gases also include nitrogen trifluoride (NF_3)



The solid line indicates central estimate of emissions trends. The shaded area indicates the uncertainty range.

	2019 emissions (GtCO$_2$-eq)	1990–2019 increase (GtCO$_2$-eq)	Emissions in 2019, relative to 1990 (%)
CO$_2$-FFI	38 ± 3	15	167
CO$_2$-LULUCF	6.6 ± 4.6	1.6	133
CH$_4$	11 ± 3.2	2.4	129
N$_2$O	2.7 ± 1.6	0.65	133
F-gases	1.4 ± 0.41	0.97	354
Total	59 ± 6.6	21	154

Figure 15: Changes in global GHG emissions from 1990 to 2019 (IPCC, 2022a)

> **"GHG emissions have continued to grow at high absolute rates"**
>
> **Working Group III (IPCC, 2022b)**

GHG emissions continue to increase across all sectors, especially in the transport and industry sectors. In 2019, 33% of global GHG emissions came from the energy sector, 24% from the industry sector, 22% from the agriculture, forestry, and other land use (AFOLU) sector, 15% from the transport sector, and 5.6% from the buildings sector (IPCC, 2022b) (Figure 16). Energy consumption is the largest driver of anthropogenic global GHG emissions. This includes energy consumption related to transportation, electricity and heating, buildings and their construction, manufacturing, and fugitive emissions (WRI, 2020).

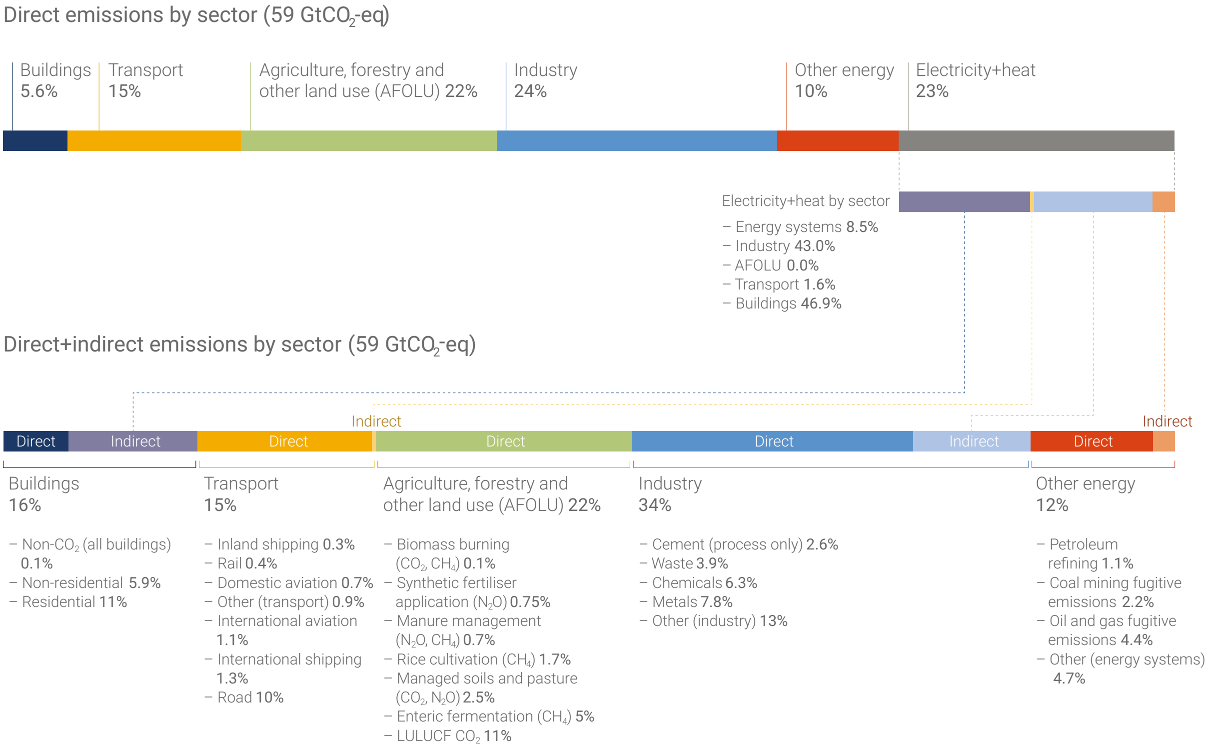


Figure 16: GHG emissions per sector (%) for 2019 (IPCC, 2022a)

Historical to present-day emissions

> **"Gross Domestic Product (GDP) per capita and population growth remained the strongest drivers of CO_2 emissions from fossil fuel combustion in the last decade"**
>
> **Working Group III (IPCC, 2022b)**

4.1 Historical emissions

In 1990, North America (16%) and Europe (14%) were the most significant contributors of GHG emissions, followed by Eastern Europe and West-Central Asia (14%) and Eastern Asia (13%) (IPCC, 2022b) (Figure 17). The United States of America and the European Union have contributed more emissions since 1850 than anywhere else (NPR, 2021) due to industrialisation, economic development, and population growth. From 1850 to 2011, developed countries were responsible for 79% of CO_2 emissions (Center for Global Development, 2022).

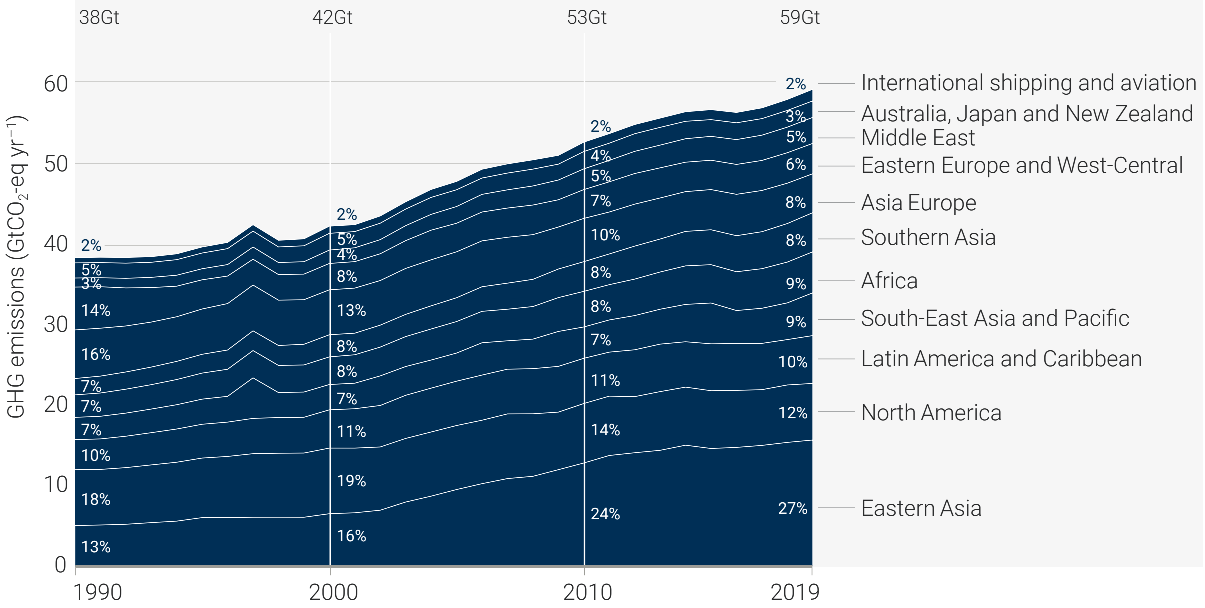


Figure 17: Global net-anthropogenic GHG emissions by region from 1990 to 2019 (IPCC, 2022a)

4.2 Current emissions (2019)

During the 1990s, Asia's gross domestic product (GDP) rose rapidly to become the largest globally in absolute terms. Since 2000, Asia and the Developing Pacific region have been significant contributors to CO_2 emissions, accounting for 52% of the global population and exceeding developed countries as the largest emitter of CO_2. Economic and population growth are the strongest drivers of CO_2 emissions from fossil fuel use.

In the last decade, both GDP and population growth outpaced energy use reduction and carbon intensity improvements. By 2019, Eastern Asia became the most significant contributor of GHG emissions in the atmosphere by region (27%), followed by North America (12%) and Latin America, and the Caribbean (10%). Australia, Japan, and New Zealand (3%) and the Middle East (5%) are the smallest contributors to GHG emissions by region (Figure 17). However, when considering GHG emissions per capita and population size, North America, Australia, Japan, New Zealand, Eastern Europe and West-Central Asia, and the Middle East are the most significant contributors to GHG emissions (IPCC, 2022b) (Figure 18). Following the 1990s, emissions per capita for regions like North America and Eastern Europe stabilised but remained much higher than regions such as Africa, Southern Asia, and Latin America and the Caribbean, where emissions continue to rise.

In AR6, the IPCC determined that at least 24 countries have been able to reduce their CO_2 emissions in absolute terms over the last 10 years[11] with some countries reducing CO_2 emissions at a rate of 4% per year. However, the IPCC highlights that:

> **"The combined emissions reductions of these 24 countries were outweighed by rapid emissions growth elsewhere, particularly among developing countries that have grown from a much lower base of per capita emissions."**
>
> **Working Group III (IPCC, 2022b)**

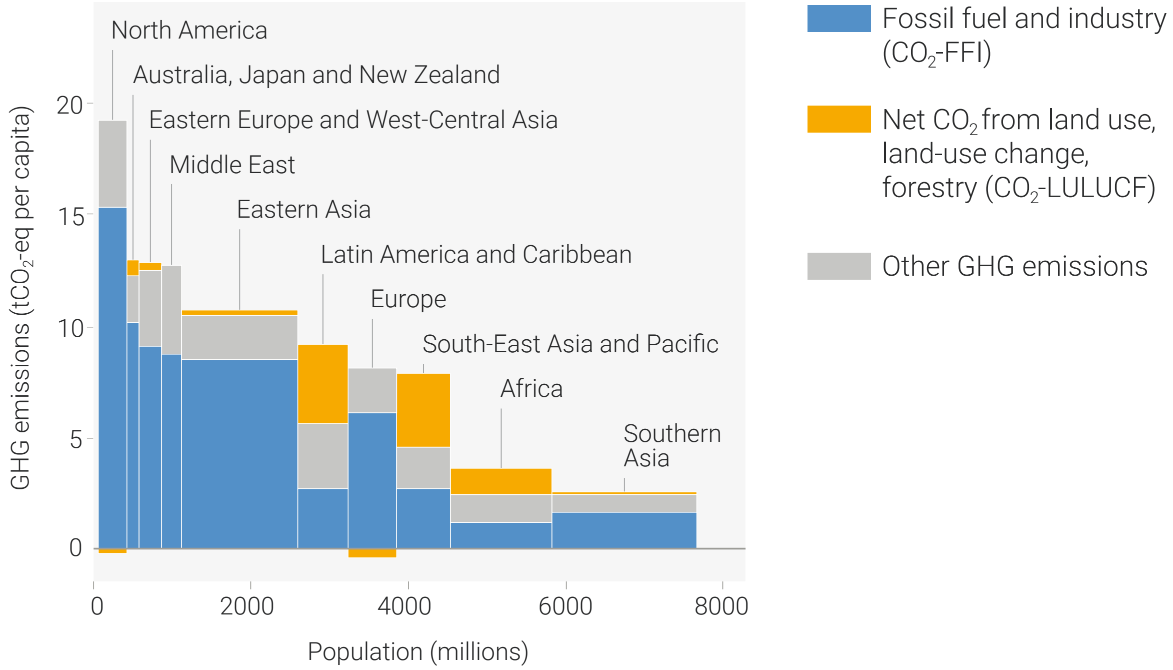


Figure 18: Regional net anthropogenic GHG emissions per capita (IPCC, 2022a)

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[11] Six Western and Northern European countries have reduced CO_2 emissions from the 1970s, six former Eastern Bloc countries have consistently reduced CO_2 emissions from the 1990s, and 12 other countries have reduced CO_2 emissions since the mid-2000s.

4.3 Emissions reductions to limit warming

Table 8: Major sources of GHGs

	Carbon dioxide	Methane	Nitrous Oxide	F-gases
Total Global GHG emissions by gas[12]	74.4%	17.3%	6.2%	2.1%
1kg of GHG as CO_2eq[13]		25kg CO_2eq	298kg CO_2eq	1,430–22,800kg CO_2eq
Key sources	1. Combustion of fossil fuels, such as coal, natural gas, and oil[12,14] ▪ These carbon-based fuels are burned primarily to generate electricity, provide heat, and as an energy source for transportation 2. Industrial processes[15] 3. Land use change, mainly due to deforestation[12]	1. Fermentation process in the stomachs of cows, sheep, and other herbivorous mammals[15,16] 2. Manure decomposition 3. Rice cultivation[16] 4. Oil and gas extraction, coal mining[15] ▪ fugitive methane can be emitted through venting, leaks, and incomplete combustion 5. Waste landfills[15]	1. Use of nitrogen fertilisers for fertilising agricultural soils[14] ▪ Reliance on over-production has led to farmers overusing fertilisers for higher yields. Excess amounts of nitrogen is released in agricultural runoff[14] 2. Decomposition of animal manure under low oxygen conditions[12]	1. Primarily used as chemical refrigerants and other industrial processes[14]
High-emitting sectors[12]	Agriculture, Energy, Transportation, Buildings, Manufacturing and Construction, and Industrials	Agriculture, Oil & Gas, and Waste	Agriculture i.e. fertiliser use, crop cultivation, livestock production	Industrial and manufacturing

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[12] WRI, 2020
[13] European Environment Agency
[14] UN, 2022
[15] EPA, 2022
[16] Global Methane Initiative

	Carbon dioxide	Methane	Nitrous Oxide	F-gases
Breakdown by sector	Electricity & heat **38%** Transport **21%** Manufacturing & construction **15%** Buildings **10%** Industry **9%** LUCAF **3%** Other **4%**	Agriculture **42%** Fugitive emissions **38%** Waste **18%** LUCAF **2%** Industry **0.1%** Other fuel combustion **0.1%**	**Agriculture 98%** **Other 2%** Waste 1% Industry 1% Land use change (LUC) & forestry <1% Other fuel combustion <1% Fugitive emissions <1%	**Industrial process 100%**
Time the GHG remains in the atmosphere	Centuries to millennia (20% may be present 10,000 years after emissions)	A couple decades	Up to 100 years	Few weeks to thousands of years

To limit global warming to 1.5°C with no or limited overshoot, a comprehensive reduction in GHG emissions needs to be implemented in the coming decade. Though other GHGs are more potent in trapping heat than CO_2, they are less abundant than CO_2 and remain in the atmosphere for a shorter time (Table 9). Due to the large concentration of CO_2 emissions in the atmosphere and their ability to remain there for centuries, their impact on rising global temperature will continue if volumes are not reduced. The relatively short-lived nature of gases such as CH_4 means that their effects dissipate more rapidly than CO_2. Low or no overshoot 1.5°C pathways therefore tend to focus on deep and rapid cuts in CO_2, with other GHG emissions following shortly thereafter. (For more on the global warming potential (GWP) of GHGs, see Appendix 1.)

Table 9: Properties of GHGs (see Appendix 1 for more information)

	CO_2	CH_4[17]	N_2O	F-gases
100-year Global warming potential (GWP)[18] (IPCC, 2021)	1.0	27.0–29.8	273	771–7,380
20-year GWP (IPCC, 2021)	1.0	79.7–82.5	273	2,693–8,321

Comparing CO_2 emissions to GHG emissions in 2030 and 2050

Under 1.5°C pathways with no or limited overshoot, global CO_2 emissions are reduced by 50% (40%–60%)[19] in 2030 and 100% (95%–105%[20]) in 2050, compared to 2019 levels. In comparison, global GHG emissions are reduced by 45% (40%–50%) in 2030 and by 85% (80%–90%) in 2050, compared to modelled 2019 emissions level. In the scenarios, overall GHG emissions peak earlier than CO_2, but their reduction is less rapid and steep afterwards.

Net zero GHG emissions are reached between 2095 and 2100 *(median)* in pathways limiting warming to 1.5°C with a low or no overshoot, though they are on a falling trajectory prior to this, while net zero CO_2 emissions are reached between 2050 and 2055 *(median)* (IPCC, 2022b).

2030 to 2050 emissions

Pathways that limit warming to 1.5°C (>50%) with no or limited overshoot further show differences in pathways for CO_2 and non-CO_2 emissions (Figure 19). Global net CO_2 emissions are reduced, compared to modelled 2019 emissions, by 48% (36%–69%) in 2030 and 80% (61%–1,098%) in 2040. In these pathways, reductions in global CH_4 emissions are slower compared to CO_2 emissions, with an average reduction of 34% (21%–57%)

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[17] GWP for CH_4-fossil is different from the GWP of CH_4-non fossil. Apart from its short life span, CH_4 from fossil fuels share more common characteristics with CO_2 from fossil fuels than CH_4 from non-fossil fuel sources, such as biogenic CH_4 from agriculture practices (UC Davis, 2020).

[18] Global warming potential (GWP) is a measure used to determine how much each GHG contributes to global warming. It measures the amount of energy one tonne of gas emissions absorb over time relative to the emissions of one tonne of CO_2.

[19] Values in this chapter are represented as median (interquartile range)

[20] Above 100% reduction indicates negative CO_2 emissions through the removal of CO_2.

in 2030 and 44% (31%–63%) in 2040. In 2050, CO_2 emissions are reduced by 100% (95%–1,058%), relative to 2019 levels. Reductions of non-CO_2 emissions by 2050 are much smaller: CH_4 is reduced by 50% (60%–45%), N_2O is reduced by 20% (5% increase to 55% reduction), and F-gases are reduced by 85% (20%–90%) (IPCC, 2022b).[21]

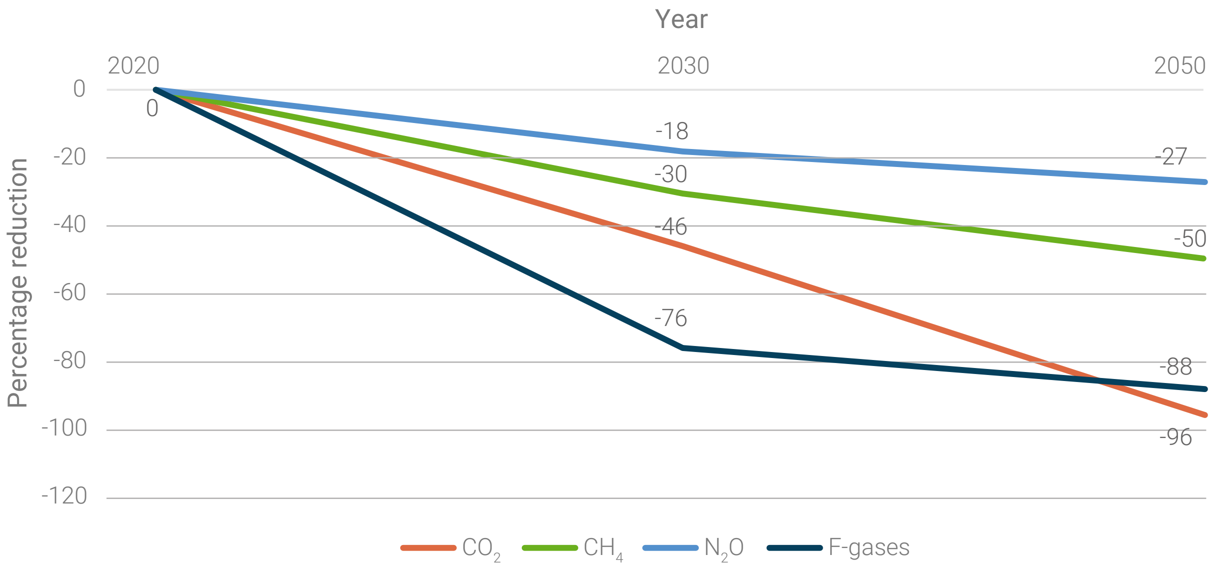

Figure 19: Median percentage reduction of GHG emissions from 2020 to 2050 for the IPCC-assessed 1.5°C scenarios with no or limited overshoot

Table 10: Summary of changes in GHG emissions from 2020 to 2050 reported in the IPCC-assessed 1.5°C scenarios with no or limited overshoot[22]

	Annual emissions in 2020	Annual emissions in 2030	Percentage decrease from 2020 to 2030 (median)	Annual emissions in 2050	Percentage decrease from 2020 to 2050 (median)
CO_2	39.9 $GtCO_2$/yr (39.2–42.0)	21.5 $GtCO_2$/yr (17.8–23.7)	46.1	1.37 $GtCO_2$/yr *(-0.49–3.5)*	96.4
CH_4	0.36 $GtCH_4$/yr *(0.35–0.38)*	0.25 $GtCH_4$/yr *(0.22–0.26)*	30.6	0.18 $GtCH_4$/yr *(146.8–199.2)*	50.0
N_2O	0.011 GtN_2O/yr *(0.010–0.013)*	0.009 GtN_2O/yr *(0.008–0.011)*	18.2	0.008 GtN_2O/yr *(0.007–0.012)*	27.3
F-gases	1.47 $GtCO_2eq$/yr *(1.41–1.50)*	0.35 $MtCO_2eq$/yr *(0.34–0.95)*	76.2	0.17 $MtCO_2eq$/yr *(0.17–0.53)*	88.4

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[21] Emissions reductions reported in this paragraph are based on a set of 92 scenarios out of the total 97 scenarios.

[22] Values in the table are represented median (interquartile range)

As CO_2 emissions continue to rise, less room is left for emitting other GHGs into the atmosphere. This is both because the remaining carbon budget is reduced and because of the long-lasting nature of CO_2 in the atmosphere. Although decarbonisation pathways prioritise reductions in CO_2 emissions, it is therefore important that reduction efforts are also directed towards other GHGs that are contributing to the rising global temperature. The trajectory of reducing these GHGs may not be as fast as the trajectory of reductions needed for CO_2 emissions but will be important to increase the chances of meeting the climate goal of limiting the global temperature rise to 1.5°C by the end of the century.

Table 11: Recommended scenario variables to use for assessing emissions (AR6 scenario explorer)

Variable	Unit	Definition	Additional information
CH_4 emissions	$MtCH_4$/yr	Total CH_4 emissions	Further variables can be used to assess CH_4 emissions for various sectors. Variables can provide information for CH_4 emissions from AFOLU, industrial processes, energy, and waste. Variables can provide information CH_4 emissions from energy demand from residential and commercial, industry and transportation.
CO_2 emissions	$MtCO_2$/yr	Total net CO_2 emissions from all *human* sources *(adapted by authors)*	Further variables can be used to assess CO_2 emissions for various sectors. Variables can provide information for CO_2 emissions from AFOLU, industrial processes and energy. Variables can provide information on CO_2 emissions from energy demand from residential and commercial, industry, transportation and agriculture.
F-Gases	$MtCO_2$eq/yr	Total F-gas emissions, including sulphur hexafluoride (SF6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs)	No additional variables for a sectoral breakdown available.
N_2O emissions	kt N_2O/yr	Total N_2O emissions	Further variables can be used to assess N_2O emissions for various sectors. Variables can provide information for N_2O emissions from AFOLU, energy, industrial processes, and waste. Variables can provide information N_2O emissions from energy demand from residential and commercial and transportation.

Reducing CO_2 emissions

> **"Pathways likely limiting warming to 2°C or 1.5°C involve substantial reductions in fossil fuel consumption and a near elimination of coal use without CCS"[23]**
>
> **Working Group III (IPCC, 2022b)**

Reducing CO_2 emissions, aligned with 1.5°C pathways with low or no overshoot, will require a broad effort spanning the economy (see Section 1). Pathways assessed by the IPCC that limit global warming to 1.5°C with no or limited overshoot estimate cumulative CO_2 emissions of 510 (330–710) $GtCO_2$ from 2020 to reaching net zero CO_2 emissions (Figure 20). To align mitigation actions with these pathways, CO_2 emissions will need to be reduced across all sectors, especially carbon-intensive sectors such as energy, power generation, industrial, real estate, transport, and land use. Though specific decarbonisation efforts can vary by sector, some common key actions include (1) a shift away from fossil fuels and towards renewable energy; (2) electrification; (3) improved energy efficiency; (4) reduction in land clearing; (5) use of carbon-negative technology for carbon dioxide removal; and (6) the implementation of carbon taxes (University Corporation for Atmospheric Research, 2022; EPA, 2021).

The IPCC states:

> **"Stringent emissions reductions at the level required for 2°C or 1.5°C are achieved through the increased electrification of buildings, transport, and industry, consequently all pathways entail increased electricity generation."**
>
> **Working Group III (IPCC, 2022b)**

Some countries have also managed to decouple economic growth from CO_2 emissions. Historically, emissions have correlated with income levels; the greater the income, the more energy consumed. But countries such as the United Kingdom, France, Germany, Sweden, Finland, Denmark, Italy, and Romania have achieved economic growth while reducing emissions. A vital cause of decreased emissions is the decoupling of energy use and economic growth. As GDP has increased, total energy use has remained the same or has fallen. Secondly, fossil fuels are being replaced with low-carbon energy alternatives (Ritchie *et al.*, 2020).

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[23] Along with the phase-out of unabated fossil fuels and the use of carbon capture and storage (CCS), other mitigation options such as land use will be important. Reducing CO_2 emissions will require efforts from across different sectors.

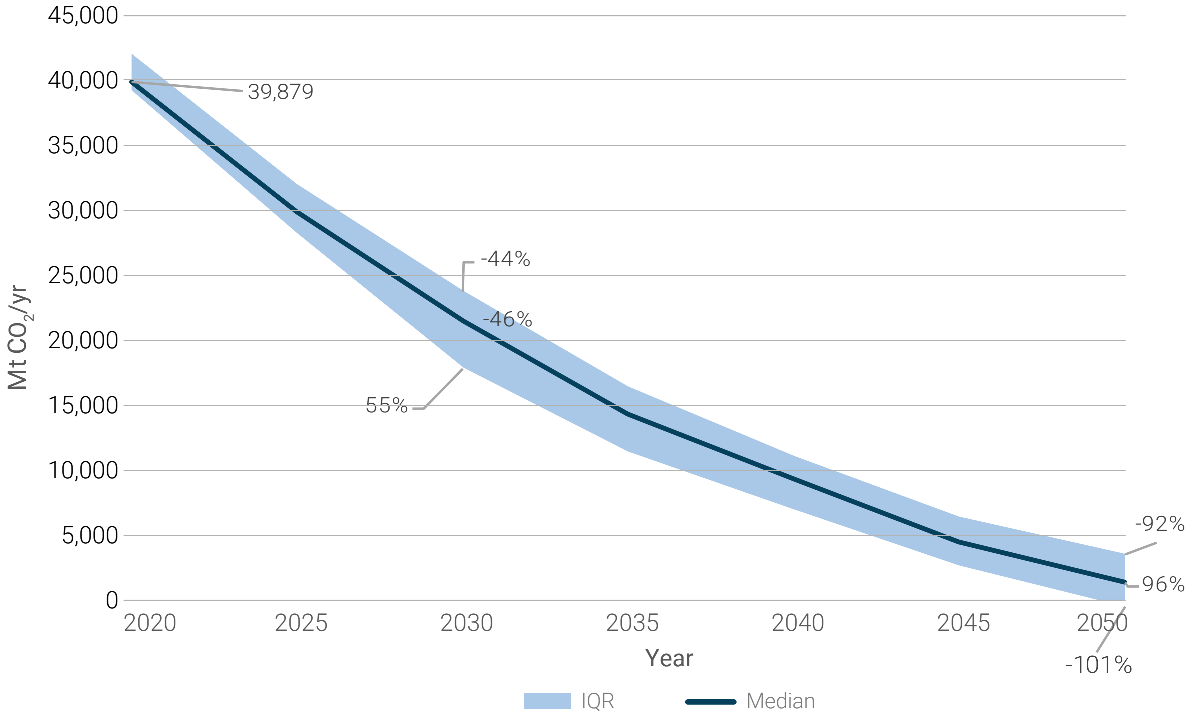
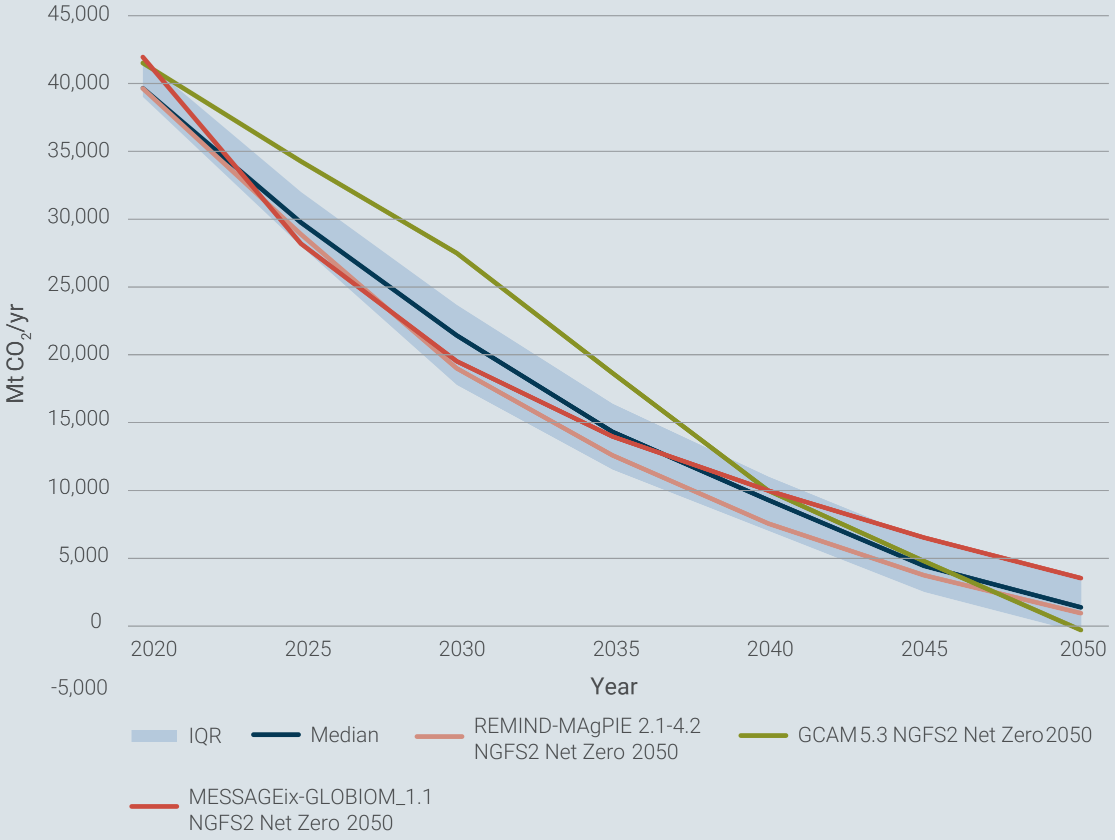


Figure 20: Global CO_2 emissions reported in the IPCC-assessed 1.5°C pathways with no or limited overshoot from 2020 to 2050

Box 2: CO_2 emissions estimates in the NGFS net-zero scenarios compared to the IPCC assessed 1.5°C scenarios with no or limited overshoot



The GCAM Net Zero 2050 scenario reports relatively higher levels of CO_2 emissions compared to the other NGFS net-zero pathways, reporting 16% higher CO_2 emissions for 2030 than the upper quartile of the IPCC-assessed scenario dataset. However, post-2030, there is a steep reduction in CO_2 emissions reported in the GCAM pathway, and by 2050, it is the only NGFS model that reports negative CO_2 emissions. REMIND and MESSAGE Net Zero 2050 scenarios report values that fall within the interquartile range of the IPCC-assessed scenario dataset. While CO_2 emission levels reported by MESSAGE remain lower than the middle of the range of values of the IPCC-assessed dataset from 2025 to 2035, between 2040 and 2050, its reduction rate is lower than the median rate for the IPCC-assessed scenarios. By 2050, MESSAGE shows CO_2 emission levels that are 158% higher than the median value of the IPCC-assessed scenarios. The REMIND pathway reports similar values to the lower range of values of the IPCC-assessed scenarios between 2020 and 2025. Still, by 2050 the CO_2 emissions reported are more in line with the median value of the IPCC-assessed scenarios.

Data source: AR6 scenario explorer

Reducing methane emissions

> **"Rapid reductions in non-CO_2 GHGs, particularly CH_4, would lower the level of peak warming"**
>
> **IPCC, 2022b**

Following CO_2, anthropogenic CH_4 emissions are the second-largest driver of global warming, accounting for 30% of the global temperature rise (McKinsey, 2021). Therefore, reducing CH_4 emissions is crucial for reaching net zero for GHG emissions and meeting the climate goal of 1.5°C, as shown in pathways limiting warming to 1.5°C with no or limited overshoot (Figure 21) (IPCC, 2022b). Efforts to reduce CH_4 must be targeted towards the agriculture and energy sectors. To curb CH_4 emissions in the agriculture sector, new approaches will need to be adopted for agricultural cultivation and livestock production (UNEP, 2021). Existing technologies, such as anaerobic manure digestion, selective breeding, and land management, can be used up to a point (McKinsey, 2021). However, new technologies will be needed to reduce methane emissions to the level required. Potential examples here could include alternative feed types, efficient manure management practices, and a shift towards meat alternatives and plant-based diets (UNEP, 2021). Fugitive methane released from oil and gas processes can be prevented by leak detections, repair, and equipment electrification (McKinsey, 2021).

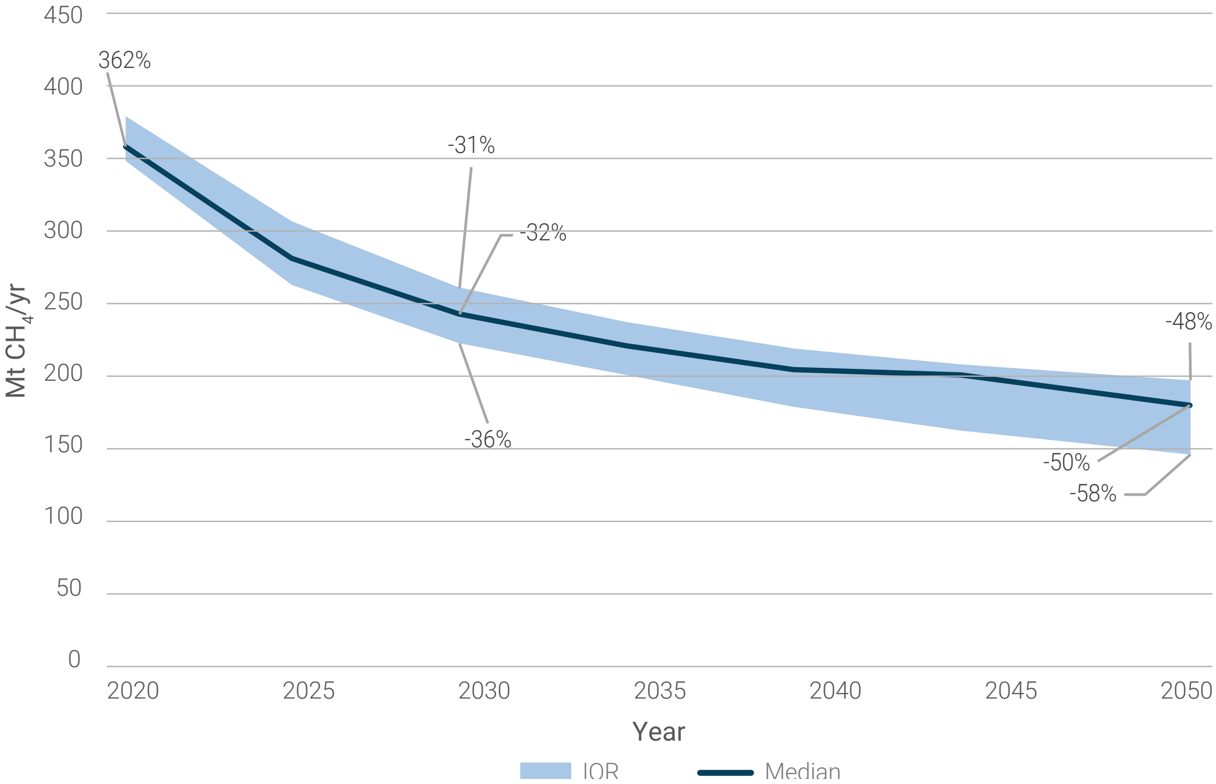


Figure 21: Global CH_4 emissions reported in the IPCC-assessed 1.5°C pathways with no or limited overshoot from 2020 to 2050[24]

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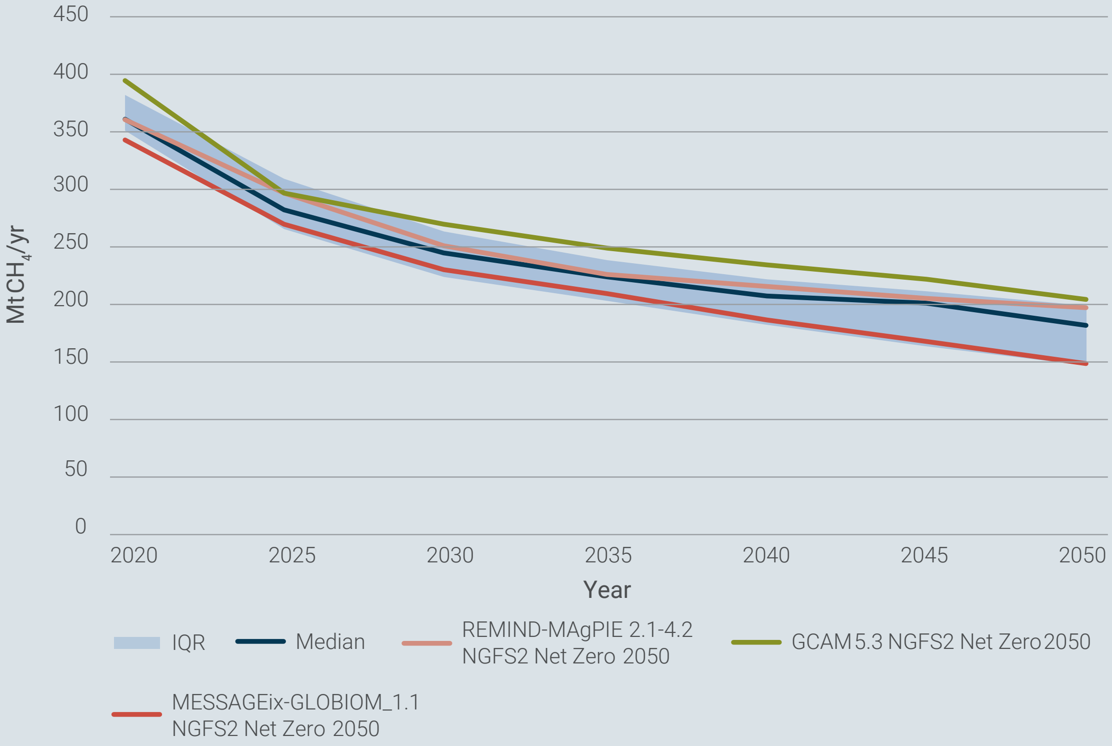
[24] 1 $MtCO_2$ = 0.001 $GtCO_2$

Box 3: CH_4 emissions estimates in the NGFS net-zero scenarios compared to the IPCC-assessed 1.5°C scenarios with no or limited overshoot



Both REMIND and MESSAGE Net Zero 2050 scenarios report CH_4 emissions levels that fall within the interquartile range of the IPCC-assessed scenario dataset, with the MESSAGE pathway being more in line with the lower range of values. Between 2020 and 2035, the REMIND pathway reports values closer to the median level of CH_4 emissions reported by the IPCC-assessed scenario dataset. However, by 2050, CH_4 emission levels reported by REMIND are in line with the upper range of values of the scenario dataset. GCAM Net Zero 2050 scenario reports relatively higher CH_4 emissions between 2020 to 2050 compared to the median value of the IPCC-assessed scenarios. After experiencing a sharp decrease in emissions between 2020 to 2025, with a decrease rate of 25%, the CH_4 emission reported under the GCAM model showcases a steady decrease but remain, on average, 6 $MtCH_4$/yr higher than the upper quartile of the IPCC-assessed scenario dataset between 2025 and 2050.

Data source: AR6 scenario explorer

Reducing nitrous oxide emissions

> **“N_2O emission reductions saturate for more stringent climate goals.”**
>
> **Working Group III (IPCC, 2022b).**

(Reductions of N_2O emissions are limited in scope in most 1.5°C–2°C pathways)

Since 1980, the concentration of N_2O in the atmosphere has increased by 30% (Tian *et al.*, 2020). Given that N_2O is a highly potent GHG and moderately longer lived than methane, it is important to take measures to decrease N_2O emissions. Pathways that limit global warming to 1.5°C with no or limited overshoot also show substantial reductions for N_2O by 2050 (Figure 22) (IPCC, 2022b). One of the most significant sources of N_2O is agriculture and, in particular, the use of synthetic nitrogen fertiliser. A critical step in reducing N_2O emissions, in line with the estimates of 1.5°C pathways with no or limited overshoot, is therefore to use fertiliser more efficiently and/or to decrease its overall use. This can partly be achieved using nitrogen in organic matter rather than synthetic fertiliser. Other mitigating actions to minimise N_2O generation from farming include minimising the use of tillage, preventing waterlogging, and using nitrification inhibitors that reduce nitrate leaching and lowers the production of N_2O (Government of Western Australia, 2021).

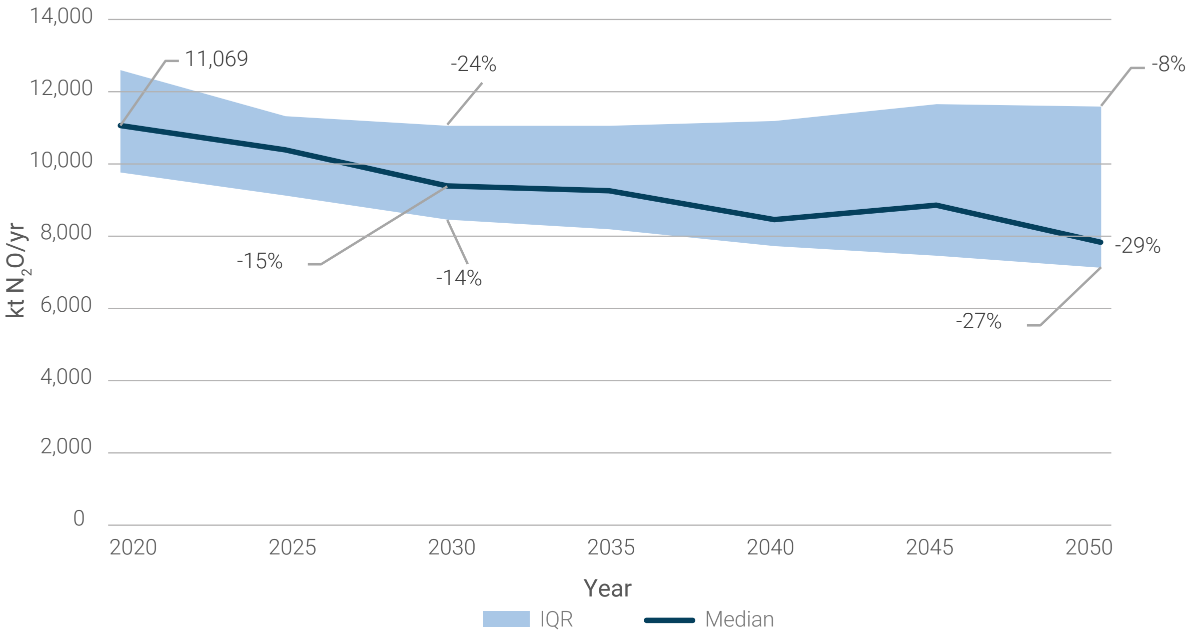


Figure 22: Global N_2O emissions reported in the IPCC-assessed 1.5°C pathways with no or limited overshoot from 2020 to 2050[25]

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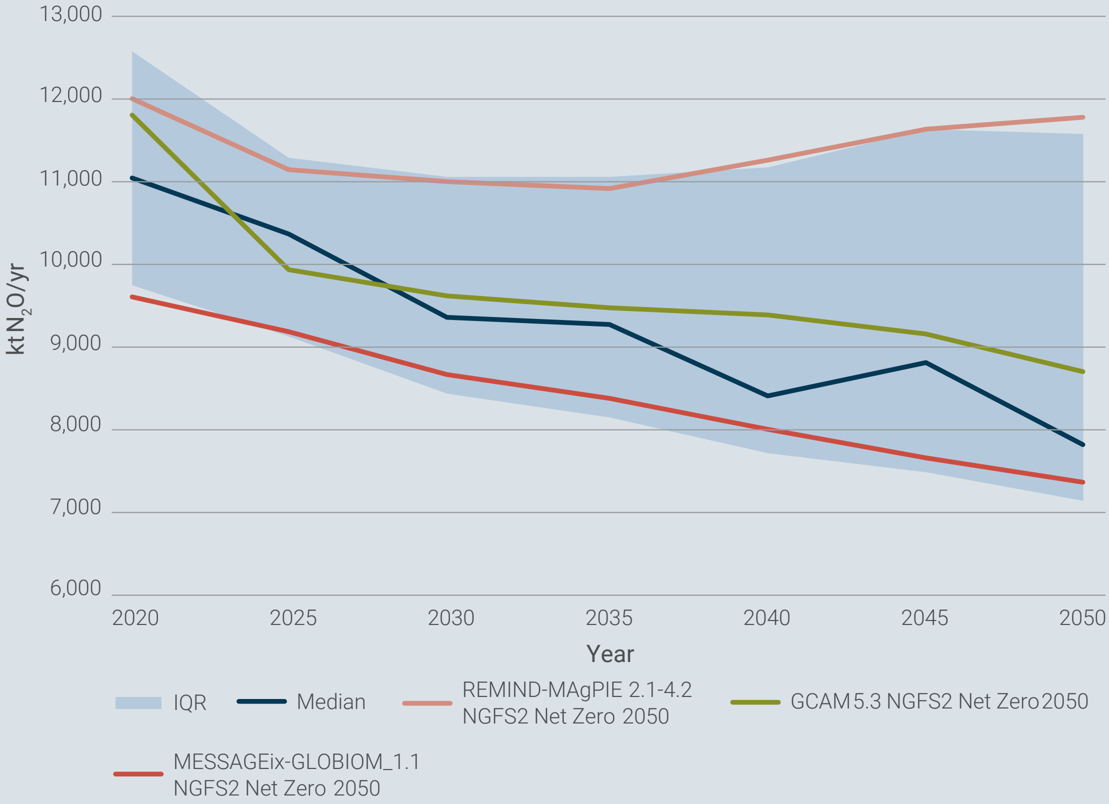
[25] 1 $MtCO_2$ = 0.001 $GtCO_2$

Box 4: N_2O emissions estimates in the NGFS net-zero scenarios compared to the IPCC assessed 1.5°C scenarios with no or limited overshoot



The IPCC-assessed scenario dataset shows a wide range of values for N_2O emissions between 2020 to 2050. While the MESSAGE Net Zero 2050 scenario reports values close to the lower quartile range of the IPCC-assessed scenario dataset, the REMIND Net Zero 2050 scenario reports higher levels of N_2O emission that are aligned with the upper quartile of the IPCC-assessed scenario dataset. After a sharp decrease of 1868.2 kt N_2O/yr from 2020 to 2025, the GCAM model showcases a less radical reduction rate from 2025 to 2050 and reports emission levels closer to the middle of the range of values reported by the IPCC-assessed scenario dataset between 2020 and 2050.

Data source: AR6 scenario explorer

Reducing F-gases

> **“Several countries also tax F-gases.”**
>
> IPCC, 2022b

Although F-gases are less prevalent in the atmosphere than other GHGs, they have a global warming potential thousands of times greater than CO_2. These man-made industrial gases must be reduced to mitigate climate change due to their high GWP. F-gases can be reduced worldwide through targeted protocol-based action. The Montreal Protocol offers an illustrative case in point. Agreed in 1987 and undergone multiple amendments, the Protocol is an international treaty aimed at phasing out gases responsible for ozone depletion (UNEP, n.d.). It succeeded in accelerating the phase-out of hydrochlorofluorocarbons (HCFCs), which are gases used in refrigeration, air conditioning, and foam applications. Under the terms of the treaty, developed countries agreed to reduce their consumption of HCFCs and phase them out by 2020. Developing countries, meanwhile, agreed to begin their phase-out in 2013 and to complete the phase-out of HCFCs by 2030 (UNEP, n.d.). Today, the use of chlorofluorocarbons (CFCs) is outlawed by 197 countries (Rapid Transition Alliance, 2019). Due to its widespread implementation, the treaty is often claimed to be the most successful international agreement (US Department of State, n.d.). In 2016, the Montreal Protocol was amended to include the phase-down of hydrofluorocarbons (HFCs) of 80–85% by the late 2040s (UNEP, n.d.).

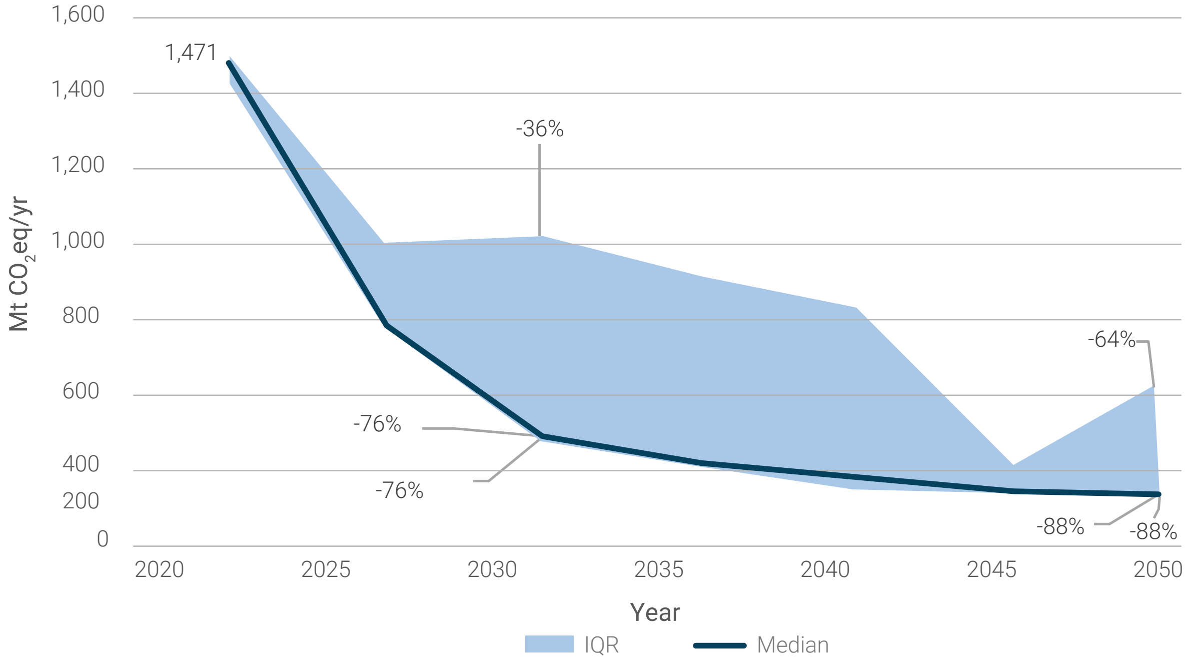


Figure 23: Global F-gases emissions reported in the IPCC-assessed 1.5°C pathways with no or limited overshoot from 2020 to 2050[26]

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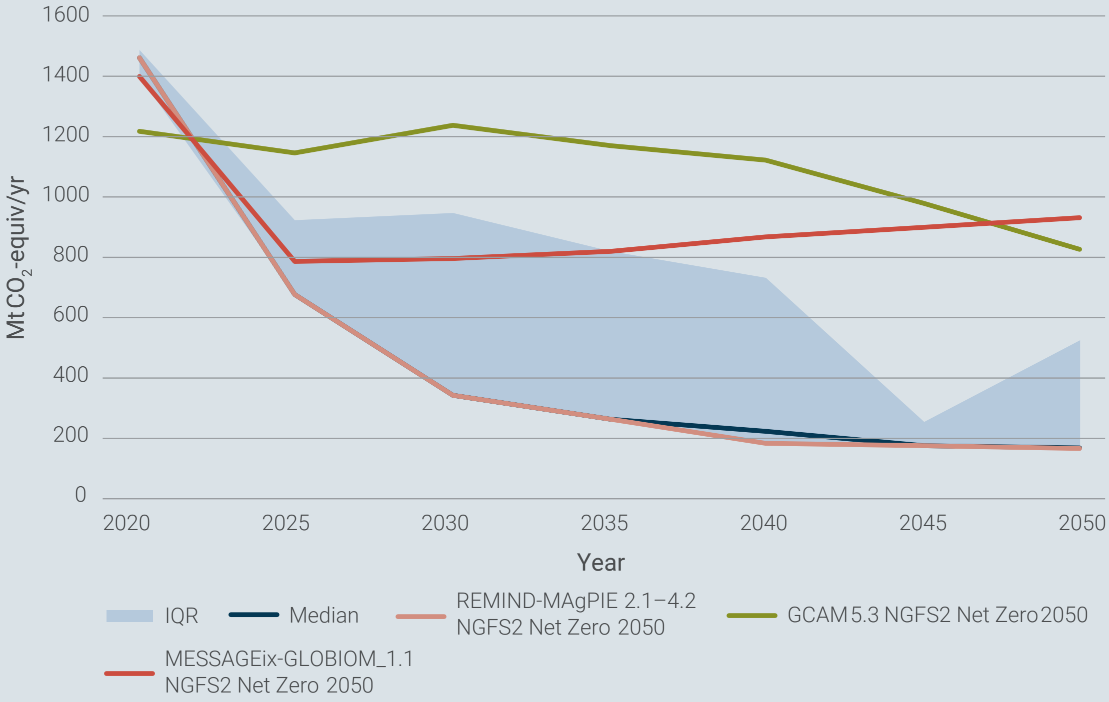
[26] 1 $MtCO_2$ = 0.001 $GtCO_2$

Box 5: F-gases emissions estimates in the IEA and the NGFS net-zero scenarios compared to the IPCC-assessed 1.5C scenarios with no or limited overshoot



The REMIND Net Zero 2050 scenario reports similar levels of F-gases emissions as the lower range of values (first quartile) of the IPCC-assessed scenario dataset over 2020–2050. The MESSAGE Net Zero 2050 scenario demonstrates a steep decrease (44%) in F-gases emissions between 2020 and 2025. However, the MESSAGE pathway reports an increase in F-gases emissions from 2025 until 2050 (18%). The GCAM Net Zero 2050 scenario reports emissions values significantly higher than the upper quartile of the IPCC-assessed scenario data set (380.46 MtCO$_2$eq/yr higher on average) between 2025 and 2050.

Differences in the emissions reported by the models can be due to the use of different data sources and their underlying assessments. These differences can be likely attributed to the different resolutions of underlying technologies and drivers of these emissions and variations between the models. For example, GCAM applies the Environmental Protection Agency (EPA) Marginal Abatement Cost curves for mitigation of non-CO$_2$ emissions.

Data source: AR6 scenario explorer

Box 6: Aerosols and warming

Aerosols are defined by the IPCC as “a suspension of airborne solid or liquid particles, with typical particle size in the range of a few nanometres to several tens of micrometres and atmospheric lifetimes of up to several days in the troposphere and up to years in the stratosphere”. Aerosols can be composed of sea salt, organic carbon, black carbon, mineral species, sulphate, nitrate, and ammonium (IPCC, 2022a).

Anthropogenic aerosols can partly counteract the warming effect of GHGs. Short-lived aerosol particles in the air reflect incoming sunlight back into outer space. Aerosols boost cloud formation, which decreases the amount of energy that reaches the ground and results in a cooling-effect (Princeton University, n.d.). However, aerosols also have a warming effect. Absorbing aerosols, such as black carbon emitted during incomplete combustion of fossil fuels (IPCC, 2022a), contribute to global warming by trapping solar energy in the atmosphere. Atmospheric heating can reduce the sunlight reaching the ground but can eventually cause the heating up of the surface (Princeton University, n.d.).

Many climate models have assumptions regarding the cooling or warming effect of aerosols; yet, some models include specific reductions of aerosols in their pathways. For example, eighty-one 1.5°C scenario pathways no or limited overshoot include reductions of black carbon.

4.4 Summary of emissions reductions in 1.5°C scenario pathways with no or limited overshoot

Pathways limiting warming to 1.5°C with no or limited overshoot show significant reductions in GHG emissions across all sectors (Figure 24). To achieve the 1.5°C climate goal, the IPCC asserts that “delaying or failing to achieve emissions reductions in one sector or region necessitates compensating reductions in other sectors or regions” (IPCC, 2022b).

In AR6, the IPCC provides a summary of mitigation options to reduce GHG emissions and their costs (Figure 24). Costs for each mitigation option are shown as the net lifetime costs of avoided GHG emissions. For each mitigation option, the IPCC also provides its mitigation potential—i.e. the quantity of net GHG emission reductions that can be achieved by the respective mitigation option in question. To determine the mitigation potential, the IPCC uses a baseline of emissions that reflect current policy reference scenarios. The mitigation potential is uncertain and will depend on various factors, including geographical location, time, the rate of adoption of new technology, and the speed at which shifts are made away from reference technology. Sources of uncertainty in the cost estimates include assumptions in technological advancement, regional differences, and economies of scale. The IPCC states that:

> **“Beyond 2030, the relative importance of the assessed mitigation options is expected to change, in particular while pursuing long-term mitigation goals, recognising also that the emphasis for particular options will vary across regions.”**

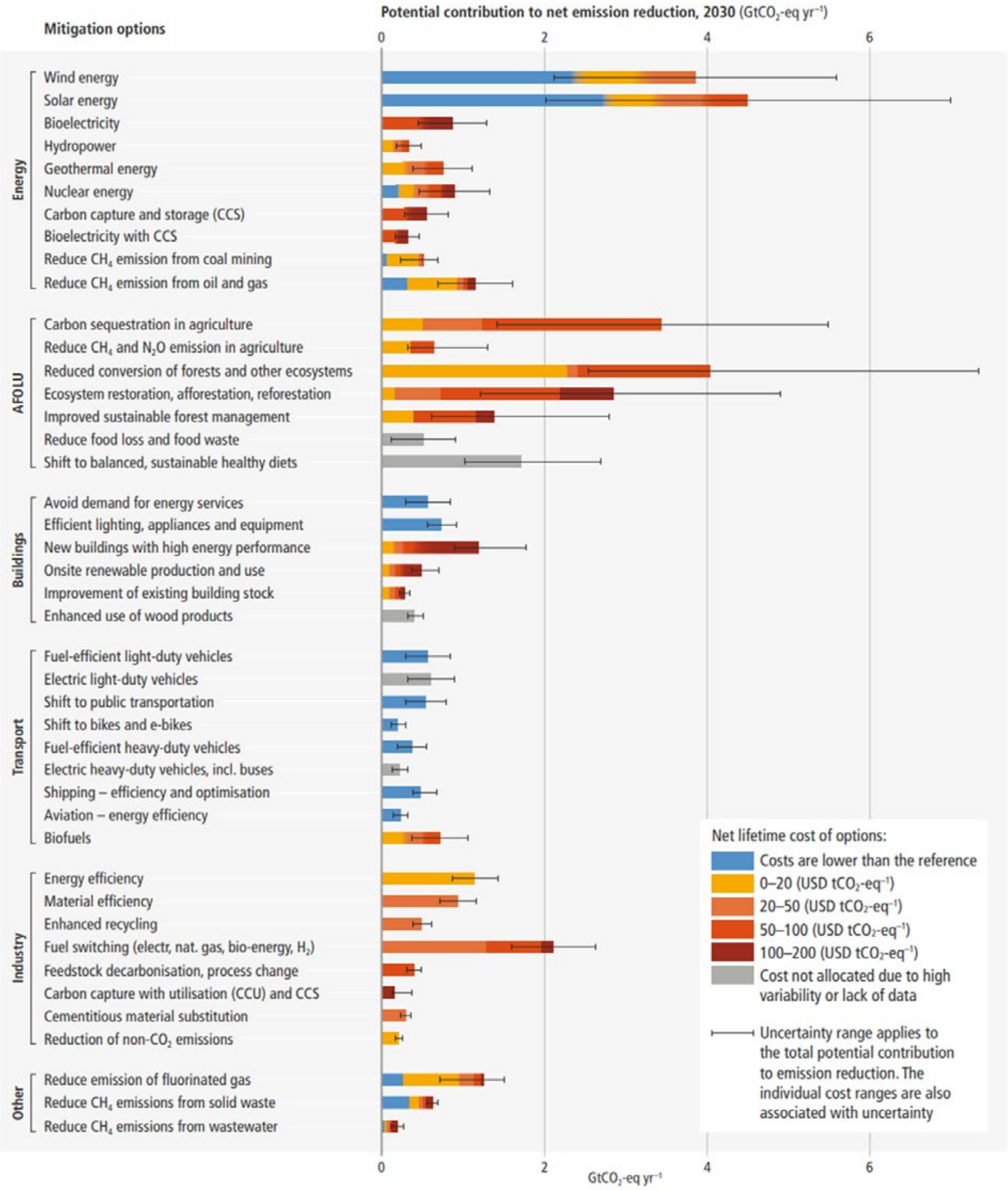


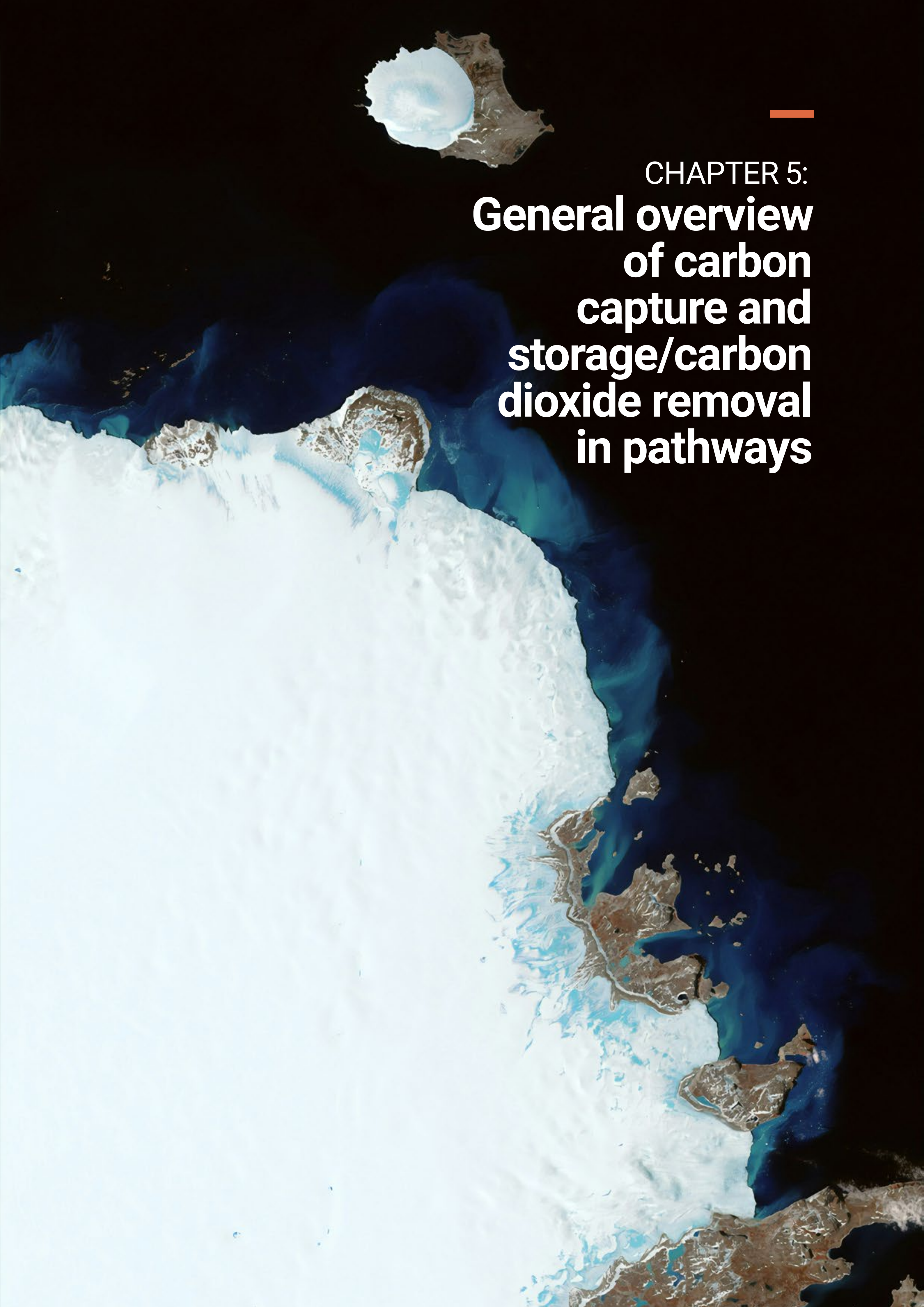
Figure 24: Summary of mitigation options to reduce GHG emissions (IPCC, 2022b)

Different mitigation options may differ in their costs. Many relatively inexpensive mitigation options are already available, for instance. These include wind and solar energy, as well as low-carbon public transportation, bikes, and e-bikes. It is recommended that these are further deployed without delay. Others are in development. Examples include fuel switching for heavy industry, CCS, and energy-efficient building materials and construction. The costs of these emerging technologies are high and further research and development are therefore needed to make them more affordable. Policies that increase the costs of emissions can also help make these mitigation options more economically competitive.

Estimates of costs and deployment assumptions differ by scenario model. Therefore, different models limiting global warming to 1.5°C with no or limited overshoot estimate different mitigation potentials for different mitigation options. As a result, different models show different pathways to limiting warming to 1.5°C with no or limited overshoot. For example, integrated assessment models are sensitive to technological assumptions. Even minor changes in assumptions about technology costs can substantially impact technology pathway models (Pathways to Paris, 2021).

Questions for readers

- What are your major emitting sectors for the GHG emissions (CO_2, CH_4, N_2O, F-gases)?
- What reduction plans does your institution have to decrease GHG emissions (CO_2, CH_4, N_2O, F-gases) to align with the reductions in the decarbonisation pathways?
- Has your institution identified methodologies to help measure the GHG emissions (CO_2, CH_4, N_2O, F-gases) of your lending and investment activities?
- Which mitigation options are potential opportunities for your institution to be involved in?



CHAPTER 5:

General overview of carbon capture and storage/carbon dioxide removal in pathways

Key insights into emissions reduction

- The deployment of carbon capture and removal technologies could be crucial to countering delays in reducing CO_2 emissions and limiting warming to 1.5°C.
- CDR deployment can serve various purposes, such as accelerating the pace of emissions reductions, offsetting residual emissions, and creating the option for net-negative CO_2 emissions.
- Significant scale-up of CDR will likely be needed in 2030 onwards; for example, 1.5°C scenarios with no or limited overshoot show BECCS and DACCS increasing by almost 12-fold and 10-fold between 2030 and 2050.
- Methods for CO_2 removal include Bioenergy with Carbon Dioxide Capture and Storage (BECCS), Direct Air Carbon Dioxide Capture and Storage (DACCS), afforestation, and soil carbon sequestration.
- BECCS, DACCS, Land Use and Afforestation are the most common methods considered in the scenarios.
- These methodologies vary in terms of maturity, removal process, storage potential, storage duration, technological readiness, mitigation potential, cost, benefits, adverse impacts, and governance requirements.
- The diverse applications for CO_2 emissions need to be considered, such as capturing, storing, and utilising carbon.
- Similar to renewable technologies, CCS costs are expected to decrease with technological advancements and economies of scale; however, economic incentives, such as carbon taxation, are needed to promote the scale-up of carbon capture and removal technologies.

Suitability considerations of scenarios for exploring CDR

Limited information and detail	Some information and detail	Good information and detail
▪ If technological developments do not occur at the rate shown in pathways over the coming years, the scenarios will need to be reviewed for their reliance on CDR. ▪ Lack of consideration for socio-political feasibility, which may lead to only a small number of pathways taking into account the limited viability of CDR for certain countries ▪ Lack of information on long term durability and permanence of the CCS & CDR options	▪ Regional granularity ▪ Lack of regional differentiation between pathways with only a small number of pathways taking into account limited viability of CDR for certain countries	▪ Coverage of different types of CDR options and the most common types used in pathways ▪ Timeframe under which CDR is deployed at a large scale is laid out, with a sizeable proportion of pathways reporting a higher reliance on CDR post-2030. ▪ Needed scale of deployment for CDR technologies

5.1 The importance of carbon capture and storage/ carbon dioxide removal in scenarios

Limiting global warming to 1.5°C requires steep and aggressive cuts in emissions. As discussed in Section 1, the world is rapidly burning through its carbon budget. Based on 2022 emissions rates, the cumulative remaining budget for 1.5°C is only six years (Lamboll *et al.*, 2023). The economic and political realities of the transition mean that it is increasingly likely that emissions will not fall fast enough to stay within this budget. Furthermore, emissions from some economic activities may be hard to abate. Even when net zero is reached, therefore, emissions will still be produced. As such, many 1.5°C models in the IPCC Assessment Report 6 make assumptions that require the use of CO_2 removal. This chapter explores the nature and prevalence of these removal assumptions across these different 1.5°C scenarios.

Carbon capture and storage (CCS) captures CO_2 emissions released from the burning of fossil fuels and stores the carbon for the long run to prevent it from entering the atmosphere. The IPCC **defines** CCS as:

> **"A process in which a relatively pure stream of carbon dioxide (CO_2) from industrial and energy-related sources is separated (captured), conditioned, compressed and transported to a storage location for long-term isolation from the atmosphere."**
>
> **IPCC, 2021**[27]

However, CCS does not directly reduce CO_2 levels from the atmosphere. The reduction in atmospheric CO_2 levels by capturing CO_2 emissions from the air and storing it for the long run is known as carbon dioxide removal (CDR) (IPCC, 2022). CDR is an important attribute of scenarios that limit warming to 1.5°C with no or limited overshoot to remove CO_2 from the atmosphere to ensure the carbon budget for 1.5°C warming is not overspent. The IPCC **defines** CDR as:

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[27] Note: The IPCC definition of CCS does not specify the different types of CCS considered in 1.5°C scenarios with no or limited overshoot. It is important to consider the various types of CCS, such as industrial and energy CCS.

> **“Anthropogenic activities removing carbon dioxide (CO_2) from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical CO_2 sinks and direct air carbon dioxide capture and storage (DACCS), but excludes natural CO_2 uptake not directly caused by human activities.”**
>
> IPCC, 2021

The deployment of carbon capture and removal technologies is critical in pathways to reach net zero CO_2 emissions globally by 2050 and net-negative emissions in the latter half of the century. The greater the delay in reducing CO_2 emissions, the greater the reliance on CDR technology to remove CO_2 emissions from the atmosphere to limit global warming to 1.5°C. CDR deployment in pathways can serve multiple purposes, such as accelerating the pace of emissions reductions, offsetting residual emissions, and creating the option for net-negative CO_2 emissions in case temperature reductions need to be achieved in the long term (IPCC, 2022).

The high concentration of global emissions in the atmosphere makes the removal of CO_2 an imperative. The IPCC’s assessed 1.5°C scenario pathways with no or limited overshoot include the use of CDR technology to some extent. All the illustrative mitigation pathways (IMPs) explored in the AR6 include CDR technology to some extent (IPCC, 2022).[28] The pathways deploy significant CDR later in the century to compensate for higher emissions before 2030 (IPCC, 2022). There is a scientific consensus that some level of CDR will be needed to limit warming to 1.5°C; however, models still differ in their estimates of how much carbon removal will be needed. CDR is favoured in models that minimise total system costs as CDR allows for later removals of CO_2. These models see costs pushed into the future (IISD, 2022). The CDR levels cited in the latest models also depend on long-term discount rates and assumptions about the development and deployment of relevant technologies. These models have faced criticism about their assumptions for CDR and have received pushback from the financial sector.

Levels of optimism concerning the use of CCS and CDR in scenario models can have strong implications on other scenario assumptions, such as fossil fuel use and carbon pricing. For example, a lower possibility of CO_2 removal at a large scale will increase the requirement to reduce carbon intensity and improve energy efficiency in 1.5°C scenario pathways. Lower availability of CDR technology will increase carbon prices and prompt a quicker phase-out of fossil fuels in the scenario pathways in order to reduce carbon emissions and stay within the carbon budget for limiting warming to 1.5°C. Therefore, assumptions of CDR technology in the models can impact the discount rates with greater optimism in CCS and CDR use in models leading to higher discount rates. High discount rates also lead to a decrease in investments in less carbon-intensive alternatives, such as renewable energy. Optimism in relation to CCS and CDR in models and

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[28] In comparison to the 1.5°C scenarios assessed in SR1.5, the 1.5°C scenarios in AR6 have a lower reliance on CDR technology to reach the warming target. See Section 3.2 for more details.

high discount rates of models have been questioned. Scenario modellers have tried to address this criticism by exploring low CCS and CDR pathways.

This section deep-dives into CCS and CDR assumptions within models and their potential value and limitations.

5.2 Overview of carbon capture and storage

Types of CCS

Technologies for capturing CO_2 at its source fall into three primary categories; post-combustion carbon capture, pre-combustion carbon capture, and oxy-fuel combustion systems (Figure 25).

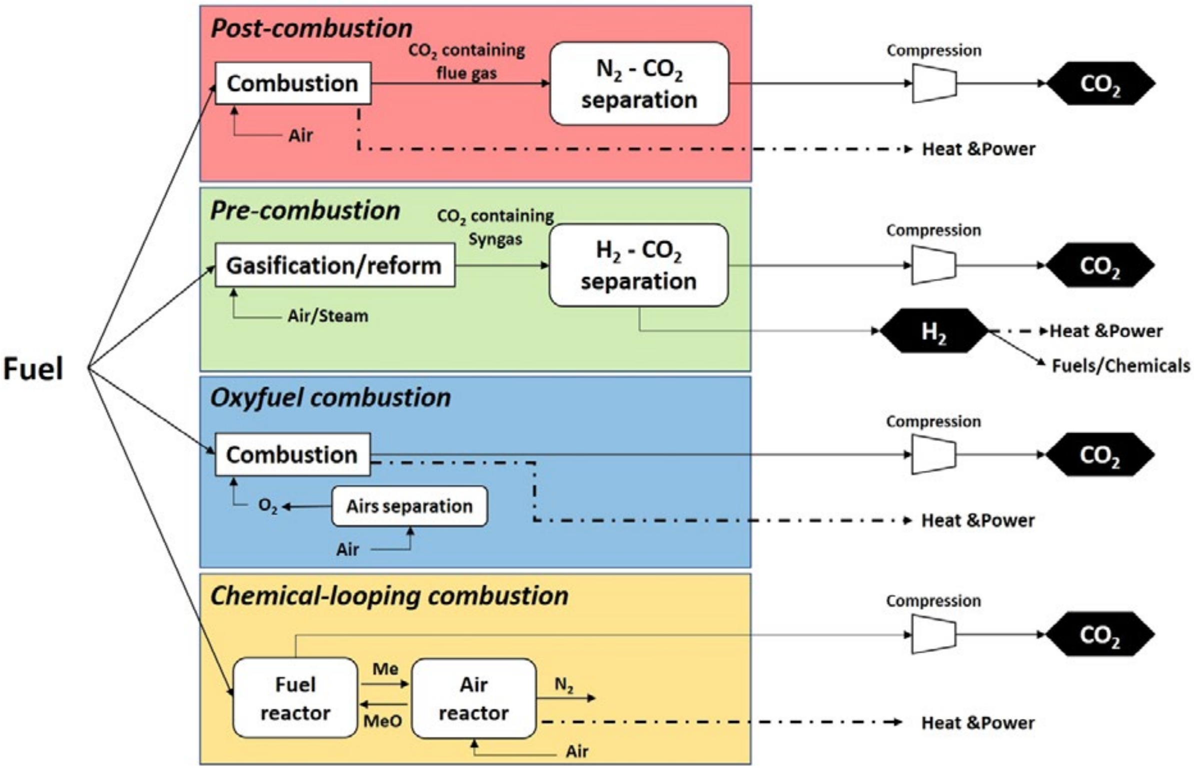

Figure 25: Schematic representation of carbon capture system (Raganati *et al.*, 2021)

- **Post-combustion** carbon capture is the main method used in existing power plants. In this approach, CO_2 is separated from the exhaust of a combustion process.
- **Pre-combustion** carbon capture is mainly used in industrial processes by gasifying fuel to separate CO_2. Such technology is currently commercially available for industrial facilities but it remains in the early stages of development for power plants. Pre-combustion capture technology can be built into new facilities or can be retrofitted onto existing facilities with the technology. The latter option is highly costly. For more information on costs of CCS, please read '*Development and costs of the technologies*'.

- In **oxy-fuel combustion systems**, fuel is burned in an almost pure-oxygen environment, generating a concentrated stream of CO_2 emissions,[29] making it easier and cheaper to capture. In CCS, captured carbon emissions are transported and stored for the long term instead of being released into the atmosphere. With this technology, CO_2 is typically injected into underground geological formations, such as former oil and gas reservoirs, deep saline formations, and coal beds (Resources for the future, 2020). Sites for carbon storage will be further discussed in this section below.

Current and estimated use of CCS

In 2023, 37 CCS projects were in operation, with a further 20 under construction and 200 in development (Global CCS Institute, 2023). The current stock of operating CCS projects store about 45 million tonnes of CO_2 annually (MIT, 2023).[30] Figure 26 shows the range of estimates for total CO_2 emissions captured and stored in geological deposits in the 1.5°C pathways with no or limited overshoot assessed by the IPCC. The IPCC assessed scenarios show 7,286.9 (5,432.6—11,969.7)[31] megatonnes of CO_2 ($MtCO_2$) captured annually using CCS in 2050, a 565.3% (median) increase from 2030 levels. 81 of the 1.5°C scenarios with no or limited overshoot also report using CCS to some extent in order to capture and store emissions from fossil fuel use between 2030 and 2050 (Figure 27).[32] Scaling up of CCS to the levels reported in the scenarios for 2030 and 2050 brings its own set of challenges, especially relating to costs (see 'Development and costs of the technologies' and 'Drawbacks and obstacles of the technology').

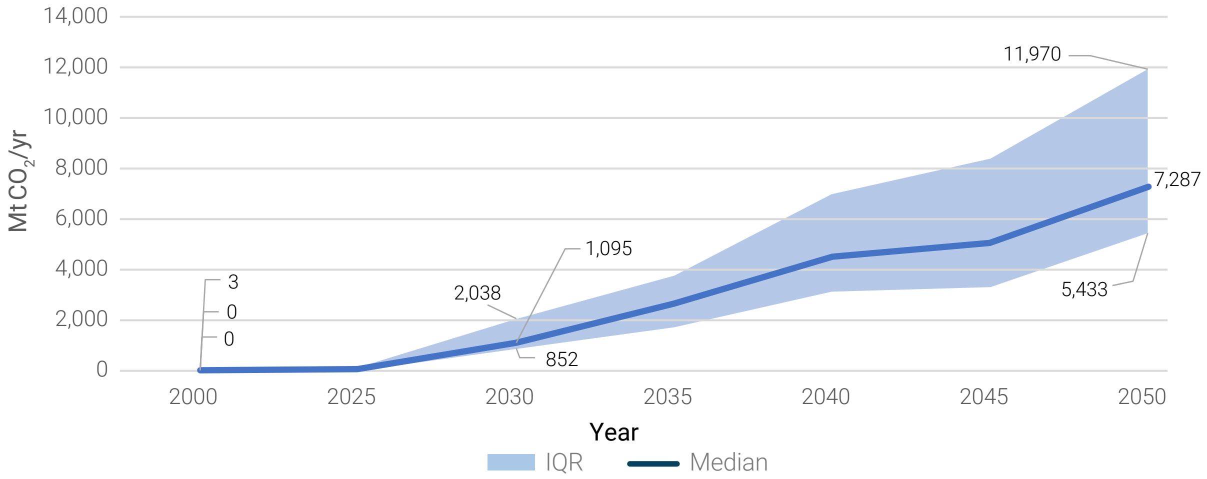

Figure 26: Use of CCS estimates in the IPCC-assessed 1.5°C pathways with no or limited overshoot from 2020 to 2050

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[29] This is 10–15% CO_2 vs 0.04% as in ambient air.

[30] As of January 2023

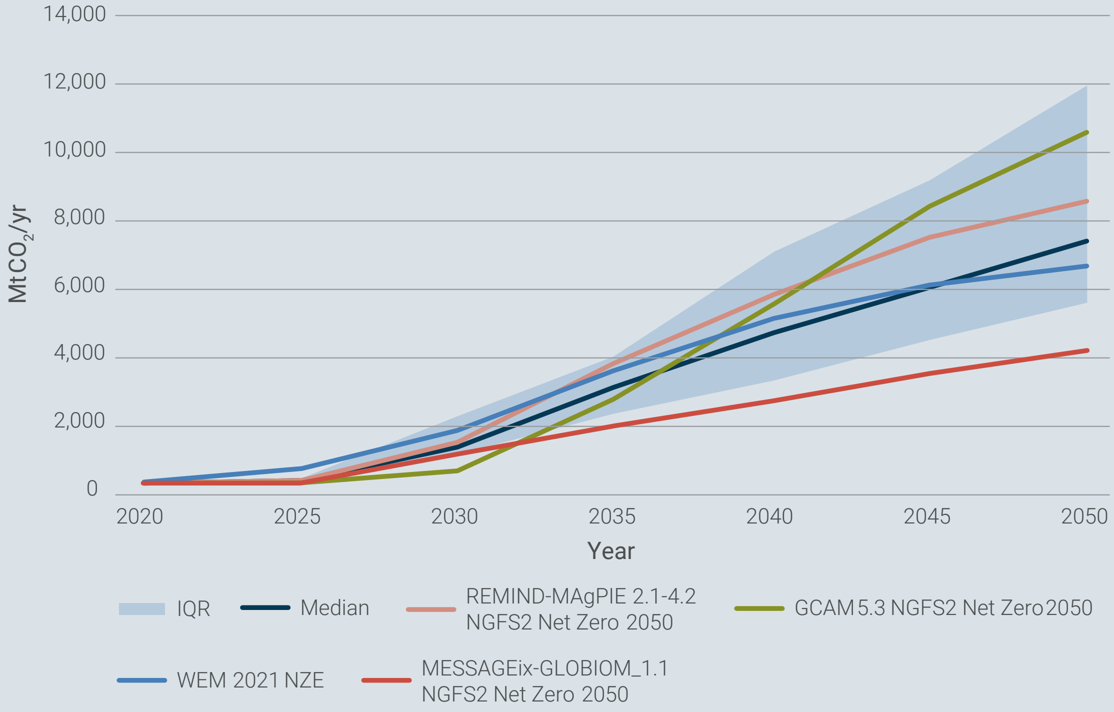
[31] Values in this chapter are represented as median (interquartile range)

[32] Many 1.5°C with no or limited overshoot scenario models include a further breakdown of CCS into fossil CCS as a variable. See Table 17 for more information on fossil CCS as a recommended variable for assessing CCS in the scenario pathways.

Table 12: Percentage of current emissions captured by CCS in the IPCC-assessed 1.5°C pathways with no or limited overshoot

Year	Quartile	Estimate emissions captured (MtCO_2)	Percentage of current emissions[33] (%)
2030	25th	852	2.3
	50th	1,095	3.0
	75th	2,038	5.5
2050	25th	5,433	14.8
	50th	7,287	19.8
	75th	11,970	32.5

Box 7: Use of CCS estimated in the IEA and the NGFS net-zero scenarios compared to the IPCC-assessed 1.5°C pathways with no or limited overshoot



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[33] Global energy-related CO_2 emissions in 2022 are estimated to be more than 36.8 billion tonnes (IEA, 2023a).

All of GCAM, REMIND, MESSAGE and IEA net zero by 2050 scenarios report a steady increase in the deployment of CCS technologies between 2020 and 2050. The GCAM Net Zero 2050 scenario reports a much more rapid increase in CCS compared to the other models, showcasing a rate of increase of 26% by 2030 onwards. The IEA NZE scenario reports a higher use of CCS than the middle of the range of values (*median*) reported by the IPCC-assessed scenario dataset between 2020 and 2045. By 2050, in comparison to the median IPCC-assessed value, the IEA pathway shows 10% less CO_2 captured by CCS. The MESSAGE Net Zero 2050 scenario reports the lowest use of CCS, falling below the lower quartile of the IPCC-assessed scenario dataset.

Data source: AR6 scenario explorer

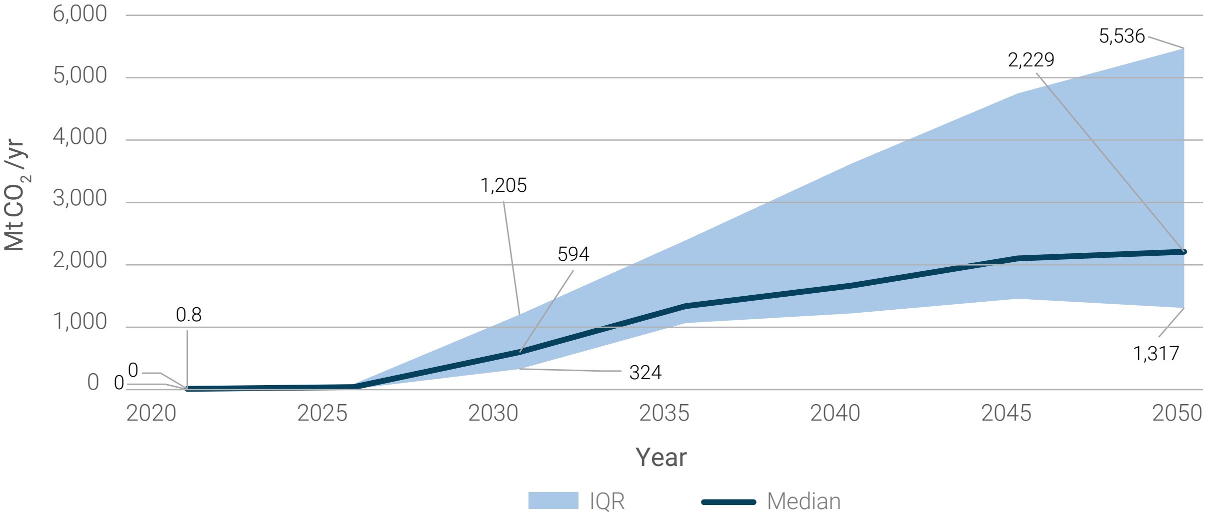
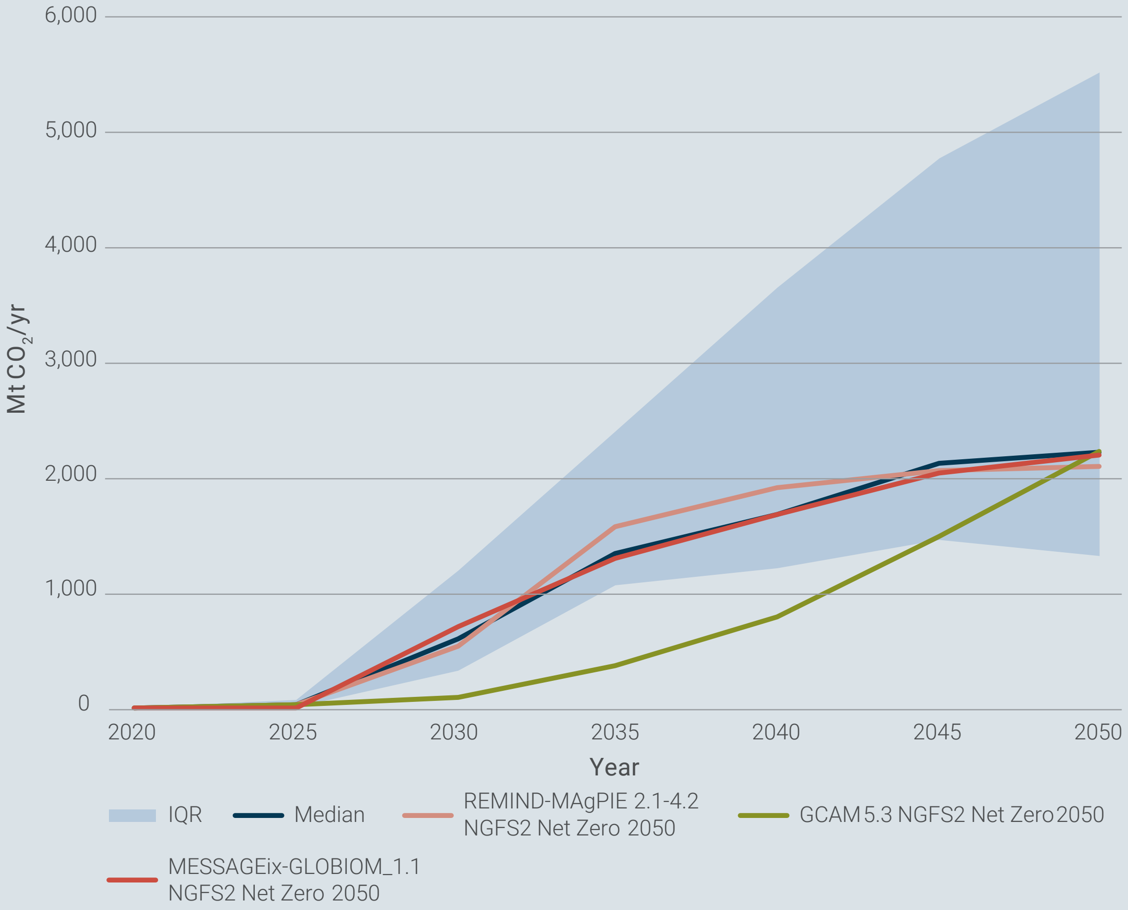


Figure 27: CO_2 emissions captured and stored from fossil fuel use in the IPCC-assessed 1.5°C scenarios with no or limited overshoot from 2020 to 2050

Box 8 : CO_2 emissions captured and stored from fossil fuel use in the NGFS net-zero scenarios compared to the IPCC-assessed 1.5°C scenarios with no or limited overshoot



From 2020 to 2025, all models, including the IPCC-assessed scenario dataset, report values close to 0 $MtCO_2$/year for CO_2 emissions captured and stored from fossil fuel use. Following 2025, the models report an increase in the deployment of CCS technologies for fossil fuel use. Both the REMIND and MESSAGE Net Zero 2050 scenarios show values close to the median levels of the IPCC-assessed scenario dataset from 2020 to 2050. However, the REMIND pathway reports slightly higher levels of CO_2 emissions captured than the median levels between 2030 and 2045. In 2035, CO_2 emissions captured and stored from fossil fuel use are 17% higher in the REMIND pathway than the median value. The GCAM Net Zero 2050 scenario reports values much lower than the other models from 2025 till 2050. However, a rapid increase in the use of CCS for fossil fuel use from 2040 in the pathway results in GCAM reporting similar levels of CCS in 2050 as REMIND, MESSAGE and the median value of the IPCC-assessed scenario dataset

5.3 Overview of carbon dioxide removal

CDR is an important attribute of scenario pathways for reducing CO_2 emissions in the atmosphere to meet the carbon budget and limit warming to 1.5°C with no or limited overshoot.

CDR has three main roles as part of decarbonisation pathways:

1. reducing net CO_2 or GHG emissions in the near term;
2. counterbalancing 'hard-to-abate' residual emissions to achieve net zero CO_2 or GHG emissions in the mid term; and
3. achieving net negative emissions in the long term if deployed at levels higher than annual residual emissions (IPCC, 2022).

Using CCS for carbon emissions linked to fossil fuels is not considered a removal technology. According to the IPCC, CCS can only be considered a part of CDR methods if carbon is biogenic or directly captured from the atmosphere and stored in geological reservoirs or products (IPCC, 2022). CCS for fossil fuels are at best carbon neutral as they do not remove any CO_2 from the atmosphere.

Race to Zero standards require the removal of any CO_2 emissions to be permanent. In addition, they must be exclusively claimed by the actor instigating the removal and they must not substitute emissions reductions targets. Limiting CO_2 leakage and securing long-term carbon storage is therefore required for there to be high confidence in these CCS technologies as viable emissions mitigation strategies.

There are a variety of CDR methods that are implemented in modelled pathways (Table 13). Atmospheric CO_2 removal methods can be categorised as biological, geochemical, or chemical. Some methods include Bioenergy with Carbon Dioxide Capture and Storage (BECCS), Direct Air Carbon Dioxide Capture and Storage (DACCS), afforestation, and soil carbon sequestration. The method of CDR deployed and the amount of CDR used in modelled pathways can vary highly in terms of maturity, removal process, storage potential, storage duration, technological readiness, mitigation potential, cost, benefits, adverse impacts, and governance requirements (IPCC, 2022). From 2020 to 2100, the total cumulative net negative CO_2 emissions, including CDR deployment across all types, are represented in the IPCC's assessed modelled pathways for 1.5°C with no or limited overshoot. These range from 20–660 gigatons of CO_2 ($GtCO_2$) (IPCC, 2022).

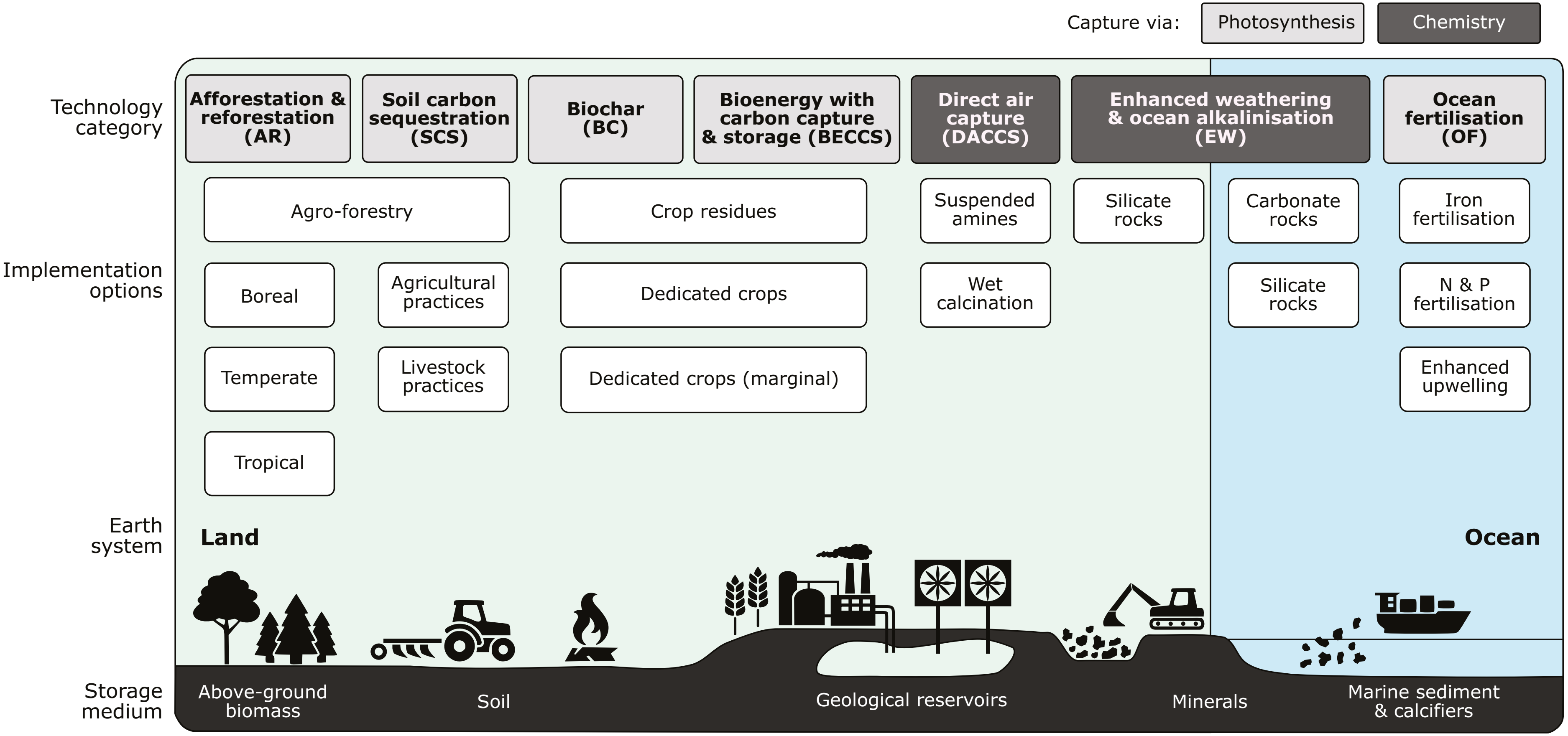


Figure 28: Overview of different CDR methodologies (IPCC, 2022)

Table 13: Number of IPCC-assessed 1.5°C scenarios with no or limited overshoot reporting types of CDR methods[34] (C2G, 2022)

n=97	Number of scenarios (including zero values)	Percentage of total scenarios (including zero values) (%)	Number of scenarios (excluding zero values)	Percentage of total scenarios (excluding zero values (%)
Bioenergy with Carbon Dioxide Capture and Storage (BECCS)	95	97.9	91	93.8
Direct Air Carbon Dioxide Capture and Storage (DACCS)	38	39.2	29	29.9
Land use[35]	64	66.0	64	66.0
Afforestation	53	54.6	53	54.6
Biochar	3	3.1	0	0.0
Soil carbon management	3	3.1	0	0.0
Enhanced weathering	32	33	2	2.1
Other[36]	10	10.3	1	1.0

Overreliance on a single CDR method can bring about risks. Research has found that a complete suite of CDR methodologies, such as BECCS, DACCS, enhanced weathering, and biochar, will need to be deployed to remove the amount of CO_2 needed to limit global warming to 1.5°C (Fuhrman *et al.*, 2023).

Deep-dive into key CDR methodologies

Four CDR methodologies—BECCS, DACCS, Land Use and Afforestation—are the most commonly included CDR methodologies in the IPCC-assessed 1.5°C scenarios with no or limited overshoot. Further details on these CDR methodologies are provided below.

Scenario pathways include the use of BECCS to varying degrees in order to reach the 1.5°C climate goal with low or no overshoot. The IPCC defines BECCS as:

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[34] Those CDR methods that are not explicitly called out in the 1.5C models are grouped under 'Other'.

[35] Includes scenarios reporting CO_2 sequestration from afforestation, soil carbon enhancement, and biochar.

[36] Total CO_2 sequestered through other techniques.

> **“Carbon dioxide capture and storage (CCS) technology applied to a bioenergy facility. Note that depending on the total emissions of the BECCS supply chain, carbon dioxide (CO_2) can be removed from the atmosphere.”**
>
> **IPCC, 2021**

BECCS is based on the natural ability of plants to remove CO_2. The process involves plants being cultivated and then burned to produce energy, with the subsequent emissions then captured and stored in geological formations underground. CO_2 emissions from biomass combustion are not released but captured and stored. Extra plant growth can remove emissions already in the atmosphere (Fern, 2018). In AR6, modelled pathways for limiting warming to 1.5°C with no or limited overshoot that report CDR, global annual CDR from BECCS is 3,834 (1,883–5,423) $MtCO_2$ in 2050, an increase of 1,076.8% (median) from 2030 (Figure 29) (IPCC, 2022). Although the scenarios report an increase in BECCS from 2025 onwards, a massive scale-up in the technology is projected to occur after 2035. This suggests breakthroughs in the technologies from 2035 onwards, resulting in decreased costs and a greater ability to deploy the technology at a larger scale.

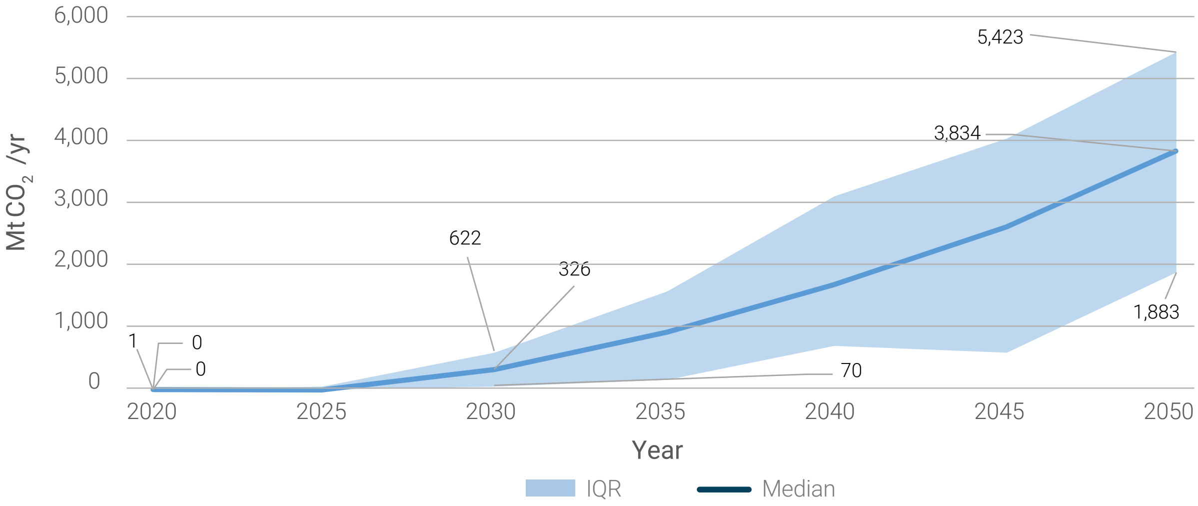
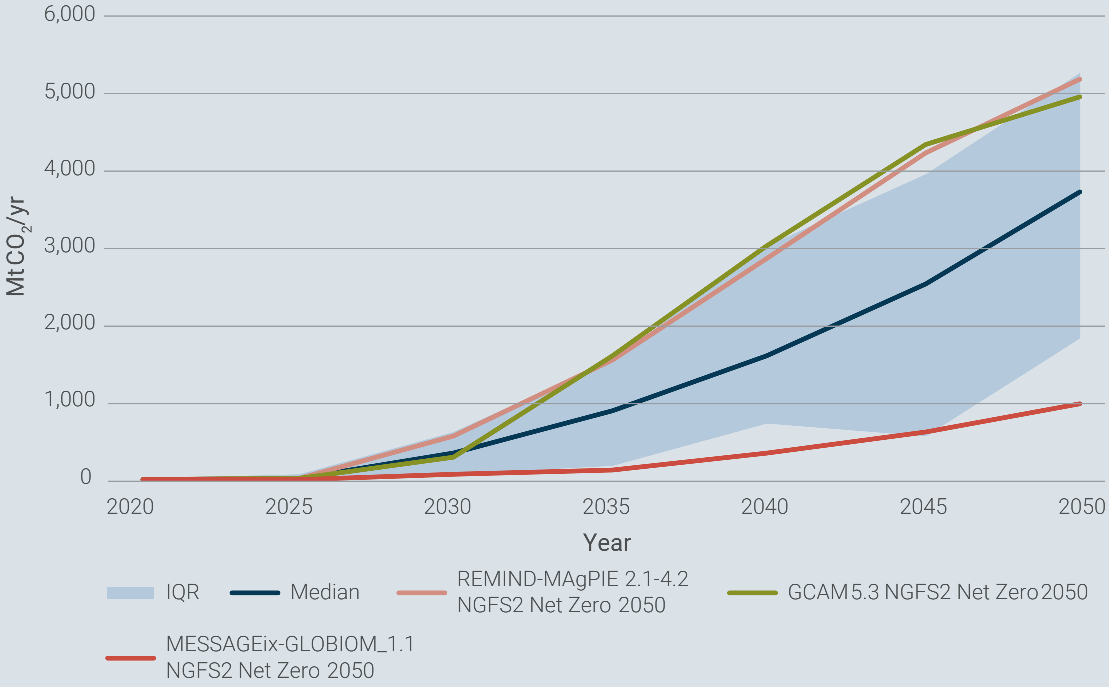


Figure 29: Use of BECCS estimates in the IPCC-assessed 1.5°C pathways with no or limited overshoot from 2020 to 2050

Box 9: Use of BECCS estimates in the NGFS net-zero scenarios compared to the IPCC-assessed 1.5°C pathways with no or limited overshoot



All models collectively show an increase in the use of BECCS from 2025 to 2050. The MESSAGE Net Zero 2050 scenario shows a slower increase in the use of BECCS from 2030 to 2050, compared to the other NGFS models and the median growth rate for the IPCC-assessed scenario dataset. In 2050, the median value for BECCS use of the IPCC-assessed scenario dataset is more than 3 times larger than the value reported by MESSAGE. In comparison, the REMIND and GCAM Net Zero 2050 scenarios show much greater, and similar, levels of BECCS use, close to the upper range of values (third quartile) of the IPCC-assessed scenario dataset.

Data source: AR6 scenario explorer

DACCS is also an emerging option for CDR in 1.5°C climate scenarios assessed by the IPCC. The IPCC defines DACCS as:

> **"A chemical process by which a pure carbon dioxide (CO_2) stream is produced by capturing CO_2 from the ambient air."**
>
> IPCC, 2021

In the case of DACCS, two types of technology predominate for the capture of CO_2 directly from the air; a high-temperature system using a liquid sorbent,[37] and a low-temperature system using a solid sorbent. In a liquid system, the air is transferred through chemical solutions, such as hydroxide solutions, that remove CO_2. The system applies high-temperature heat when releasing the air into the environment (IEA, 2023b). A high-temperature system requires a large amount of energy. This high temperature is achieved mainly through natural gas combustion but can also be achieved through biogas combustion or an electric arc furnace (Lehtveer and Emanuelsson, 2021). This technology uses solid sorbent filters to bind with CO_2. The filters are heated and placed under a vacuum to release the captured CO_2 for storage (IEA, 2023b). As DACCS does not have to be coupled with an emission source and can instead be placed near a location for storage, it can be independent of transport infrastructure for CO_2 (Lehtveer and Emanuelsson, 2021).

In AR6, modelled pathways for limiting warming to 1.5°C with no or limited overshoot that report CDR, global annual CDR from DACCS is 103.4 (0.12–985) $MtCO_2$ in 2050, an increase of 3,312.5% (median) from 2030 (Figure 30) (IPCC, 2022). Most 1.5°C scenarios with no or limited overshoot report low levels of DACCS. By 2050, at the higher end of estimates (third quartile) in scenarios where DACCS is more prominent, only 2.7% of global CO_2 emissions[38] are removed by DACCS. The majority of the scale-up occurs after 2040, especially from 2050 onwards. This indicates that a late development of technology will be needed to scale up DACCS to commercial levels. Scenarios that report higher levels of DACCS are optimistic in their assumptions concerning both the cost of the technology and its deployment at a large scale.

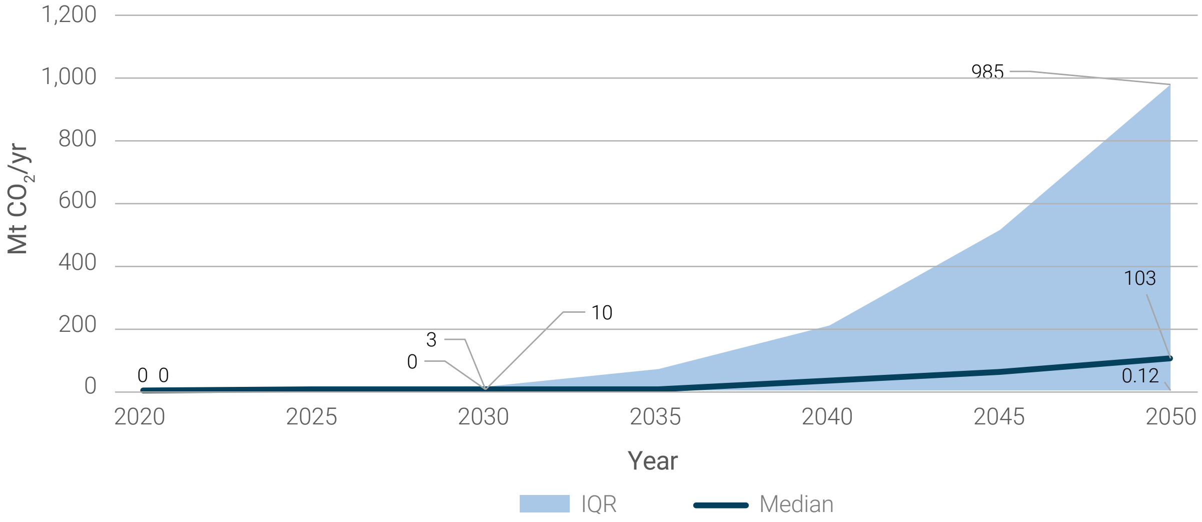


Figure 30: Use of DACCS estimates in the IPCC-assessed 1.5°C pathways with no or limited overshoot from 2020 to 2050

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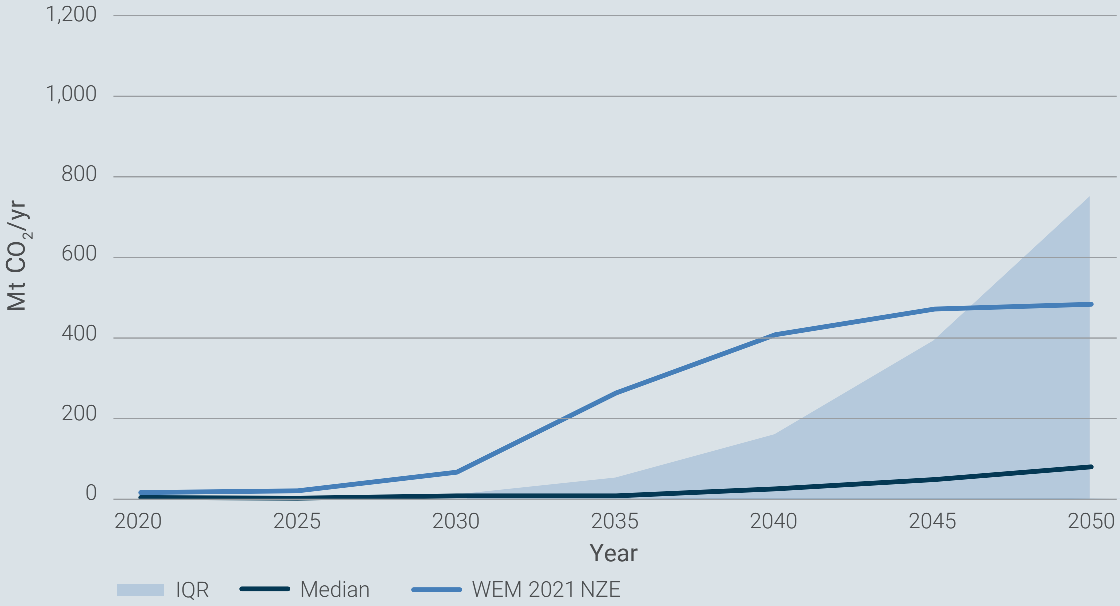
[37] Materials used to recover liquids through absorption, or adsorption, or both (EPA, 2016)

[38] 2022 levels (IEA, 2022a).

Box 10: Use of DACCS estimates in the IEA net-zero scenario compared to the IPCC assessed 1.5°C pathways with no or limited overshoot



Compared with the IPCC-assessed scenario dataset, the IEA NZE pathway reports much higher levels of CO_2 captured using DACCS from 2025 to 2045. On average, the IEA NZE pathway reports 3.48 $MtCO_2$/yr captured from DACCS more than the upper quartile of the IPCC-assessed scenario dataset till 2045. In 2050, though within the interquartile range of estimates, the IEA NZE pathway reports 529 $MtCO_2$/yr more CO_2 captured using DACCS than the median value of the IPCC-assessed scenario dataset.

Data source: AR6 scenario explorer

Land use and afforestation currently comprise the largest CDR methods. Forests can act as carbon sinks by accumulating carbon emissions in vegetation and soils; notably, however, human activities such as deforestation affect carbon sequestration by land use and forestry. The IPCC has found that afforestation will be required to a certain degree to limit global warming to 1.5°C. In modelled pathways limiting warming to 1.5°C with no or limited overshoot in AR6, the agriculture, forestry, and other land-use (AFOLU) sector contributes 3,437 (315–4,087) $MtCO_2$ in net-negative emissions in 2050, an increase of 370% (median) from 2030 levels (Figure 31). The scenarios report an increase in carbon sequestered from land use from 2020 onwards. However, a major increase in CO_2 emissions removed through land use is reported from 2035 onwards in the upper range of the scenarios. These scenarios are optimistic in their estimates for a shift in actions to sequester carbon from land use via afforestation, soil carbon enhancement, biochar, and related methods.

The use of land systems to remove carbon brings co-benefits, such as enhanced employment and local livelihoods, improved biodiversity and other environmental impacts, and greater nutrient cycling. However, expanding the use of land systems to sequester carbon brings its own challenges. Large-scale deployment will require massive land areas dedicated to the technology, leading to competition for land with conservation efforts and food production (IPCC, 2022).

Although all 1.5°C models with no or limited overshoot report a net change in land use that includes afforestation, only two-thirds of the models report an afforestation variable for CO_2 removal directly. Therefore, there are limitations in estimating the amount of carbon sequestration from afforestation in the models (C2G, 2022).

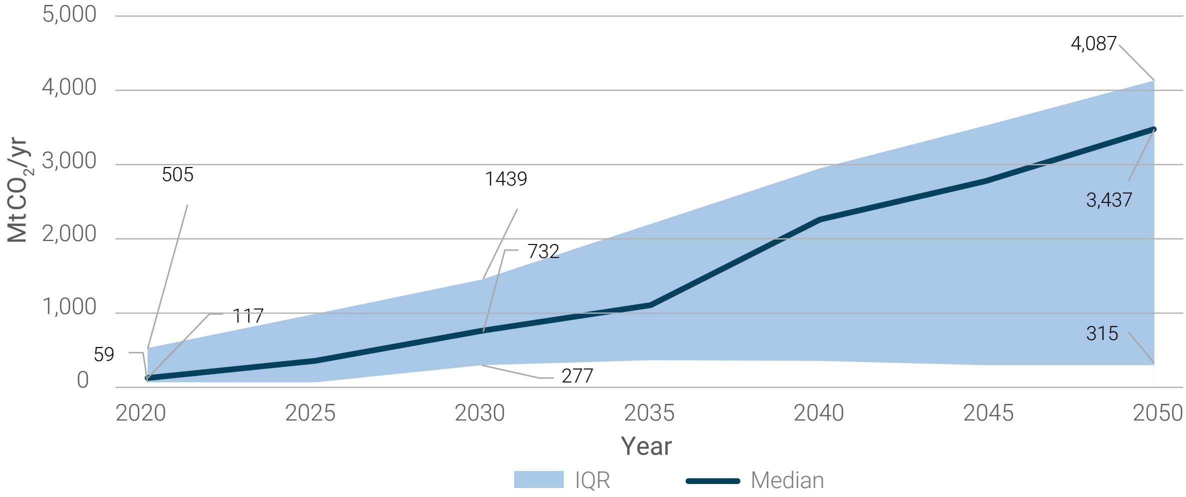
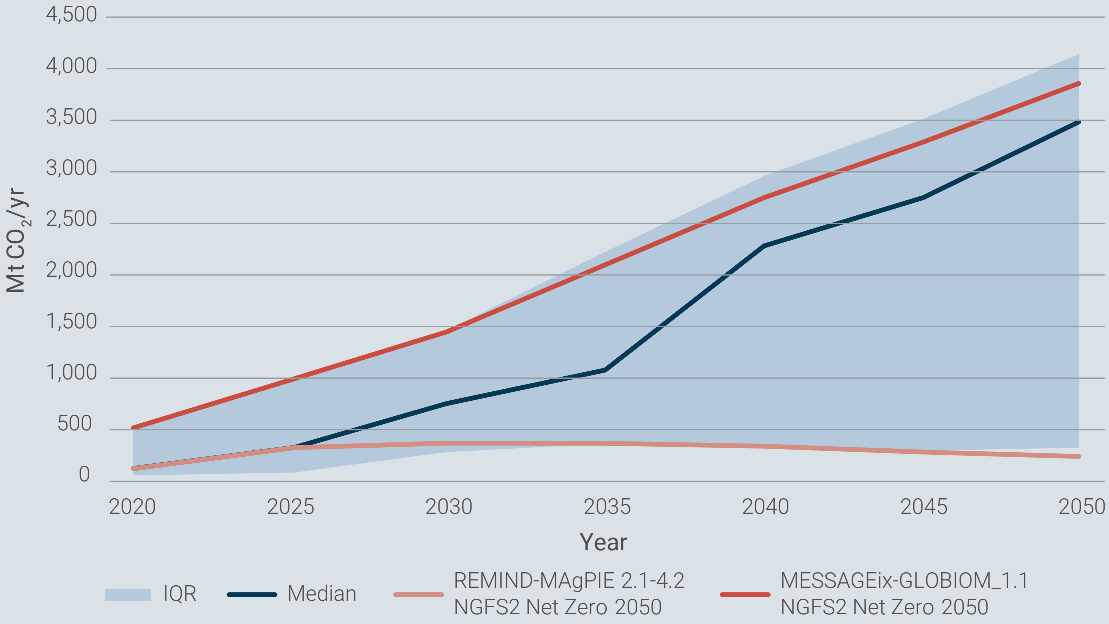


Figure 31: Carbon sequestration from land use as estimated in the IPCC-assessed 1.5°C pathways with no or limited overshoot from 2020 to 2050

Box 11: Carbon sequestration from land use as estimated in the NGFS net-zero scenarios compared to the IPCC-assessed 1.5°C pathways with no or limited overshoot



The MESSAGE net-zero pathway and the median values of the IPCC-assessed scenario dataset report a steady growth in carbon sequestration from land use from 2020 to 2050. The pathway reports similar values as the upper quartile of the IPCC-assessed scenario dataset. The REMIND pathway shows a decrease in carbon sequestration from land use from 2030 to 2050. Between 2035 and 2045, the values reported by the pathway are in line with the first quartile of the IPCC-assessed scenario dataset. In 2050, the REMIND pathway reports carbon sequestration values of about 230 $MtCO_2$/yr, about 90% lower than the median value of the IPCC-assessed scenario dataset. The lower values compared to the rest of the IPCC-assessed scenario dataset can be attributed to the MAgPIE land-use model as it assumes limited potential for direct carbon removal from land.

Data source: AR6 scenario explorer

Box 12: Are land-use measures a long-term solution to CO_2 removal?

Despite being one of the largest CDR methods currently deployed, the long-term ability of land use to remove CO_2 from the atmosphere has come into question. It is important to note that CO_2 released from the burning of fossil fuels is “fundamentally different” to how carbon is stored in trees, wetlands, and the soil (Morgan, 2023). Below are described the key concerns of using land-use based methods for CDR.

Although storing carbon in land systems has benefits for reducing CO_2 levels from the atmosphere to mitigate climate change, it does not store carbon away from the atmosphere permanently. Carbon stored in land, such as the carbon sequestered by forests and soil, is vulnerable to being released back into the atmosphere through various channels, such as wildfires, land clearing, disease, erosion, severe weather events, and damage from wildlife. Such physical hazards are expected to increase in severity and frequency as global temperatures rise. Therefore, as the impacts of climate change rise, the risk of carbon stored in land being released back into the atmosphere increases (Climate Council, 2016; Climate Analytics, 2023.

The ability to sequester carbon by land is limited and depends on the climate, soil, nutrient availability, and topographic conditions of the areas. Hotter and drier areas will be less likely to absorb carbon, especially in the coming decades as global warming continues to increase (Climate Analytics, 2023). According to the Global CCS Institute, 26 commercial CCS facilities captured CO_2 equivalent to 1.6 billion trees in 2020 (Trendafilova, 2021).

As droughts and wildfires increase in severity and frequency over time due to climate change, the ability of forests and soil to uptake, store, and hold carbon will reduce. CO_2 released from fossil fuel burning remains in the atmosphere for up to 10,000 years (*see section ‘Emissions’*). However, land-based CDR methods cannot guarantee long-term sequestration for this length of time (Climate Council, 2016; Climate Analytics, 2023).

Comparison of use of CDR methodologies in the IPCC-assessed 1.5°C scenarios with no or limited overshoot

Table 14 provides a comparative overview on the scaling up of CCS and CDR reported by 1.5°C scenarios with no or limited overshoot for various methodologies. For BECCS, DACCS, and Land Use, the scenarios report a median increase of between 370% and 3,313% in their deployment from 2030 to 2050. Assumptions of CO_2 captured using land use are much lower than the assumptions of deployment of BECCS and DACCS between 2030 and 2050, as shown in Figure 32. This suggests that the expansion of land use shown in the scenarios could be more attainable than the massive deployment of BECCS and DACCS reported.

Table 14: Comparison of carbon capture and removal methodologies reported in the IPCC-assessed 1.5°C scenarios with no or limited overshoot from 2020 to 2050

	Annual emissions captured in 2020 ($MtCO_2$/yr)	Annual emissions captured in 2030 ($MtCO_2$/yr)	Annual emissions captured in 2040 ($MtCO_2$/yr)	Annual emissions captured in 2050 ($MtCO_2$/yr)	Median percentage change in emissions captured from 2030 to 2040 (%)	Median percentage change in emissions captured from 2030 to 2050 (%)
CCS	0 *(0.04–2.75)*	1,095.2 *(851.6–2,038.4)*	4,508.5 *(3,114.0–6,998.3)*	7,286.8 *(5,432.6–11,969.7)*	311.7	565.3
BECCS	0 *(0–1.025)*	325.8 *(69.8–621.7)*	1666.4 *(726.3–3,117.9)*	3,833.9 *(1,883.2–5,422.9)*	411.5	1,076.8
DACCS	0 *(0–0)*	3.03 *(0–10.1)*	29.5 *(0.06–212.2)*	103.4 *(0.12–985.2)*	873.6	3,312.5
Land use	116.8 *(59.0–504.7)*	731.6 *(276.6–1,439.3)*	2,255.1 *(350.0–2,925.7)*	3436.7 *(315.1–4087.2)*	208.2	369.8

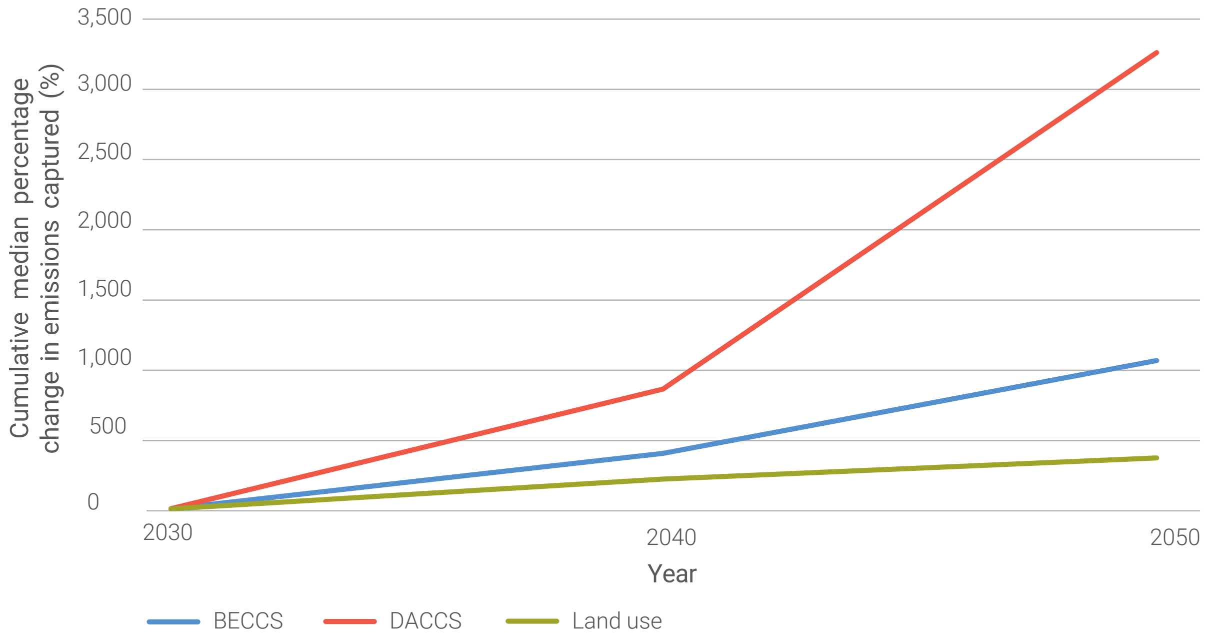


Figure 32: Cumulative median percentage change in emissions captured from 2030 to 2050 shown in 1.5°C scenarios with no or limited overshoot

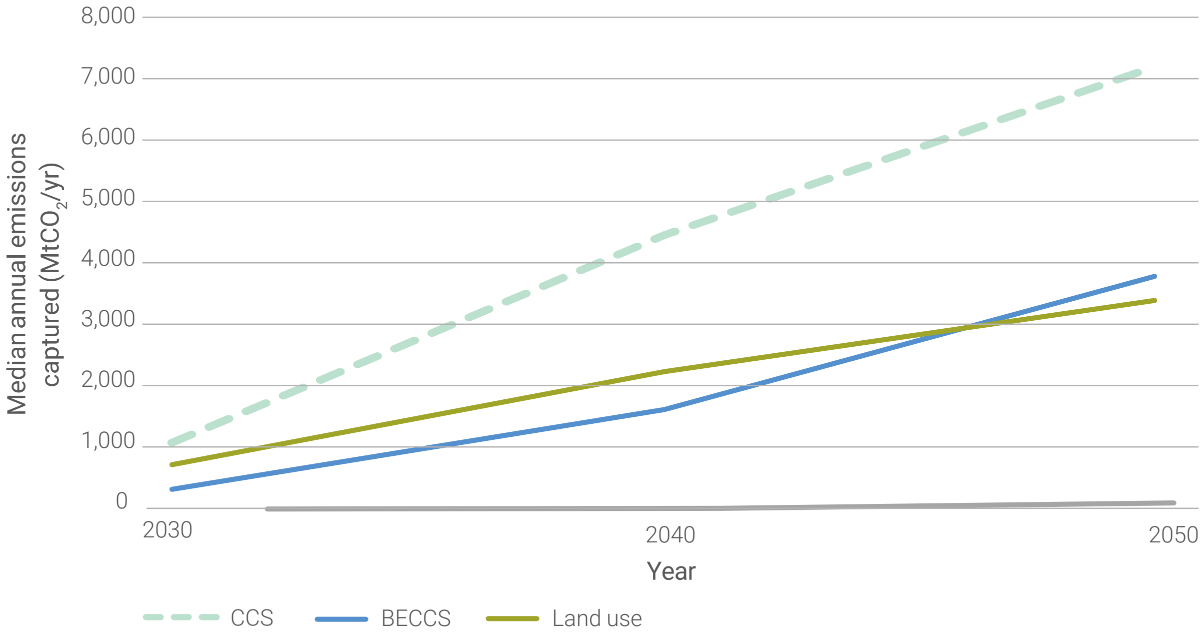


Figure 33: Median annual emissions captured from 2030 to 2050 shown in 1.5°C scenarios with no or limited overshoot

Table 15: Recommended scenario variables to use for assessing CCS and CDR in pathways (AR6 scenario explorer)

Variable	Unit	Definition	Additional information
Carbon Sequestration from BECCS	$MtCO_2/yr$	Total CO_2 emissions captured from bioenergy use and stored in geological deposits and the deep ocean. This variable can be used to look at the pathways for BECCS. Stored amounts are reported as positive numbers.	Further variables are available for CCS using biomass with CO_2 emissions captured from bioenergy use for energy demand, energy supply (electricity, gases, hydrogen and liquids) and industrials.
Carbon Sequestration from CCS	$MtCO_2/yr$	Total CO_2 emissions captured and stored in geological deposits and the deep ocean. Stored amounts are reported as positive numbers.	The variable includes CO_2 emissions captured from bioenergy use and the emissions captured from industrial processes and from fossil fuel use. Further granular variables are available for CO_2 emissions captured from energy supply and industrial processes. Variables are also available for other types of CCS, such as enhanced weathering and feedstocks.

Carbon Sequestration from Direct Air Capture	$MtCO_2/yr$	Total CO_2 sequestered through direct air capture.	n/a
Carbon Sequestration from Land Use	$MtCO_2/yr$	Total CO_2 sequestered through land-based sinks, such as afforestation, soil carbon enhancement, and biochar.	Further variables available for CO_2 sequestered through specific land-based sinks, such as afforestation, biochar, soil carbon management and others.

Box 13: CDR in the IPCC's Illustrative Pathways

All IMPs assessed by the IPCC use either land-based biological CDR, such as afforestation and reforestation, or BECCS. Some pathways also include DACCS. Figure 34 illustrates the different mitigation strategies of IMPs and the role of CDR in these pathways.

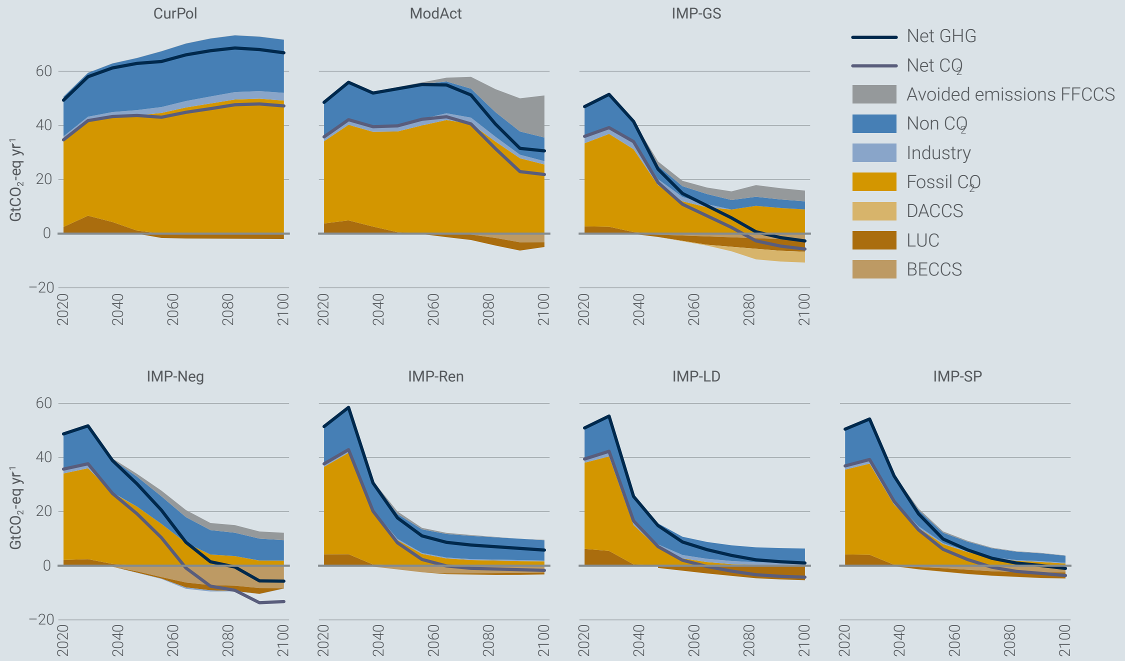


Figure 34: The role of CDR in each of the seven illustrative pathways (IPCC, 2022)

- Neg and GS IMPs are the pathways with the highest reliance on CDR:
    - GS IMP: Fossil fuels are slowly phased out, meaning CDR is deployed later in the century to achieve net zero emissions during the early 2070s and limit global temperature to 2°C.
    - Neg IMP: Dependent on the large-scale deployment of CDR after 2030, resulting in the phase-out of fossils fuels with a high dependence on biomass and BECCS so as to limit global temperature to 1.5°C with high overshoot.
- CurPol show the least amount of use of CDR:
    - Limited use of CDR in the pathways result in high emissions by the end of the century and warming limited to below 4°C.

- IMP-Ren requires more than 2Gt of CO_2 to be captured and stored annually by 2050:
    - Policy action favours the uptake of renewable energy and the phase-out of fossil fuels. However, CDR and CCS are needed to capture and store CO_2 in order to limit global temperature to between 1.5°C or below 2°C.

Table 18: CDR use reported in illustrative pathways in 2050 and 2100 (IPCC, 2022)

IMP	Warming Limit	BECCS ($MtCO_2$)		DACCS ($MtCO_2$)		Land use ($MtCO_2$)	
		2050	2100	2050	2100	2050	2100
Neg	2°C (>67%)	2,230[39]	11,700	0	0	650	120
Ren	1.5°C (>50%)	2,390[40]	6,470	5	5	230	440
LD	1.5°C (>50%)	0	0	-	-	3,160	6,600
SP	1.5°C (>50%)	910	2,420	0	0.01	785	1,740
GS	2°C (>67%)	660	2,330	0.35	4,000	2,000	4,010
ModAct	3°C (>50%)	10	3,140	-	-	2,190	5,060
CurPol	4°C (>50%)	0	0	-	-	-	-

5.4 Carbon dioxide storage

CO_2 can typically be stored in two ways; deep geological and mineral storage. Storage in deep geological formations requires CO_2 to be converted into a high-pressure, liquid-like form called 'supercritical CO_2'. It is then injected into sedimentary rocks, such as in old oil and gas fields or in saline formations. Un-mineable coal seams and certain volcanic rocks are also suggested sites for CO_2 storage (BGS, n.d.). Storage depths range from 1km to 5km. Once the CO_2 is injected, the risk of a carbon leak is expected to be small. Research has shown that 98% of carbon remains trapped for 10,000 years. However, average sites are monitored for only 20 years (Royal Society, n.d.).

Coal seams and saline aquifers comprise other sinks for CO_2 storage. Coal seams that are too deep or difficult to mine—referred to as 'unmineable'—can be used to store CO_2 if the coal is porous enough for the gas to penetrate. Saline aquifers are deep rock formations with a high concentration of brine, which is salty water. Brine present in rock pores acts like a giant sponge. These aquifers can be found in abundance (BGS, n.d.) and they

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[39] Includes scenarios from IMP Neg and Neg-2.0

[40] Includes scenarios from IMP Ren and Ren-2.0 (Limits warming to 2°C (>67%))

are judged to have the largest storage potential of all subterranean features (Wei *et al.*, 2022). However, in relation to CCS storage, less is currently known about saline aquifers than about oil fields (BGS, n.d.). Significant CO_2 that has been captured is stored in oil and gas sites after the process of enhanced oil recovery (EOR) takes place (BGS, n.d.).

In mineral storage, captured CO_2 is reacted with naturally occurring minerals, such as iron, magnesium, and calcium. Minerals like these are abundant and stable. This "carbonation" process can occur naturally when rocks weather but can take thousands to millions of years to occur. Large amounts of energy are needed to create the ideal temperature and pressure to speed up the process (BGS, n.d.). According to the IPCC, a power plant with CCS using mineral storage requires 60 to 180% more energy than a power plant without CCS (IPCC, 2005; The University of Melbourne, 2019).

Uses of captured carbon

Today, a significant majority of captured carbon is used for EOR, a method for extracting oil that uses CO_2 and water to improve oil recovery (Resources for the future, 2020). Injecting CO_2 into existing oil fields increases overall pressure, forcing oil towards production wells (IEA, 2019a). The injected CO_2 is trapped in the subsurface (Nuner-Lopez and Moskal, 2019). EOR can help produce up to 30 to 60% of the reservoir's original oil. In comparison, primary and secondary recovery methods only recover 10 to 40% of the oil in the reservoir (Energy.gov, n.d.). At present, EOR is the dominant use of captured carbon, although research indicates that this approach can result in negative emissions for up to the first 18 years of production, depending on the technology (Nuner-Lopez and Moskal, 2019). Despite CO_2 being captured and stored in EOR, oil combustion will release CO_2 emissions back into the atmosphere, driving climate change in the long run. Therefore, the use of carbon capture for oil production does not align with the definition of carbon capture set by the IPCC—namely, the goals to scale up CCS do not couple with the respective scaling up of EOR (see description of CCS above).

There are diverse applications for CO_2 emissions, encompassing the processes of capturing, storing, and utilising carbon. This involves the permanent retention of CO_2 in products or its utilisation in processes that can lead to permanent storage (The CCUS Hub, 2023). In certain instances, captured CO_2 may be reintroduced into the atmosphere. Key use cases for captured carbon are summarised below.

Utilisation and storage

- **Ironically, most captured carbon is used for EOR.** EOR is a process that has been taking place for numerous years in which CO_2 is injected into declining oil fields to increase oil production. Costs of injections might be partly offset by selling the additional oil recovered, but the recovered oil will offset the reduced carbon emissions. Significant CO_2 that has been captured is stored in oil and gas after the process of EOR takes place (BGS, n.d.). The Global CCS Institute estimates that 73% of CO_2 captured annually is used for EOR (IEEFA, 2022).

- **Incorporating carbon into concrete is one of the productive uses of captured carbon.** Carbon can be stored in cement which can improve the properties of the material. CO_2 gas can be turned into a solid to cure concrete (Columbia Climate School, 2019).

Injected CO_2 in cement reacts with calcium ions to produce more calcium carbonate. In turn, increased calcium carbonate can allow concrete to withstand larger loads (Nature, 2021). Storing carbon in cement could sequester CO_2 in buildings, walls, and sidewalks for centuries (Columbia Climate School, 2019).

- **Captured carbon can serve as feedstock for chemical and plastic production.** Carbon can be made into chemical intermediaries for materials, such as methanol and polymers, to make plastics and adhesives. Instead of fossil fuels, products such as solvents, synthetic rubber, and plastics can be made from captured carbon using a catalyst. Such catalysts include heat, hydrogen, electricity, and enzymes for energy. However, CO_2-based chemicals that are burned quickly (i.e. within days or weeks) will return the CO_2 into the atmosphere (Columbia Climate School, 2019).
- **Captured carbon is used in the food and beverage industry in processing, packaging, and preservation.** For example, CO_2 can be used as a non-toxic gaseous pesticide for fruit and vegetable preservation, as well as a method to prevent the ripening of fresh produce. Carbonation of drinks is a significant use of captured carbon in the food and beverage industry, as well as the use of CO_2 in the frozen meat industry through cryogenic freezing or with dry ice. The preservation of other food products through freezing also requires captured CO_2 in gaseous form (nexAir, n.d.).
- **With a growing demand for carbon materials, such as graphene, carbon fibers, and carbon nanotubes, captured carbon can be used to manufacture these materials.** Researchers are developing new methodologies for manufacturing these products from CO_2, including using "molten electrolysis" to transform CO_2 into carbon nanotubes (Ren *et al.*, 2017) and simple processes for converting CO_2 into graphene (KIT, 2019).

Carbon neutral utilisation

- **Capture carbon can be used to create synthetic fuels and improve energy efficiency.** For example, Carbon Recycling International runs a CO_2 and H2 to methanol plant in Iceland, which captures CO_2 from the steam emissions of geothermal power plants. Electricity from renewable sources is used to make hydrogen that reacts with the captured CO_2 to produce methanol. Methanol is sold as a gasoline additive for biodiesel production, producing fewer emissions in the production process (Carbon Recycling).

Storage

- **Underground formations such as mineralisation, saline aquifer storage, and weathering can be used for storage purposes.** CO_2 can be injected into locations capable of securely storing it, particularly in sedimentary basins and geological formations. These sites possess qualities such as structures to retain and facilitate the flow of CO_2 throughout the formation.

The effectiveness of utilising captured CO_2 for emissions reduction is influenced by factors like scalability and the use of low-carbon energy. To comprehensively understand the benefits for a particular use case, a life cycle assessment is necessary. Products that involve permanent carbon retention, such as building materials, are often more effective in reducing emissions compared to those that release emissions (IEA, 2019b).

5.5 Development and costs of the technologies

Deployment of carbon capture for industrial processes can be traced back to the 1930s, when the natural gas industry used chemical solvents to separate CO_2 from methane. In the 1940s, physical solvents were used to capture CO_2 from process gas streams that contained higher CO_2 concentrations under higher-pressure conditions. In the 1950s and 1960s, the use of solid sorbents in adsorption processes allowed gas separation in hydrogen production, nitrogen production, and dehydration applications. In the 1970s and 1980s, membranes were developed to capture carbon for use in natural gas processing. Over time, carbon capture to decarbonise industries with low-concentration dilute gas streams began to be increasingly applied (Global CCS Institute, 2021).

The costs of carbon capture and removal technologies vary depending on the scale, source and concentration of CO_2, location, permanence of the storage methodology, and application (IPCC, 2022). However, these technologies are typically expensive (Global CCS Institute, 2021). The technology can range from comparatively low costs, such as USD 45–USD 100 per tonne of CO_2 (tCO_2) for soil carbon sequestration, to markedly high costs, such as USD 100–USD 300/tCO_2 for DACCS (IPCC, 2022). According to the IPCC, afforestation cost ranges from USD 0–USD 240/tCO_2. The cost for BECCS and for DACCS ranges from USD 15–USD 400/tCO_2 and from USD 100-USD 300/tCO_2, respectively (IPCC, 2022). Details on the costs for each type of CDR method can be found in Appendix 2. The costs of transporting and storing carbon can also vary based on volume, distances, and storage conditions. For example, the cost of onshore pipeline transport in the United States of America can range from USD 2–USD 14/tCO_2 (IEA, 2021a).

High costs can also be attributed to the relatively small number of companies developing CCS projects (WRI, 2022). Although the technology is in the early stages, costs will fall as it scales. Capital costs of process plants, such as CO_2 capture plants, rise non-linearly with scale (Global CCS Institute, 2021). According to the International Energy Agency, the development of CCUS hubs (such as industrial centers which share CO_2 transport and storage infrastructure) could support economies of scale and reduce unit costs. Improved efficiencies and reduced duplication of infrastructure can result in cost savings per tonne of CO_2 captured in the long-term (IEA, 2020a). Huge sums of investments and incentives are therefore needed to drive carbon capture technology from a small-scale to a full-scale installation that captures millions of tonnes of CO_2 annually. Research has shown that the direct air capture (DAC) industry will need to grow more than 300 times to limit costs to USD 100 per tonne (Lackner and Azarabadi, 2021).

As with renewable technologies in recent decades, the cost of CCS is expected to decrease in the coming years as technology advances, the market grows, and economies of scale are reached (IEA, 2021a). Second-generation technologies are targeting a reduction in costs of 20%. Second-generation technologies are expected to become available for demonstration by 2025. Transformational technologies are expected to be available by 2030 and are targeting to reduce costs by 30% (Global CCS Institute, 2021). For example, DAC currently operates at a small scale, but it is expected to grow. At present, 18 DAC facilities operate in Canada, Europe, and the USA. Of these 18 plants, only two facilities sell their CO_2 for use. The largest of these is located in Iceland and captures 0.004 $MtCO_2$ per year. The first large-scale DAC plant is expected to operate in the USA by the mid-2020s, capturing up to 1 $MtCO_2$ annually, about 0.0002% percent of the country's CO_2 emissions in 2020. The costs of DAC depend on capture technology, energy costs for heating and electricity, plant configurations, and financial assumptions. DAC costs could fall below USD 100/tCO_2 by 2030 with increases in deployment and innovation. Examples in this regard include the use of renewable energy and the introduction of the best available technologies for electricity and heat generation (IEA, 2022b).

It is non-economic to install and run CCS on fossil fuel plants based on current costs. This can be seen in Figure 35 illustrating the Levelized Cost of Energy (LCOE) for coal with, and without, CCUS. Coal with CCUS becomes competitive at a carbon price of about USD 50 to USD 60 per tCO_2 (IEA, 2020b). A price on carbon is critical to promoting the economic incentives to get CCS and CDR to scale. Carbon price mechanisms, such as carbon taxes and emissions trading, are critical to incentivising the implementation of CCS and CDR methods. A carbon tax can be an effective financial incentive if: (i) the tax is applied to industrial and power processes from which carbon emissions are captured; (ii) the costs for capturing, transporting, and storing carbon are less than the amount of tax that would have to be paid; (ii) the project is financially viable after expenditures on the technology; and (iv) the tax is expected to be implemented throughout a significant portion of a project's life. Therefore, companies will be incentivised to develop CCS projects if the cost of capturing and storing CO_2 is lower than the carbon tax. Similarly, emission trading schemes can also incentivise willingness to adopt carbon capture technologies. Currently, Norway is one of the only countries to have implemented a carbon tax that is sufficiently high to provide financial motivation for the geological storage of CO_2 emitted during gas production.

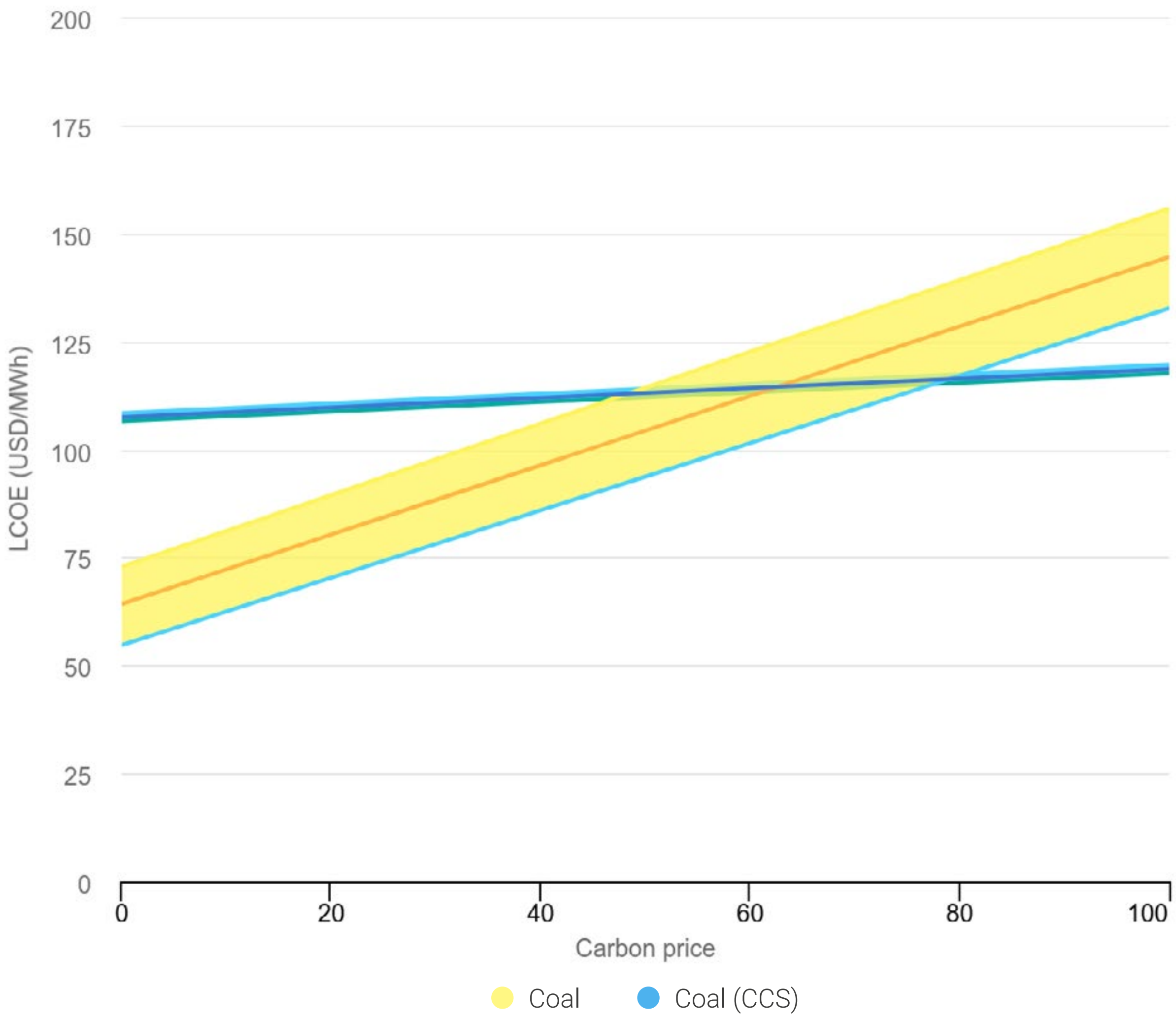

Figure 35: LCOE for coal with, and without, CCUS for various carbon prices (IEA, 2020b)

Other incentives include subsidies for governments to bear a portion of the costs and tax credits to reduce a company's tax liability. The US government provides tax credits to those who capture, store, or use CO_2 as part of the 45Q tax credit. It has put a significant value on CO_2 storage. In 2022, 45Q provided tax credits of up to USD 85 per tCO_2 of permanently stored CO_2 and USD 60 per tCO_2 used for EOR or other industrial uses. For DAC, USD 180 per tCO_2 was given to permanently stored CO_2 and USD 130 per tCO_2 for used CO_2 (IEA, 2023c). Regulation can also play an important role in driving the development of these technologies. A case in point is mandating the storage of a percentage of released CO_2 when approving industrial and energy projects. In Australia, for example, one of the mandatory conditions for the approval of the Gorgon project, a multi-decade natural gas project, was the capture of 80% of the CO_2 from the operations (Global CCS Institute, 2019; IEAGHG, 2014).

5.6 Drawbacks and obstacles of CDR and CCS technologies

As emerging technologies are still in development, a few drawbacks and obstacles are described below. Trade-offs for different CDR methods can also be found in the Appendix 2.

1. High costs

As discussed above, high costs represent a significant obstacle when deploying CCS and CDR technologies. Today, carbon capture technology is expensive and cannot compete with wind and solar energy, which have significantly decreased in costs. For industrial processes, CCS is currently cost-prohibitive for many businesses. For example, CO_2 capture costs for cement production are estimated to reach up to USD 205 per tonne, while the costs for steel mills are up to USD 133 per tonne (Harvard Kennedy School, 2022). Costs for CCS can be associated with equipment and energy needs for capturing, compressing, and transporting CO_2 (Resources for the future, 2020). As deployment is in its early stages, the financial returns for such projects are not secure. Investors have therefore imposed high risk premiums on CCS projects (Resources for the future, 2020). Models that are optimistic in their estimates for the decrease in the price of such technologies will assume greater deployment of CCS and CDR. Furthermore, carbon pricing is as yet insufficient to make CCS economically viable (IEA, 2021a). That said, models that estimate higher carbon prices will find CCS as a more suitable option for limiting warming to 1.5°C with no or limited overshoot.

2. Early stages

Carbon capture and removal technology is still in its early stages and has not been deployed on a large scale. However, 1.5°C pathways with no or limited overshoot rely on CO_2 removal to reach climate targets and achieve net zero CO_2 emissions by 2050. There are several concerns about the ability to expand carbon capture and removal to the scale required to limit global warming. For example, to promote BECCS, researchers have argued that a billion hectares of trees can be planted globally to remove 200 billion tonnes of CO_2 (Bastin *et al.*, 2019). However, other studies have maintained that the carbon removal capacity of trees is overestimated (Legal Planet, 2019). Afforestation already exists today, but it is currently offset by deforestation, with land-use change leading to net deforestation. The scalability of CCS and CDR technology remains uncertain, as does its status as a permanent solution in the face of climate change. Engineered CDR options, like BECCS or DACCS, have not been deployed at any meaningful scale to date. In addition, many concerns continue to be raised with regards to the technology's potential, its feasibility, and, therefore, its necessity. Models that do not consider the duration of removals and obstacles related to the expansion of carbon capture and removal will be more open to various types of CCS and CDR to get to net zero CO_2 by 2050.

3. Transportation

There are also challenges in transporting carbon once captured. Transportation by pipelines requires large amounts of energy to compress and chill CO_2 at high pressure and low temperatures. The costs of building pipelines are also high as they need to be specially designed. As pipelines are constructed to connect source sites with storage sites, pipelines need to be built across large distances. An alternative to pipelines is shipping but this has not yet been used on a large scale to transport captured carbon (Resources for the future, 2020; Global CCS Institute, 2021). Models that are more optimistic in their assumptions for the transportation of captured carbon and their related costs will assume greater deployment of carbon capture and storage technologies to limit warming to 1.5°C with no or limited overshoot.

4. Energy Use

CCS requires a lot of energy due to high energy consumption and low energy efficiency. Power stations with CCS will require more fossil fuels to produce the same energy as plants without CCS. Energy wastage is a problem, especially for power stations where capture systems are not fully compatible with the existing infrastructure (MIT, 2019; IISD, 2023). Research has shown that scaling up DACCS at a rate of 1.5 $GtCO_2$ per year would require up to 300 exajoules (EJ) of energy input every year by 2100 (Realmonte *et al.*, 2020). The world's largest DAC plant—Orca, by Climeworks—is located in Iceland. To capture 4,000 tonnes of CO_2 annually, the plant requires energy equivalent to the energy consumption of more than 495,500 inhabitants. Though the plant runs on renewable energy, this is more than Iceland's population of 361,000 residents (Geoengineering Monitor, 2021). Models with lower estimates for energy consumption of CCS and CDR technologies will rely to a larger extent on carbon capture and removal technologies to limit global warming to 1.5°C with no or limited overshoot.

5. Water use

Deployment of CCS technologies will also increase water use by power plants. Power generation plants already consume large amounts of water. Introducing CCS technologies to these plants will require additional water to capture and separate CO_2. Power plants equipped with CCS technology use double the amount of water as power plants without CCS technology (Eldardiry and Habib, 2018). Models that do not consider the water consumption of CCS technology will be more open to CCS use in order to get to net zero CO_2 by 2050.

6. Risk of leakage

There is a risk of a potential leakage with large amounts of carbon stored in a single location. If carbon storage is not handled carefully, it could lead to environmental contamination. There is currently insufficient data to quantify the risk of leakage, but even low leakage rates could impact mitigation efforts. Carbon leakage from CCS could cause an estimated 25 $GtCO_2$ of additional emissions till 2100, at a leakage rate of 0.1% annually (Vinca *et al.*, 2018). CO_2 leakage could also represent a hazard to groundwater. Carbon leakage at geological sites could impact the water quality of nearby aquifers. For example, CO_2 dissolved in freshwater aquifers increases the concentration of dissolved carbonate, which causes an increase in water acidity (Eldardiry and Habib, 2018). Models with limited consideration of the risk of leakage will be more open to CCS use to reduce emission levels in order to reach net zero by 2050.

7. Land use

CDR methods, like BECCS and afforestation, require large amounts of land for cultivation. Questions have been raised about the sustainability of this approach due to the large land area required and the possibility that this might cause a reduction in food crops. The IPCC has emphasised the competition for land with biodiversity conservation and food production as a major trade-off for BECCS (IPCC, 2022). The amount of land needed depends on the scenario pathway. For example, the required land for BECCS in models for limiting warming to below 1.5°C can range from 10 million hectares (Mha) (equivalent to the landmass of South Korea) to more than 1,000 Mha (equivalent to the size of Canada) (Fern, 2018). If poorly implemented, afforestation and the production of biomass crops for BECCS could have adverse socio-economic and environmental impacts. This could include negative effects on biodiversity, food availability, water security, livelihoods, and Indigenous Peoples' rights (IPCC, 2022). Models that do not take into account the tradeoffs of land use by CDR methods and their potential negative impacts will rely more on methods such as BECCS and afforestation to remove CO_2 from the atmosphere in order to limit warming to 1.5°C with no or limited overshoot.

8. Pollution

High levels of pollution can also be associated with CDR methods. For example, enhanced weathering poses environmental risks through the release of heavy metals, in particular nickel and chromium. These can leech into surrounding soils and biomass, and can be toxic to ecosystems (Beerling *et al.*, 2018; Amann *et al.*, 2020).

Table 16: Examples of limitations of CDR methodologies (Smith *et al.*, 2023; WRI, 2022; Fern, 2022)

Afforestation, reforestation, improved forest management	Soil carbon sequestration	Biochar	BECCS	DACCS	Enhanced weathering	Peatland and coastal wetland restoration	Ocean alkalinity enhancement	Ocean fertilisation
Require large amounts of land use	Source for N_2O emissions	Biodiversity loss Source for GHG emissions	Require large amounts of land use High costs High water use Pollution	High costs High energy consumptions Increased water use in some instances	Pollution	Source for methane emissions	Pollution	Pollution

Box 14: CDR reliance and the status quo of fossil fuels in 1.5°C scenarios with no or limited overshoot

Interquartile ranges reported in Figures 26, 29, 30, and 31 show a large variation in the use of CCS and CDR technologies reported in 1.5°C pathways with no or limited overshoot. Such technologies remain speculative, with concerns that they will not be able to deliver sequestrations on the scales assumed. Strong use of CDR technologies can have trade-offs in the climate models.

Scenarios that report a large scale-up in CDR technologies over the next 10–20 years show the need to build a global carbon-removal industry from scratch in the near- and medium-term. Most importantly, 1.5°C pathways with no or limited overshoot with high reliance on CDR imply a delay in transitioning away from a fossil fuel-based energy system. Within the same carbon budget, models that report large amounts of carbon sequestered and stored allow for the continuation of fossil fuel use for a longer amount of time. Models assuming CCS retrofits within fossil fuel burning facilities, such as coal and gas power plants, link CCS deployment to continued fossil fuel use. This means that a delay exists in the necessary mitigation measures for limiting global warming to 1.5°C. Therefore, the status quo of fossil fuels in society is likely to stay longer in 1.5°C pathways with no or limited overshoot that rely more heavily on CDR technologies than in pathways with minimal CDR use (Asayama, 2021).

5.7 The path forward

Table 17 shows the percentage increase needed from 2023 levels of carbon capture to meet the assumptions of the 1.5°C scenarios with no or limited overshoot assessed by the IPCC. Even when considering only the median and low-end estimates of carbon capture in these scenarios, a massive gap exists between current and future levels of deployment of various carbon capture and removal methods. For example, deployment of CCS assumed in 1.5°C scenarios with no or limited overshoot to capture CO_2 emissions in 2030 is 2,047% (median) larger than 2023 levels. DACCS would require a 30,200% increase in deployment from 2023 levels to meet the DACCS levels estimated by 2030 in the scenarios. Similarly, CO_2 removal by BECCS would have to be scaled up by 16,190% from 2023 levels to meet the levels estimated by 2030 in the scenarios. Taking into consideration the limitations of CCS and CDR discussed above, the massive scale-up needed to meet the pathways reported in the 1.5°C scenarios with no or limited overshoot represents an astronomical uptake for countries. Given that land-use estimates as a CO_2 sink were about 2,300 $MtCO_2$ in 2023 (Friedlingstein *et al.* 2024), in comparison to BECCS and DACCS, scenario assumptions for land use to capture CO_2 from the atmosphere seem more reachable.

Table 17: Comparison of emissions captured in 2023 to 1.5°C scenarios with no or limited overshoot estimate for 2030 and 2050 (Friedlingstein *et al.* 2024; IEA, 2023d; IEA, 2023b; Global CCS Institute; 2024)

	Emissions captured in 2023 ($MtCO_2/yr$)[41]	Annual emissions captured in 2030 in 1.5°C scenarios with no or limited overshoot ($MtCO_2/yr$)	Annual emissions captured in 2050 in 1.5°C scenarios with no or limited overshoot ($MtCO_2/yr$)	Median percentage increase needed in emissions captured from 2023 levels to 2030 (%)	Median percentage increase needed in emissions captured from 2023 levels to 2050 (%)
CCS	51.0	1,095.2 *(851.6–2,038.4)*	7,286.8 *(5,432.6–11,969.7)*	2,047.5	14,187.8
BECCS	2.0	325.8 *(69.8–621.7)*	3833.9 *(1,883.2–5,422.9)*	16,190.0	191,595.0
DACCS	0.01	3.03 *(0–10.1)*	103.4 *(0.12–985.2)*	30,200.0	1,033,900.0
Land use	2,300	731.6 *(276.6–1,439.3)*	3,436.7 *(315.1–4087.2)*	-68.2	49.4

Questions for readers

- Which CDR technologies are most likely to be used to remove majority of the CO_2 emissions and how much CO_2 will they remove by 2030 and 2050?
- Identify key actions that are needed over the next five, 10, and 20 years to scale up CDR technologies.

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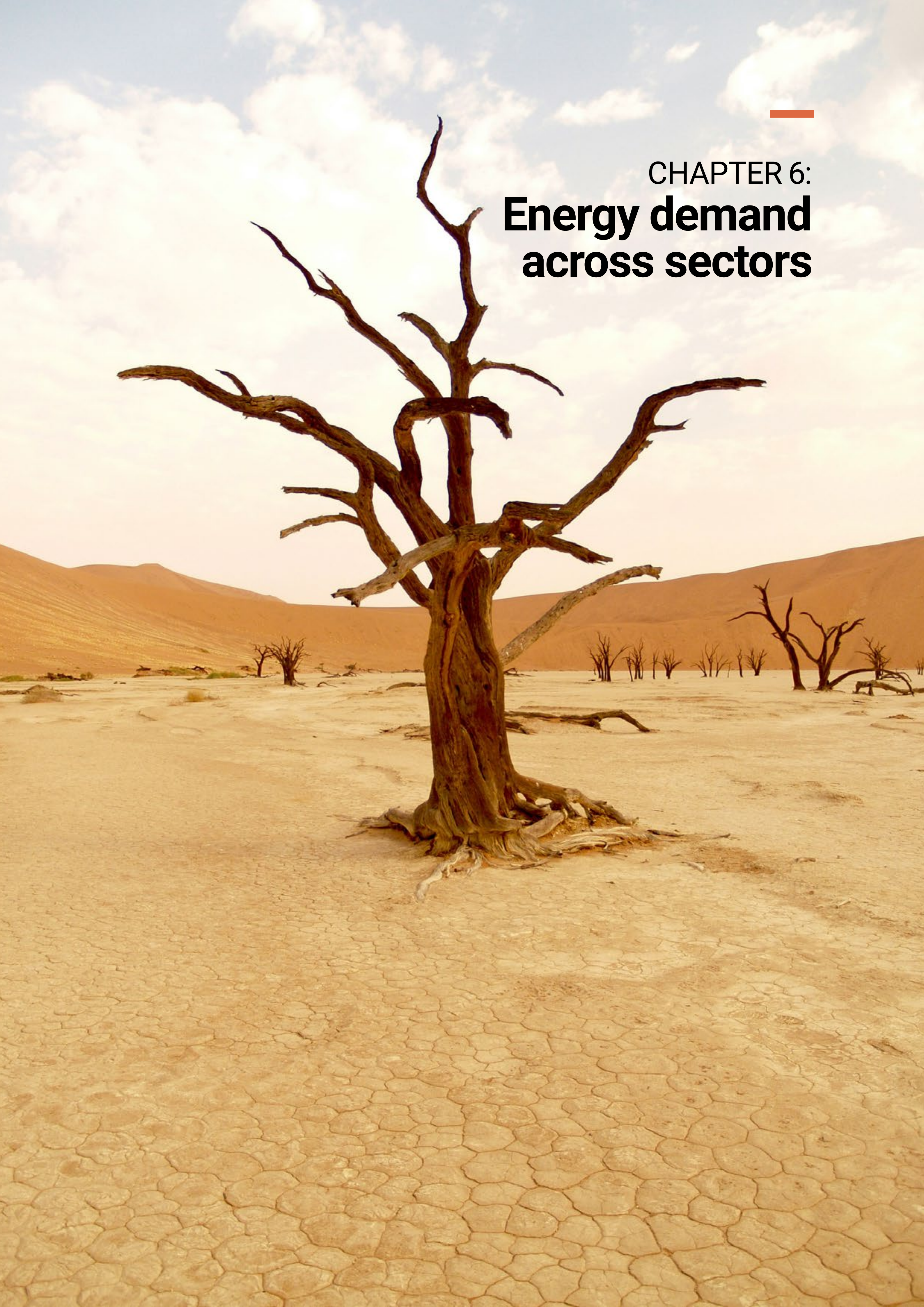
[41] Estimates on emissions captured in 2021 for CDR methodologies can greatly vary depending on the sources used for estimates. This indicates the high uncertainty in the CDR data available.



CHAPTER 6:

Energy demand across sectors

Sector	Strategies for decarbonising	Challenges in decarbonising
Energy	**Electrification and efficiency:** Firms in the sector should shift towards electrification, renewable energy, and nuclear power, while enhancing energy efficiency and implementing Carbon Capture and Storage (CCS) technologies at fossil fuel power plants, upgrade transmission networks, and encourage lifestyle changes of consumers. Key indicators in 1.5°C scenarios with no or low overshoot: ▪ Primary energy generated from coal, oil and natural gas decreases by 73%, 10% and 11% (*median*), respectively, from 2020 to 2030. ▪ Primary energy generated from solar and wind increases by 746% and 323% (*median*), respectively, from 2020 to 2030. ▪ Primary energy generated from nuclear increases by 35% (*median*) from 2020 to 2030. ▪ Energy efficiency of electricity generated from coal with CCS ranges from 34% to 36% (*median*) from 2020 to 2050.	▪ Supply chain shortages of critical minerals, ▪ Persistent subsidies for fossil fuels, ▪ Intermittency issues with renewable sources, ▪ High installation and maintenance costs, ▪ Geographical dependency on renewable sources, ▪ Risk of carbon lock-ins from existing infrastructure, and ▪ Need for significant investments.
Transportation	**Electrification and infrastructure:** Firms should support widespread electrification, especially for smaller and short-distance vehicles, as well as support enhancements in EV battery performance, development of fast-charging infrastructure, transition to alternative fuels, improve fuel efficiency of aviation and shipping, utilise hydrogen fuel cells for heavy-duty EVs, increase rail network capacity and the implementation of stringent energy efficiency standards. Further actions for decarbonisation include incentivising used EV purchases, redesigning cities to reduce transportation needs, expanding cycling and walking networks, and improving public transportation accessibility. Key indicators in 1.5°C scenarios with no or low overshoot: ▪ Final energy generated from electricity increases from 1.8 exajoules per year (EJ/yr) (*median*) in 2020 to 22.8 EJ/yr (*median*) in 2050. ▪ Use of hydrogen for energy increases from almost nothing in 2020 to 3.6 EJ/yr (*median*) in 2050. ▪ Biofuel energy consumed by passenger and freight vehicles increases from 1.3 EJ/yr (1.2 EJ/yr–4 EJ/yr) in 2020 to 13 EJ/yr (10 EJ/yr–16 EJ/yr) by 2050. ▪ Scenarios can consider behavioural change by implying a shift to public transport, walking and cycling, reduction in per capita car ownership, avoidance of short flights and telework.	▪ Human rights and environmental concerns linked to EVs and alternative fuels, ▪ Regional disparities in charging infrastructure availability, ▪ Supply chain limitations for critical minerals, ▪ Commercial viability concerns of certain technologies and alternative fuels, ▪ Cost challenges, ▪ Need for large fuel storage capacity for long-distance travel, ▪ Need to repurpose infrastructure for cycling and walking paths and incentivise behaviour change.

Sector	Strategies for decarbonising	Challenges in decarbonising
Agriculture	**Alternative practices and behavioural changes:** To decarbonise, firms in the sector should consider electrification, agrivoltaics, alternative fuels, digitalisation, conservation practices, smart irrigation, carbon sequestration, innovative carbon reduction technologies, efficiency of fertiliser supply chains, improvements in livestock management, reductions in food loss, dietary shifts, and nature-based solutions. Key indicators in 1.5°C scenarios with no or low overshoot: ▪ Increase in demand for per capita calories from 2,946 kcal per capita per day (kcal/cap/day) (*median*) to 3,025 (kcal/cap/day) (*median*) from 2020 to 2050 ▪ Agriculture demand increases by 69% (*median*) from 2020 to 2050. ▪ Agriculture production increases by 72% (*median*) from 2020 to 2050. ▪ Land cover remains constant at 12805 million ha (*median*) from 2020 to 2050.	▪ Higher costs and initial investments for energy-efficient technologies, net-zero fertiliser production, and certain decarbonisation methods, ▪ Environmental trade-offs, ▪ Knowledge gaps in animal health, ▪ Capital costs for infrastructure, ▪ Limited awareness among producers, and ▪ Potential conflicts between production-focused policies and mitigation incentives.
Industrials	**Efficiency and technological innovation:** Firms should expand direct electrification, pilot innovative decarbonisation technologies, use CCUS, enhance material efficiency, improve energy efficiency, minimise waste, and supplement materials with low-carbon alternatives. Reduced demand for carbon-intensive products will also be needed. Key indicators in 1.5°C scenarios with no or low overshoot: ▪ Carbon intensity of steel decreases by 84% (*median*) from 2020 to 2050 ▪ Carbon intensity of cement decreases by 81% (*median*) from 2020 to 2050.	▪ Long lifetimes and high capital intensity of facilities, ▪ Extended construction timelines for less carbon-intensive options, ▪ Challenges in meeting safety and quality criteria with reduced carbon content, ▪ Limited local availability of resources and infrastructure, ▪ Substantial initial and ongoing investments, ▪ Costly advanced technology, ▪ Limited commercial deployment, and ▪ Global constraints on sustainably produced biomass (alternative for fuel and feedstock).

Sector	Strategies for decarbonising	Challenges in decarbonising
Real estate	**Efficiency, Low-Carbon Materials, and Renewable Integration:** Firms in the sector should prioritise building renovations and reuse, incorporate design of lower-carbon concrete mixes, limit carbon-intensive materials and choose low-carbon alternatives, use carbon-sequestering materials, reuse and incorporate high-recycled content materials, maximise structural efficiency, reduce finished materials and minimise waste, enhance green spaces, improve energy efficiency, implement advanced building and energy management systems, integrate renewables, and provide clean energy access. Key indicators in 1.5°C scenarios with no or low overshoot: ▪ Global final energy consumption of electricity in residential buildings increase by 38% (*median*) from 2020 to 2050. ▪ Gas consumption for energy in residential buildings decrease by 60% (*median*) from 2020 to 2050.	▪ Scalability and cost challenges with high upfront costs, ▪ Difficulty in reaching consensus on retrofitting decisions, ▪ Lack of standardisation in terms of technology, ▪ Processes and financing mechanisms across the industry, ▪ Limited awareness of the benefits of retrofits, and existing building codes, ▪ Regulations posing obstacles to retrofitting projects.

Suitability considerations of scenarios for exploring energy demand

Limited information and detail	Some information and detail	Good information and detail
▪ Lack of variables covering the direct energy demand and production changes ▪ Limited consideration of socio-politics of energy-mix changes & income distribution ▪ No reflection on how national priorities can differ from projected changes in energy use ▪ Information on security & affordability of national energy sources not provided ▪ Models inherently rely on historical data which puts them at risk of being unable to capture current trends. For example, models are not updated frequently enough to incorporate new trends in the deployment rates of renewable technologies, potentially leading to underestimates in their future use.	▪ Granularity of energy systems at the geographic and temporal scale across scenarios and their underlying models ▪ Simplified information on technological innovations and their respective adoption	▪ Granularity for the energy sector & energy systems across the global economy ▪ Details on change in energy mix, the expansion of electrification across sectors, energy efficiency gains, and alternative fuel types available to limit warming to 1.5°C ▪ Breakdown into different energy types—primary, secondary and final energy ▪ Energy use breakdowns for sectors & regions (e.g. final energy use of passenger vehicles, heating in residential buildings, industrial processes, etc.)

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Suitability considerations of scenarios for exploring energy demand in the energy sector

Overall rating: good

Potential areas of greatest suitability: Risk analysis and stress testing, sensitivity analysis, client engagement, opportunity assessment, benchmark for target setting, internal strategy setting

Limited information and detail	Some information and detail	Good information and detail
▪ Integration delays in models may lead to under/overestimation of trends in certain pathways, with a risk of missing existing trends or underestimating future trends due to the reliance on historical data or infrequent updates (e.g. deployment rates of renewables) ▪ Limited consideration of socio-politics of energy-mix changes & income distribution ▪ No reflection on how national priorities can differ from projected changes in energy use ▪ Information on security & affordability of national energy sources not provided ▪ Feasibility of grid integration & disruption of current energy systems not addressed	▪ Granularity of energy systems at the geographic and temporal scale across scenarios and their underlying models ▪ Simplified information on technological innovations and their respective adoption	▪ Granularity for the energy sector & energy systems across the global economy ▪ Details on change in energy mix, the expansion of electrification, energy efficiency gains, and alternative fuel types available to limit warming to 1.5°C ▪ Breakdown into different energy types—primary, secondary and final energy

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Suitability considerations of scenarios for exploring energy demand in the transportation sector

Overall rating: average to good

Potential areas of greatest suitability: Risk analysis and stress testing, sensitivity analysis, client engagement, opportunity assessment, benchmark for target setting, internal strategy setting

Limited information and detail	Some information and detail	Good information and detail
▪ Limited variables covering direct energy demand changes ▪ Limited consideration of socio-politics of energy-mix changes & income distribution ▪ No reflection on how national priorities can differ from projected changes in energy use ▪ Models do not address the feasibility of raw materials availability and infrastructure needs to electrify the sector ▪ Models inherently rely on historical data which puts them at risk of being unable to capture current trends. For example, models are not updated frequently enough to incorporate new trends in the deployment rates and sales of EVs, potentially leading to underestimates in their future use.	▪ Granularity at the geographic and temporal scale across scenarios and their underlying models ▪ Simplified information on technological innovations and their respective adoption ▪ Energy use breakdowns for sub-sectors covered by some pathways (e.g. final energy use of ICE freight vehicles, final energy use for aviation, etc.)	▪ Details available on change in energy mix, the expansion of electrification, and alternative fuel types available to limit warming to 1.5°C

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Suitability considerations of scenarios for exploring energy demand in the real estate sector

Overall rating: average to limited

Potential areas of greatest suitability: Risk analysis and stress testing, sensitivity analysis, client engagement, opportunity assessment, benchmark for target setting, internal strategy setting

Limited information and detail	Some information and detail	Good information and detail
▪ Limited variables covering direct energy demand changes and by building type ▪ Models inherently rely on historical data, which puts them at risk of being unable to capture current trends. For example, models are not updated frequently enough to incorporate new trends in the deployment rates of renewable technologies, potentially leading to underestimates in their future use. ▪ Information not available on renovation and construction rates ▪ Lack of data provided on improving energy and operational efficiency of buildings ▪ Limited consideration of socio-politics of energy-mix changes & income distribution	▪ Granularity at the geographic and temporal scale across scenarios and their underlying models ▪ Simplified information on technological innovations and their respective adoption ▪ Changes in energy use, such as for cooking, lighting and appliances, covered by some pathways	▪ Details available on the changes in energy mix and the expansion of electrification needed to limit warming to 1.5°C ▪ Energy use breakdown available for residential & commercial buildings covered

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Suitability considerations of scenarios for exploring energy demand in the industrials sector

Overall rating: average to limited

Potential areas of greatest suitability: Risk analysis and stress testing, sensitivity analysis, client engagement, opportunity assessment, benchmark for target setting, internal strategy setting

Limited information and detail	Some information and detail	Good information and detail
▪ Limited variables covering direct energy demand changes ▪ Limited consideration of socio-politics of energy-mix changes & income distribution ▪ Lack of data provided on improving energy efficiency ▪ No reflection on how national priorities can differ from projected changes in energy use ▪ Models are inherently prone to lagging behind current time, which can lead to the underestimation and overestimation of various trends in pathways. For example, models are not updated frequently enough to incorporate new trends in the deployment rates of renewable technologies, potentially leading to underestimates in their future use.	▪ Granularity at the geographic and temporal scale across scenarios and their underlying models ▪ Simplified information on technological innovations and their respective adoption ▪ Carbon intensity of production for sub-sectors covered by some pathways.	▪ Details available on the expansion of electrification and alternative fuel types for sub-sectors available to limit warming to 1.5°C

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Suitability considerations of scenarios for exploring energy demand in the agriculture sector

Overall rating: limited

Potential areas of greatest suitability: High-level risk analysis

Limited information and detail	Some information and detail	Good information and detail
▪ Lack of variables covering direct energy demand changes, including final energy, electrification and change in energy type ▪ Limited consideration of socio-politics of energy-mix changes & income distribution ▪ No reflection on how national priorities can differ from projected changes in energy use ▪ Lack of information on technological innovations and their respective adoption ▪ Models inherently rely on historical data which puts them at risk of being unable to capture current trends. For example, models are not updated frequently enough to incorporate new trends in the deployment rates of renewable technologies, potentially leading to underestimates in their future use.	▪ Granularity at the geographic and temporal scale across scenarios and their underlying models	▪ Details available on changes in agriculture production & demand

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Table 18: Definitions of key energy terms

Scenario variable term	Definition
Primary energy	Energy available in its resource form before it has been transformed. Examples: Coal before it is burned; oil barrels
Secondary energy	Energy converted from primary energy into a transportable form such as electricity. Examples: Electricity generated from coal; oil refined into gasoline and diesel
Final energy	Energy that is received by the consumer. It is secondary energy transported to the consumer.

6.1 Energy sector

Rapid and profound near-term decarbonisation of the energy supply and demand

Production of fossil fuels

1.5°C scenarios with no or limited overshoot assessed in Assessment Report 6 (AR6) show a major decline in the production and primary energy use of fossil fuels. There are variations in the reduction rates across scenarios and nuances depending on where technologies like carbon capture and storage (CCS) are deployed. Still, in all cases, fossil fuel use is a major deviation from a current policy baseline. The level at which fossil fuels are used is higher than one might expect given net zero emissions in 2050, but this is due to a high deployment of CCS in those scenarios.

6.1.1 Coal

Coal combustion accounts for about 40% of global CO_2 emissions generated from energy use. Therefore, it is vital to phase out energy production from coal in order to limit global warming to 1.5°C (Jakob *et al.*, 2021). AR6-assessed 1.5°C scenarios with no or limited overshoot report a massive decrease in primary energy from coal of 95% (80% to 100%)[42] in 2050, relative to 2019 levels. The majority of the decrease in coal production needs to take place in the first ten years, with primary energy from coal decreasing by 75% (65% to 80%) by 2030, relative to 2019 levels (Figure 36a).

Between 2020 and 2030, projections of primary energy production of coal need to decrease much faster in North America (median 94%) and Europe (median 85%) than in Asia (median 72%) (Figure 36b). Regional divergence in the production of energy from coal can be attributed to geographical variation in the level of development, climate policies, and investment action. In some countries, climate action to phase out coal is leading to coal power plants shutting down, but increasing energy demand in some countries view coal as a source of affordable energy. In the United States of America, the share of coal in power generation has been decreasing due to increased domestic

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[42] Values in this chapter are represented as median (interquartile range)

gas production, increased renewable generation, and plateauing energy demand. Similarly, in the European Union, primary energy sourced from coal is declining due to falling electricity demand and lower natural gas prices. In Asia, for many emerging countries with growing energy demands, such as Indonesia, Vietnam, Malaysia, Bangladesh and Pakistan, coal will continue to be seen as an relatively affordable option in the coming years as increased local renewables and energy efficiency measures gain larger share in the medium term. Furthermore, China is the world's largest coal producer, accounting for one-third of global coal consumption due to rising electricity demand and growing industrial production. India is the second largest coal producer globally. Given its strong economic growth and rising energy demand, India's appetite for coal is growing. Due to coal supply shortages, Asian coal-producing countries like China, India, and Indonesia are further expanding their coal outputs (World Economic Forum, 2019; IEA,2021a; Global Data, n.d.). That said, coal primary energy in Asia is projected to decrease by 2030. This is despite growing renewable energy alternatives in countries like China and India, and in spite of the announcement by some Asian governments to downsize coal development plants with no new coal-fired power. However, Asia's decline will be slower than that of North America and Europe. In developed countries, unabated coal use needs to be rapidly phased out to near elimination, which means no new coal projects.

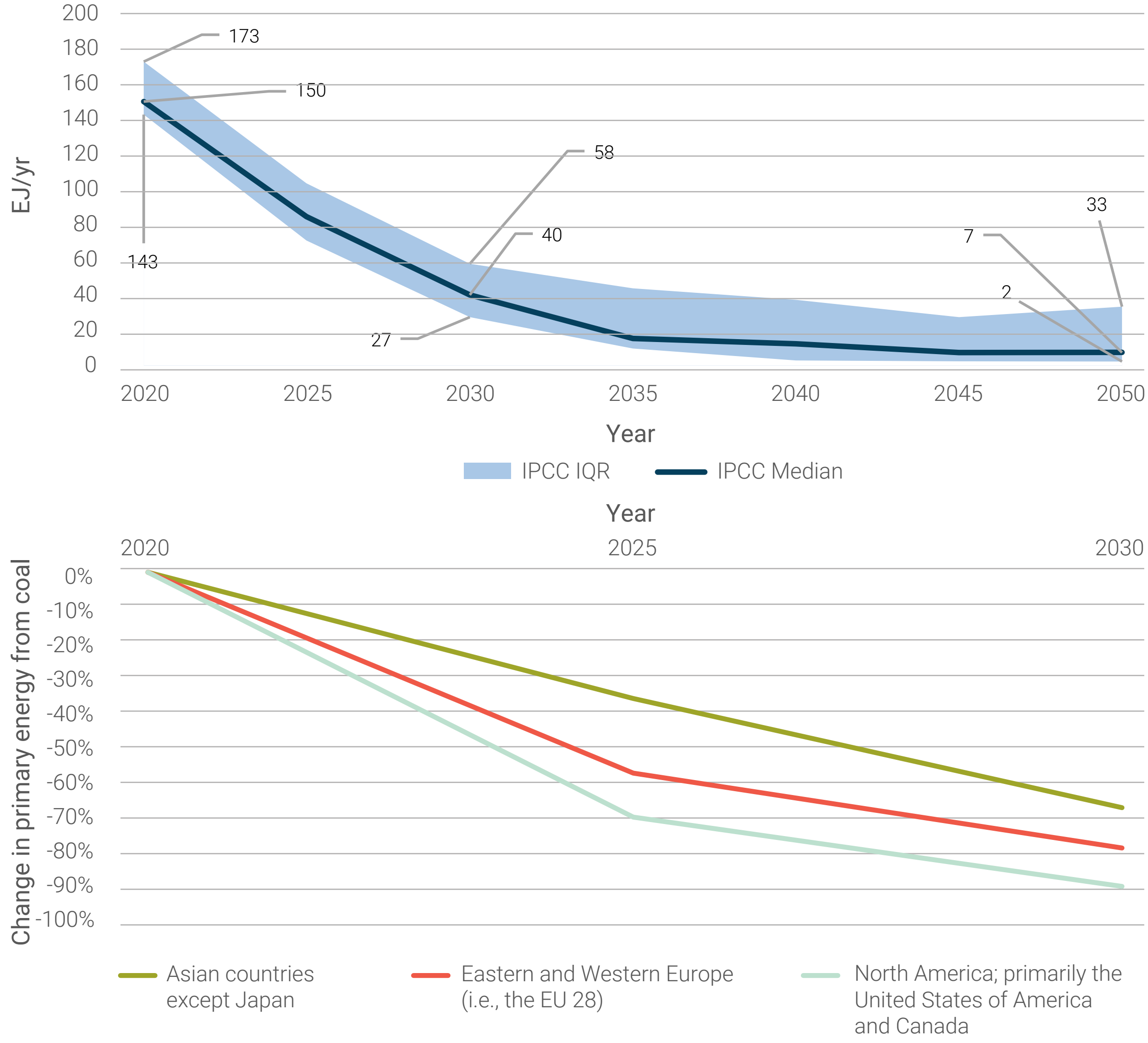
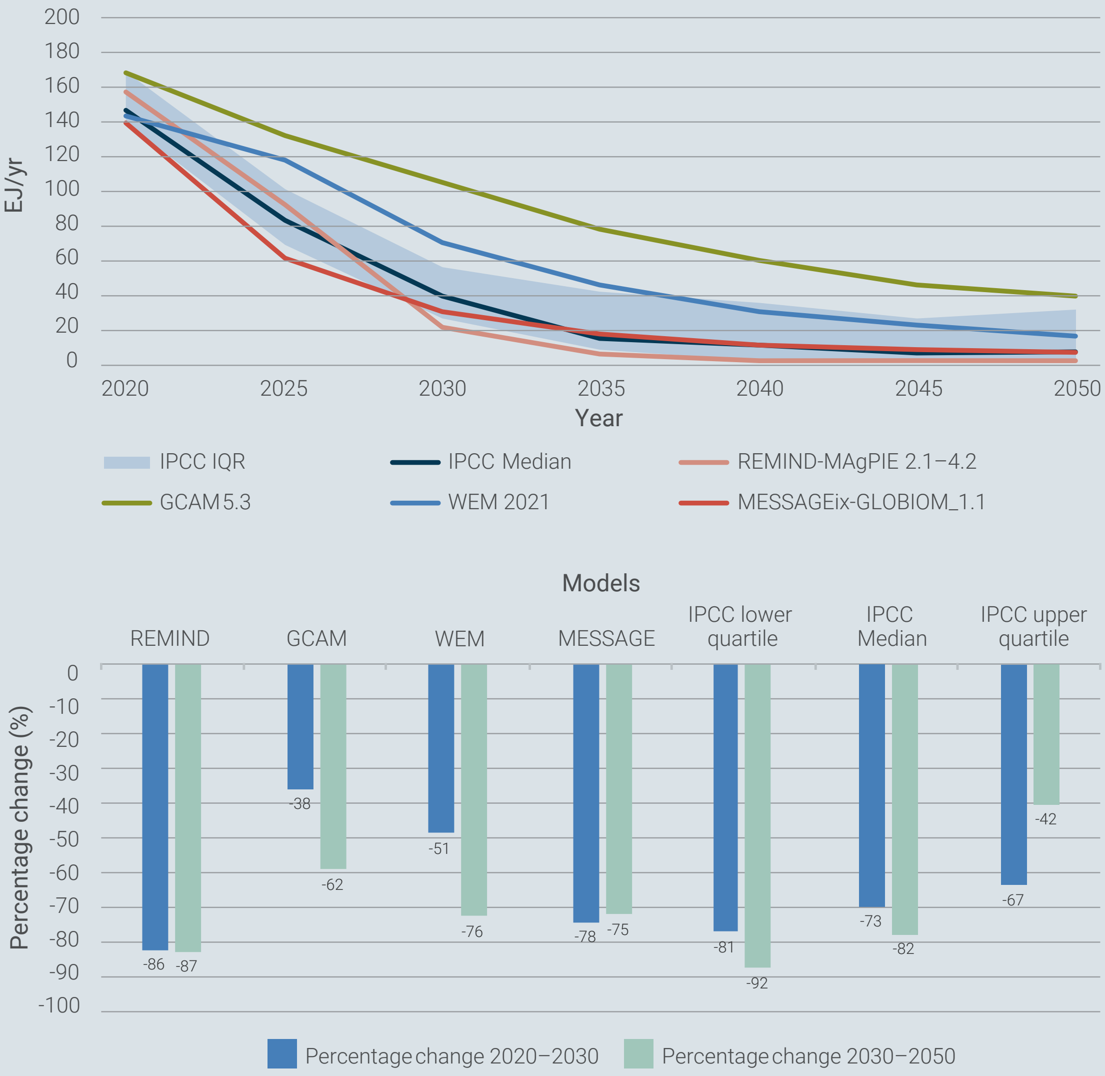


Figure 36 (a): Global primary energy from coal from 2020 to 2050; **(b)** Regional trends in coal production from 2020 to 2030 in the IPCC-assessed 1.5°C scenarios with no or limited overshoot

Box 15: (a) Primary energy from coal shown in the IEA and the NGFS net-zero scenarios compared to the IPCC-assessed 1.5°C scenarios with no or limited overshoot; (b) Percentage change during 2020–2030 and 2030–2050 of primary energy from coal reported by different models

All NGFS scenarios shown are Net Zero 2050.



GCAM shows a higher amount of coal primary energy in comparison to the amount of coal primary energy reported by the upper quartile of the IPCC-assessed scenarios dataset. By 2030, GCAM reports more than 67 exajoule per year (EJ/yr) of coal primary energy than the upper quartile. It is important to note that the phase-down or phaseout of coal are not explicitly modelled in GCAM. The results shown are economic outcomes with an economy-wide carbon price.

The IEA's NZE scenario also reports higher values for primary energy from coal from 2025 to 2035, ranging from 47 to 121 EJ/yr. After this, its pathway falls within the inter-quartile range of the IPCC-assessed scenarios dataset. The amount of primary energy from coal shown in MESSAGE is in line with the median value reported by the IPCC-assessed scenarios. REMIND reports the greatest decrease in the primary energy of coal from 2020 to 2030, with values around 4 EJ/yr below the lower quartile of the IPCC-assessed scenarios between 2030 and 2035.

For MESSAGE, a more significant phase-out of coal primary energy occurs in the near term (2020 to 2030) rather than in the long term (2030 to 2050). However, for GCAM and the IEA's NZE scenario, a greater percentage reduction in coal primary energy occurs between 2030 to 2050 than between 2020 and 2030. GCAM reports the least percentage decrease (38%) between 2020 to 2030, about half of the median percentage decrease (73%) reported by the IPCC-assessed scenario dataset.

Differences between IAMs for 2020 levels of primary energy can result from the calibration processes and the fact that data for 2020 has become available recently. Discrepancies can also occur as modellers use different methodologies to simulate the impact of COVID-19 on the model.

Data source: AR6 scenario explorer

Coal types

Thermal coal is commonly used to generate electricity and can be replaced by various renewable alternatives and even natural gas. Metallurgic coal is used in steelmaking, a process that is hard to decarbonise due to fewer alternatives available to replace metallurgic coal as a raw material. Furthermore, metallurgical coal makes up a relatively small proportion of the total volume of coal produced. As a result, a reduction in the production and consumption of thermal coal will be targeted to a greater extent due to its large production volumes and the availability of greater alternatives (S&P Global, 2020). The phase-out of metallurgical coal depends on advancements in alternative clean technologies such as hydrogen. It is therefore less affected than thermal energy by clean-energy transitions in both the short and medium term (IEA, 2021a). As a consequence, thermal coal will need to be phased out first, followed by metallurgic coal.

6.1.2 Oil

Reductions in primary energy from oil is more scenario dependent, with most reductions taking place between 2030 and 2050.

Oil production is projected to fall much more slowly in comparison to coal production from 2020 to 2050, with a significant decrease in production expected after 2030. The scenarios project a global median decrease in primary energy from oil of 10% (0% to 25%) by 2030 and 60% (40% to 75%) by 2050, relative to 2019. The transition away from oil will not be straightforward. This is because oil is a more critical fossil fuel than coal as its uses across the global economy are more integrated and diverse. Another factor is the complexity of the global oil market. The speed of transition away from oil will depend on the availability, deployment, cost, and uptake of alternatives across oil-reliant sectors. Apart from energy, other sectors like transportation and industries rely heavily on oil. Many economies are also dependent upon oil exports for revenue. Due to society's reliance on oil, its phase-out will take decades (World Economic Forum, 2022a).

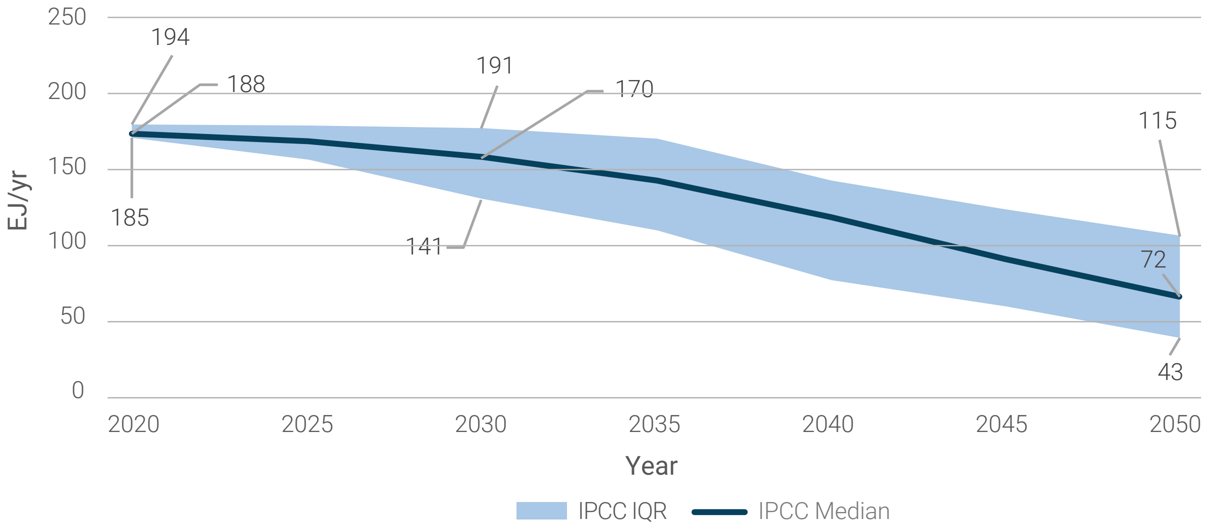
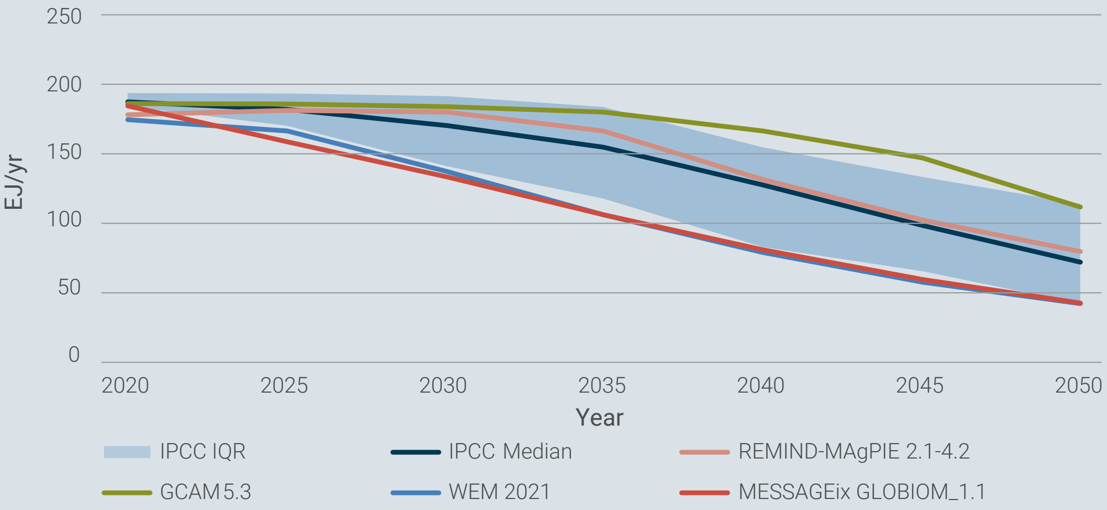
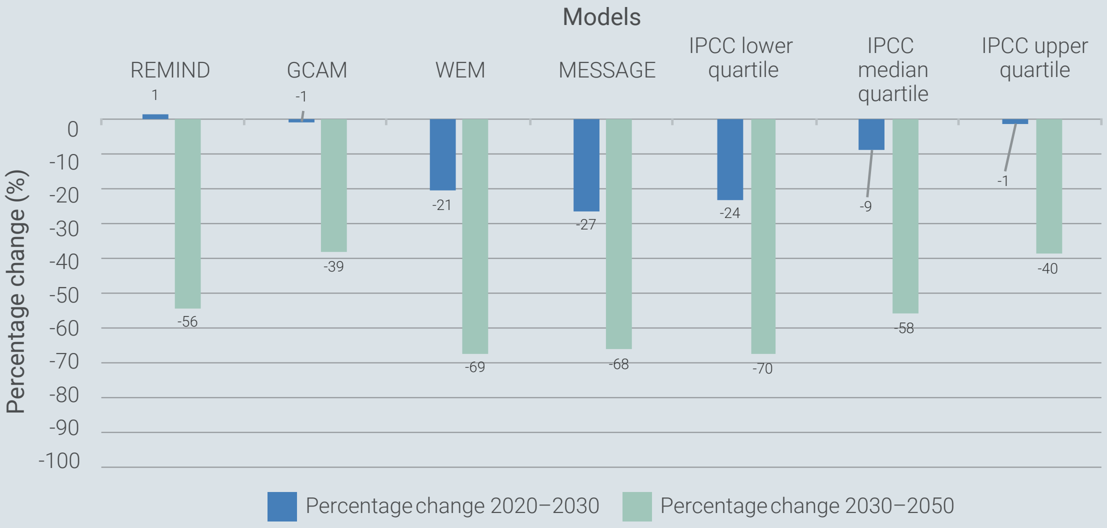


Figure 37: Global primary energy from oil from 2020 to 2050 in the IPCC-assessed 1.5°C scenarios with no or limited overshoot

Box 16: (a) Primary energy from oil shown in the IEA and the NGFS net-zero scenarios compared to the IPCC-assessed 1.5°C scenarios with no or limited overshoot; (b) Percentage change during 2020–2030 and 2030–2050 of primary energy from oil reported by different models

All NGFS scenarios shown are Net Zero 2050.





GCAM reports higher levels of oil primary energy than REMIND, MESSAGE, the IEA NZE scenario, and the median value of the IPCC-assessed scenario dataset from 2020 to 2030. The amount of oil primary energy reported by GCAM for 2050 is 55% higher than the IPCC median value. REMIND's pathway of oil primary energy is similar to the median values of the IPCC-assessed scenario dataset, which range approximately from 79.7 to 181 EJ/yr from 2020 to 2050. Pathways of the IEA NZE scenario and MESSAGE report values for primary energy from oil that are around 5.5 EJ/yr less than the lower quartile of the IPCC-assessed scenarios dataset for primary energy of oil from 2020 to 2050. By 2050, they reach around 50 EJ/yr, which is around half the median oil primary energy reported by the IPCC-assessed scenario dataset.

For all models, the majority of the phase-out of oil primary energy occurs after 2030. REMIND reports a similar percentage decrease (56%) in oil primary energy from 2030 to 2050 to the median IPCC-assessed scenario data set (58%). MESSAGE (68%) and the IEA's NZE scenario (69%) report a similar percentage decrease in oil primary energy between 2030 and 2050. GCAM reports the smallest percentage decrease in oil primary energy from 2030 to 2050 (39%), similar to the percentage decrease of the upper quartile values of the IPCC-assessed scenario dataset (40%).

Data source: AR6 scenario explorer

A number of alternative energy sources are available to replace oil, such as hydropower, wind, biofuels, and solar. Solar power has experienced the highest energy growth of any energy source over the past decade in the USA (Pew Research, 2020). For road transport, traditional vehicles reliant on oil need to be replaced with electric vehicles (EVs). As road fuel accounts for around half of the global oil demand, the adoption of EVs represents a major driver of future oil demand (IMF, 2021). In 2021, EV usage displaced about 1.5 million barrels of oil per day globally (Bloomberg NEF, 2022). Other sectors such as shipping, aviation, freight, and petrochemicals are further behind the automotive sector when it comes to phasing out oil and switching to alternative fuel sources (Reuters, 2022).

However, the replacement of oil with other alternative energy sources will be a difficult task. Crude oil is the world's most actively traded commodity (TD Ameritrade, 2022). As one of the most vital energy sources globally, trade in crude oil also comprises a significant component of many national economies. Currently, for example, over 100 countries export oil (Humbativa S.I. and Hajiyev N.Q., 2019). This leads to a large financial trading market for oil and its derivatives. In 2022, the estimated market size of global oil and gas exploration and production was about USD 5 trillion. Initial estimates indicate this could have increased by 27.5% in 2023 (IBISWorld, 2022). The global economy is also susceptible to changes in oil prices, with fluctuations affecting both oil importers and exporters (Humbativa S.I. and Hajiyev N.Q., 2019). In the USA, the Federal Reserve estimates that every USD 10 per barrel rise in oil prices cuts the country's GDP growth by 0.1 percentage points and increases inflation by 0.2 percentage points (Reuters, 2022). According to data from the USA Energy Information Administration, every USD 10 per barrel increase in oil is equivalent to a USD 200 million per day tax on American households and businesses (New York Times, 2022). Similarly, in the Euro Zone, every rise of 10% in the oil price increases inflation by 0.1 to 0.2 percentage points (ECB, 2022). As economies rely heavily on oil and oil products, oil factors can influence economic growth, financial markets, inflation, and politics (Humbativa S.I. and Hajiyev N.Q., 2019). They can also affect the kind of mitigation efforts that countries take to address climate change.

Between 2020 and 2030, the fall in oil as a dominant source of primary energy is expected to be much steeper in North America (median 24%) and Europe (median 25%) than elsewhere in the world. In comparison, for example, oil primary energy is projected to increase in Asia (median 6%) (Figure 38) over the next ten years.

Eastern and Western Europe (i.e., the EU27)

The EU has a 55% GHG reduction target for 2030, compared to 1990 levels. To achieve this target, the EU will need to increasingly use instruments like implementing a carbon price in order to accelerate the switch to renewable energy and improve energy efficiency—and thereby decarbonise key sectors in the coming years. The EU has already proposed a Carbon Border Adjustment Mechanism (CBAM), a ban on the sale of carbon emitting cars from 2035, the installation of charging and fuelling points at regular intervals, and the inclusion of transport emissions in its emissions trading scheme (ETS) (Sustainable Development Solutions Network, 2021). The EU's CBAM will initially require importers to declare embedded CO_2 emissions of electricity, iron, steel, aluminium, cement, and fertilisers, as well as transition into a carbon import tax. For a three-year period starting in 2023, importers will need to report embedded emissions on a quarterly basis. If they fail to do so from 2025 onwards, they will face a penalty charge. From 2026 onwards, meanwhile, a carbon price will be applied in line with domestic carbon prices. Tightening of such regulation could reduce oil demand and increase prices, as well as decrease the dependence of countries on revenues from oil exports (KAPSARC, 2022).

Energy security concerns will also be a key driver in reducing reliance on oil use for EU members states. The EU produces just 3% of the oil that it consumes (ICCT, 2022). The Russian Federation's invasion of Ukraine and the resulting economic sanctions have led many European countries to rethink their reliance on imported oil from the Russian Federation (World Economic Forum, 2022b). Over-dependence on a single oil supplier or the reliance of oil from unstable regions represent a concern for many countries. Under the REPowerEU Plan, the EU seeks to end energy dependence on the Russian Federation and reduce GHG emissions by replacing oil through the ramping-up of renewable energy and by improving energy efficiency for a green transition (European Commission, 2022). The European Commission agreed to end the bloc's reliance on Russian fossil fuels by 2027 and increase the share of renewables in final energy consumption to 45% by 2030.

North America (primarily the United States of America and Canada)

In the USA, the shale oil and hydrological fracturing (fracking) boom transformed the country from the world's largest importer of oil to one of its largest producers (Wall Street Journal, 2022). Fracking has allowed the USA to have greater energy independence than most of Europe. USA oil import dependency (the ratio of imports compared to consumption) was around 43% in 2020, compared to around 97% in the EU (EIA, 2021; European Commission, 2021). Despite strong energy policies supporting oil production, the USA (along with North America as a whole) is expected to shift production from oil to low-carbon energy alternatives (IEA, 2021b). Leading the way will be the transport sector, which accounts for the majority (67.2%) of the country's oil consumption (EIA, 2022).

Asia (excluding Japan and the Middle East)

Asia differs from Europe and North America in that population growth and consumer class growth are expected to drive the growth for oil as a source of primary energy. Replacement of oil in the transport sector by EVs will be slower in emerging markets due to limited infrastructure availability of charging stations (IMF, 2021). Due to such factors, the Russian Federation has been able to re-route its oil shipments to Asia, where the transition to renewable energy from oil has been slower (IEA, 2023a). India and China have proved receptive markets for Russian Federation oil exports, for instance. This is largely due to the cheaper price of Russian Federation oil, as well as the rising value of the US dollar.

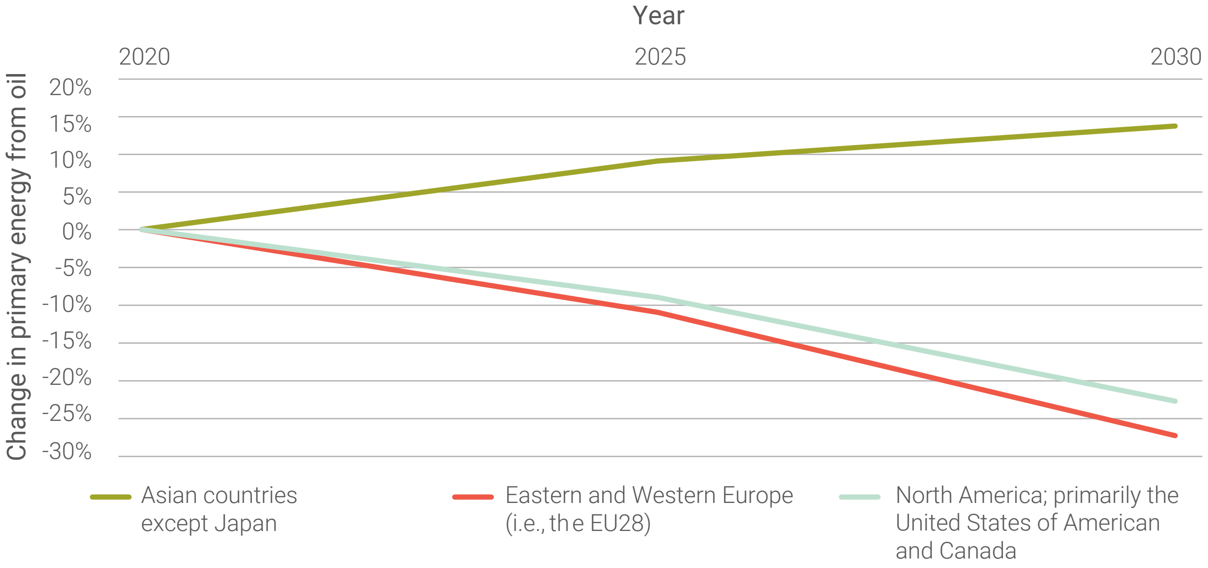


Figure 38: Regional trends in primary energy from oil from 2020 to 2030 in the IPCC-assessed 1.5°C scenarios with no or limited overshoot

Oil types

Gasoline, distillate fuel oil (including diesel fuel and heating oil), hydrocarbon gas liquids, and jet fuel comprise some of the most commonly used oil types (US Energy Information Administration, 2021). The most carbon-intensive oil types will need to be phased out first. Oil can be classified as either light or heavy; light oil is more expensive but easier to refine, while heavy oil is cheaper but more carbon-intensive to refine. Canadian heavy tar sand oils is an example of a heavy oil and makes up three of the top five most carbon-intensive oils (Oil Climate Index). GHG emissions from oil sands have risen more than 225% since 2000 due to increase in demand (Financial Times, 2022). An example of this is Canada's Cold Lake tar sands operation. At 81.87 kg CO_2eq/barrel, this is three times as emissions-intensive as the average barrel (25.11 kg/barrel) (S&P Global, 2021). A study found that shale oil has a lower-than-average carbon intensity of about 12 kg CO_2/barrel of oil equivalent (BOE), compared to the estimated industry average of 18–19 kg/BOE. Offshore and onshore producers have a carbon intensity of about 17 kg/BOE and 19 kg/BOE, respectively, while the rate for oil sands producers stands at 73 kg/BOE (Rystad Energy, 2021).

6.1.3 Natural gas

The pathway for natural gas production from 2020 to 2050 in 1.5°C scenarios with no or limited overshoot has significant variability by scenarios. Natural gas is often seen as a 'bridge fuel' to replace higher emitting sources, such as coal. However, this is not a long-term solution for limiting global warming to 1.5°C. The transition from the use of natural gas to renewable energy is vital for mitigating climate change. Gas production is projected to fall much more slowly in comparison to coal production from 2020 to 2050, with a significant decrease in production for gas projected in many of the scenarios only after 2030. Until 2030, primary energy from gas decreases by 10% (0% to 30%), relative to 2019 levels. Primary energy from gas decrease by 45% (20% and 60%) in 2050, relative to 2019 levels (Figure 39).

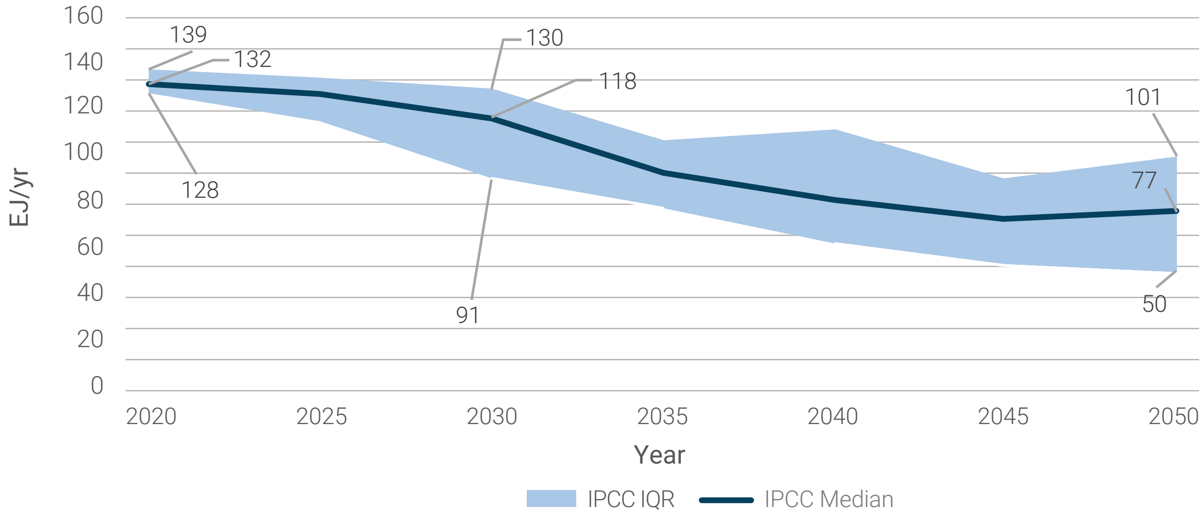
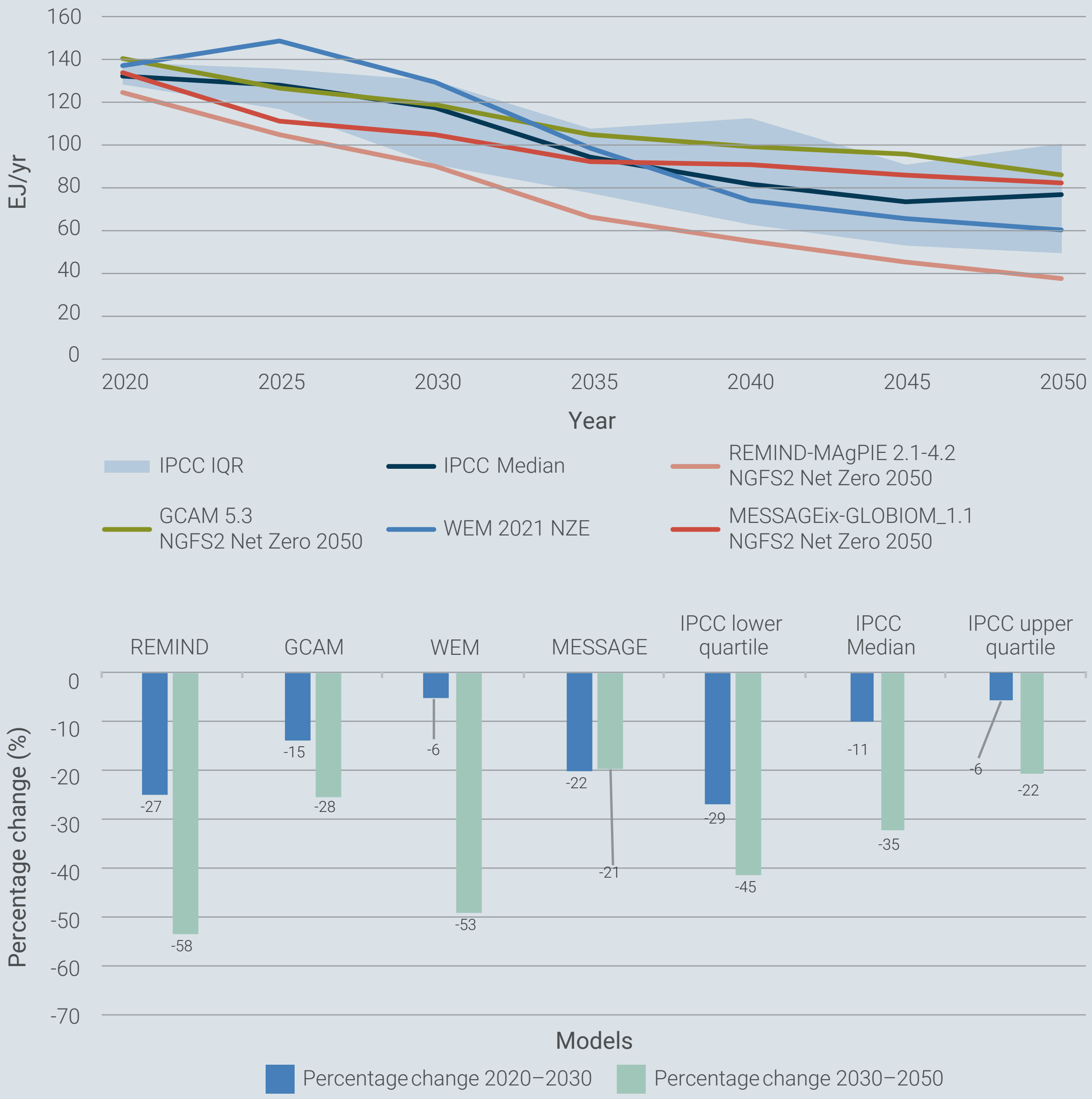


Figure 39: Global primary energy of natural gas in the IPCC-assessed 1.5°C scenarios with no or limited overshoot from 2020 to 2050

Box 17: (a) Natural gas primary energy shown in the IEA and the NGFS net-zero scenarios compared to the IPCC-assessed 1.5°C scenarios with no or limited overshoot (b) Percentage change during 2020–2030 and 2030–2050 of natural gas primary energy reported by different models

All NGFS scenarios shown are Net Zero 2050.



The REMIND pathway shows the greatest decrease in gas primary energy from 2020 to 2050. The level of gas primary energy reported in the model in 2050 is about half that of the IPCC median and less than the lower quartile of the IPCC-assessed scenario data-set for primary energy of gas from 2020 to 2050 (on average 7.7 EJ/yr lower than the lower quartile value of IPCC). The IEA NZE pathway also reports a substantial decrease of almost 56% in primary energy of gas over the course of 2020 to 2050. Pathways for gas primary energy by GCAM and MESSAGE report values within the interquartile range of the IPCC-assessed scenario dataset. In terms of the percentage change, almost all models report a need for a more substantial reduction in gas primary energy from 2030 to 2050 when compared to the decrease from 2020 to 2030. The exception is the MESSAGE model, which reports a relative steady percentage change of around 22% among the two time ranges.

Data source: AR6 scenario explorer

The historical role of natural gas as a bridge fuel

As developed countries increasingly retired coal plants, many switched from coal to natural gas as a bridge fuel to meet electricity demand. Natural gas generates relatively lower carbon emissions than coal. When used for generating electricity, for instance, gas produces up to half the power plant emissions compared to coal. Indeed, since 2010, the use of gas for electricity generation avoided about 500 million tonnes of CO_2 emissions compared to coal, equivalent to using an additional 200 million EVs over the same period. The fact that natural gas can be used with existing energy infrastructure also made it a preferred fuel option. In contrast, switching from coal to renewable energy requires the need to build up new renewables which required more time and higher initial capital investment. Gas was therefore seen as a relatively quick way of reducing short-term emissions (IEA, 2019).

However, the total emissions footprint of natural gas may be larger than thought due to methane leakage. Methane is the largest component of natural gas.[43] When it leaks, the benefits of natural gas over other fossil fuels may well be undermined (Hmiel *et al.*, 2020). Methane has more than 80 times the warming power of CO_2 over the first 20 years of reaching the atmosphere (EDF, n.d.). The largest regional studies from Canada and the USA have shown that previous studies underestimate methane leakages by 50 to 60% (Kemfert *et al.*, 2022). The USA's Environmental Protection Agency (EPA) suggests that the oil and gas industry emits eight million metric tons of methane a year.[44] The Environmental Defense Fund (EDF) puts the figure higher, at 13 million metric tons or more.[45] This represents a loss of gas with a value of around USD 2 billion (EDF, 2018). A separate study also showed that 3.7% of natural gas produced in the Permian Basin, in the south west of the USA, leaked into the atmosphere (Zhang *et al.* 2020). This amount of leakage is enough to undermine the GHG reduction benefits of switching from coal to natural gas in the near term (Scientific American, 2020).

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[43] Natural gas is also comprised of smaller amounts of natural gas liquids and nonhydrocarbon gases (US Energy Information Administration, n.d.)

[44] 84 million metric tons of CO_2eq emissions (Greenhouse Gas Equivalencies Calculator)

[45] 364 million metric tons of CO_2eq emissions (Greenhouse Gas Equivalencies Calculator)

Increasing reliance on natural gas will lead to risks in carbon lock-ins. Gas pipelines, liquified natural gas (LNG) terminals and gas-fired powered plants tend to have a lifetime of many decades (Kemfert *et al.*, 2022). If current existing energy infrastructure[46] operates the same way as it has in the past, an estimated 658 $GtCO_2$ will be released into the atmosphere, exceeding the remaining carbon budget for limiting global warming to 1.5°C (Tong *et al.*, 2019). However, the global use of natural gas continues to grow. Legal protection of properties, opposition from asset owners, and other lock-in mechanisms will make it difficult to retire natural gas infrastructure after only a fraction of its lifespan and can reduce the availability of adequate renewable infrastructure. Currently, not enough information is available on whether repurposing infrastructure is technically or economically possible (Kemfert *et al.*, 2022).

The role of natural gas in hydrogen production

Natural gas can be a feedstock for hydrogen. Hydrogen is often viewed as an important energy source for decarbonisation as hydrogen fuel burns clean. However, the process to produce hydrogen can be highly carbon intensive (World Economic Forum, 2021). Grey hydrogen (the most common hydrogen form today) is produced through steam-based conversion of methane in natural gas, which can generate high CO_2 emissions. As a result, the use of CCS to reduce these emissions is viewed as an option; this is known as ‘blue hydrogen’ (Howarth & Jacobson, 2021).

As with grey hydrogen, blue hydrogen can be produced from steam-based conversion of natural gas but the CO_2 emissions generated are captured during production (Howarth & Jacobson, 2021). However, the energy sector has not reached consensus on whether blue hydrogen can be considered ‘clean’ (S&P, 2022). In addition, blue hydrogen shares the same problem of grey hydrogen regarding potential leakage, which could increase the warming impact (EDF, 2022). Other GHG emissions from the production of blue hydrogen are quite high due to the release of fugitive methane. In fact, the GHG footprint of blue hydrogen is more than 20% greater than burning natural gas or coal for heat and some 60% greater than burning diesel oil for heat (Howarth & Jacobson, 2021). Furthermore, the use of CCS at a commercial scale for blue hydrogen production has yet to achieve the industry target. As of early 2023, only two commercial plants globally were producing hydrogen from natural gas with CCS. In light of these factors, blue hydrogen production also needs to be considered energy intensive and costly (IEEFA, 2023).

Regional pathways for natural gas

Over the next ten years, the use of natural gas needs to change substantially in all regions. Highly developed countries will need to reduce their reliance on natural gas in order to accelerate their energy transition. Demand from emerging countries for natural gas is expected to increase as countries transition away from coal. Between 2020 and 2030, projections of primary energy production of gas indicate a decrease in North America (median 37%) and Europe (median 32%) but an increase in Asia (median 37%) (Figure 40).

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[46] Existing fossil fuel infrastructure including natural gas

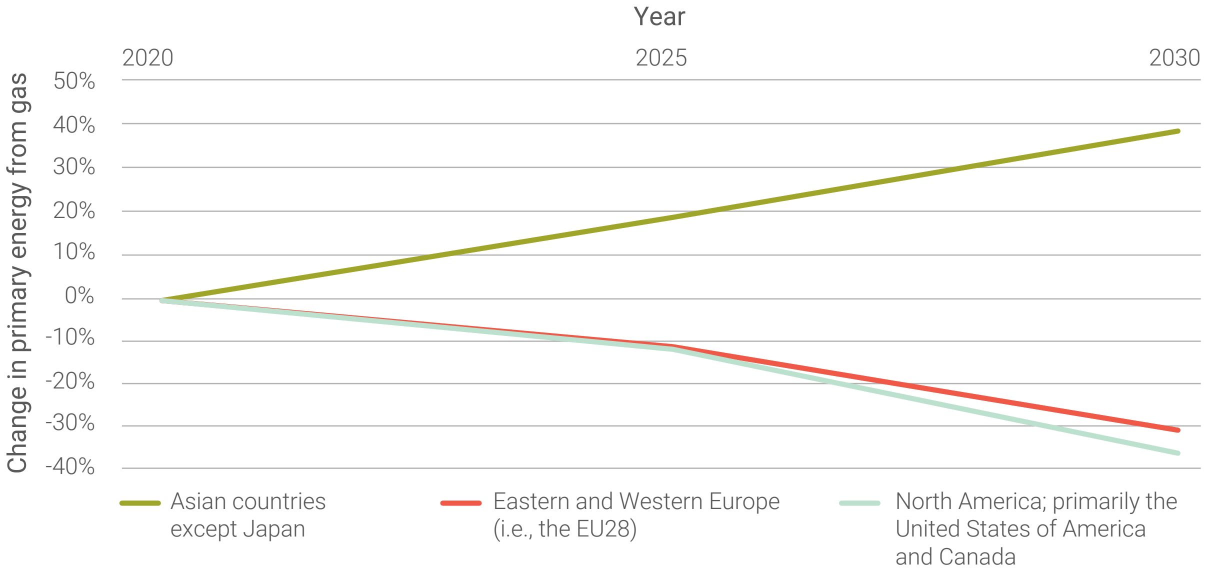


Figure 40: Regional trends in gas primary energy from 2020 to 2030 in the IPCC-assessed 1.5°C scenarios with no or limited overshoot

Asia (excluding Japan and the Middle East)

Growing energy demand from China and India, plus South and Southeast Asia, position Asia as a key driver for increasing gas production over the next decade. Rising demand for primary energy from natural gas can be attributed to the increasing rate of economic growth and growing urbanisation in the absence of stronger measures on renewable electricity and efficiency across all sectors. China and India were the largest consumers of electricity in 2017, with China accounting for 46.7% of total global electricity consumption among non-OECD countries (Market Watch, 2022). High rates of GDP and strong growth in energy demand due to rapid population growth will result in a rise in natural gas production for Asian markets. Growth in Chinese markets has great potential due to expansion of the industrial and transport sectors.

North America (primarily the United States of America and Canada) and Eastern and Western Europe

In North America and Europe, a growth in natural gas production is projected to be limited in scenarios due to the rapid expansion of energy production through renewable sources (IEA, 2020). This is despite the phase-out of coal. The USA is the world's leading producer of natural gas and was the largest LNG supplier to the EU and the United Kingdom in 2023. Despite this, natural gas production will need to decline in the country and the rest of North America as electricity generation capacity from renewable energy sources expand (EIA, 2022; UK Government, 2023). A key driver for Europe to accelerate the switch to renewable energy was the need to strengthen its energy security following Russian Federation's invasion of Ukraine. Until the invasion, Russian Federation was the world's second largest producer of natural gas and the world's largest exporter. In 2021, Russian Federation natural gas accounted for 45% of imports and almost 40% of EU gas demand (IEA, 2022a). Countries such as Germany relied heavily on Russian Federation gas to transition to a low carbon future (BMWK, n.d.). However, following the Russian invasion, many countries placed sanctions on the Russian Federation and announced plans to make their energy security more resilient. In comparison to 2021, the EU was able to reduce its dependence on Russian Federation gas by 48% in 2022 and an estimated 71%–74% in 2023 by increasing imports from other countries, such as the USA and Qatar, and expanding electricity generation from renewables. Renewables generated 39% of the EU's electricity in 2022 (Tollefson, 2022; European Commission, 2023).

Replacing natural gas

Green hydrogen is seen as a leading replacement for natural gas as a fuel source. Green hydrogen is produced by splitting water into hydrogen and oxygen using renewable energy, such as wind or solar power. Green hydrogen has also been featured in many climate pledges since COP26 as a way to decarbonise industrial, freight, shipping, and the aviation sectors (World Economic Forum, 2021). More recently, at COP28, 30 countries expressed their commitment by signing a declaration to support and adopt certification schemes for low-carbon hydrogen (COP28, 2023). In recent years, hydrogen manufacturing companies have begun scaling up. In 2019, the estimated global electrolyser manufacturing capacity amounted to just 200 MW; by 2021, it had expanded to 6.3 GW (Wood Mackenzie, 2021). In 2022, electrolyser manufacturing capacity rose to almost 11 GW (IEA, 2023b). Currently, green hydrogen remains too expensive to compete against conventional sources of hydrogen and other fuels. However, various cost drivers are expected to bring these costs down over the next decade or less. Cost drivers include economies of scale, newcomers in the market, and increased automation. Despite high prices at present, the number of hydrogen projects underway grew seven-fold in 2020 as investors bet on the long-term potential of green hydrogen (Wood Mackenzie, 2021).

Reduction in energy production from fossil fuels is a pivotal feature of all 1.5°C scenarios with no or limited overshoot. Rapidly reducing energy production from coal is the first immediate step to reduce CO_2 emissions. Reducing global reliance on oil and gas will take greater effort and a longer time as oil and gas are more integrated into society.

6.1.4 Renewables

As the 1.5°C scenarios with no or limited overshoot report a rapid phase-out of fossil fuels in the coming decades, they are nearly unanimous in requiring a major scale-up of renewable energy. Primary energy produced from non-biomass renewables is reported to increase by 187% (median) from 2020 to 2030 and by 687% (median) from 2020 to 2050 in scenarios limiting warming to 1.5°C with no or limited overshoot. Primary energy from the different types of non-biomass renewables reported in the scenarios—solar (2,594%), wind (1,028%), hydro (56%) and geothermal (725%)—are shown to increase markedly by 2050.

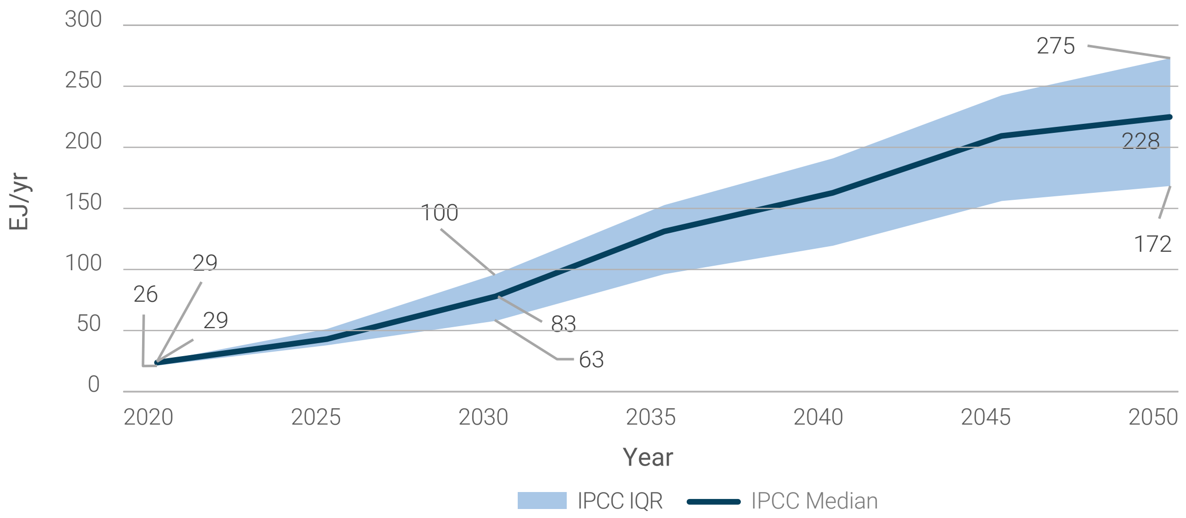
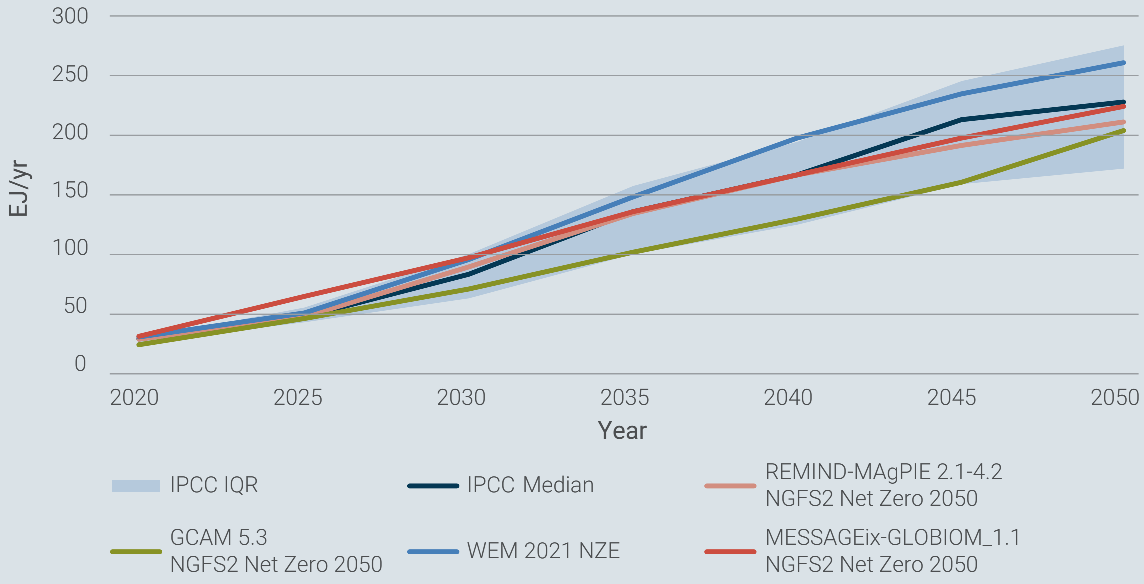


Figure 41: Global primary energy from non-biomass renewables in the IPCC-assessed 1.5°C scenarios with no or limited overshoot from 2020 to 2050

Box 18: Primary energy from non-biomass renewables shown in the IEA and the NGFS net-zero scenarios compared to the IPCC-assessed 1.5˚C scenarios with no or limited overshoot

All NGFS scenarios shown are Net Zero 2050.



The REMIND, GCAM, MESSAGE, and the IEA NZE scenarios all report pathways for non-biomass renewable primary energy that fall within the interquartile range of the IPCC-assessed scenario dataset. The IEA NZE scenario shows the highest levels of non-biomass renewable primary energy, close to the upper quartile of the IPCC-assessed scenario dataset. In 2050, the IEA NZE scenario reports around 50 EJ/yr more than the IPCC median value and 14.6 EJ/yr lower than the IPCC upper quartile value. REMIND and MESSAGE show similar levels of non-biomass renewable primary energy, close to the median of the IPCC-assessed scenario dataset. GCAM reports the lowest levels of non-biomass renewable primary energy, falling close to the lower quartile of the IPCC-assessed scenario dataset during 2020 and 2045. During 2045 and 2050, the GCAM pathway's value falls between the lower and median of the IPCC-assessed values, ranging from 161 EJ/yr and 204 EJ/yr. In 2050, the GCAM value is 31 EJ/yr higher than the lower quartile of IPCC scenario dataset.

Data source: AR6 scenario explorer

The scenarios also show a shift in the primary energy mix of non-biomass renewable energy from 2020 to 2030 and 2050 (Figure 42). Across the decades, the percentage of primary energy produced from hydro within the total primary energy mix of non-biomass renewables decreases. In contrast, there is a significant increase in the percentage of primary energy produced from solar and wind sources, which together account for a larger share of total primary energy mix of non-biomass renewables. This can be attributed to a much faster growth in energy from solar and wind than hydro till 2040, with solar growing by about 746% from 2020 to 2030 (Table 19).

Table 19: Primary energy of types of non-biomass renewables from 2020 to 2050 as shown in the IPCC-assessed 1.5°C scenarios with no or limited overshoot[47] (median)

Type of non-biomass renewable	2020 (EJ/yr)	2030 (EJ/yr)	Compound annual growth rate (2020–2030) (%)	2040 (EJ/yr)	Compound annual growth rate (2030–2040) (%)	2050 (EJ/yr)	Compound annual growth rate (2040–2050) (%)
Geothermal	0.8	2.4	11.6%	3.7	4.4%	6.3	5.5%
Hydro	16.0	22.0	3.2%	23.9	0.8%	24.8	0.4%
Solar	2.9	24.2	23.6%	60.0	9.5%	77.0	2.5%
Wind	5.2	21.9	15.5%	44.6	7.4%	58.4	2.7%

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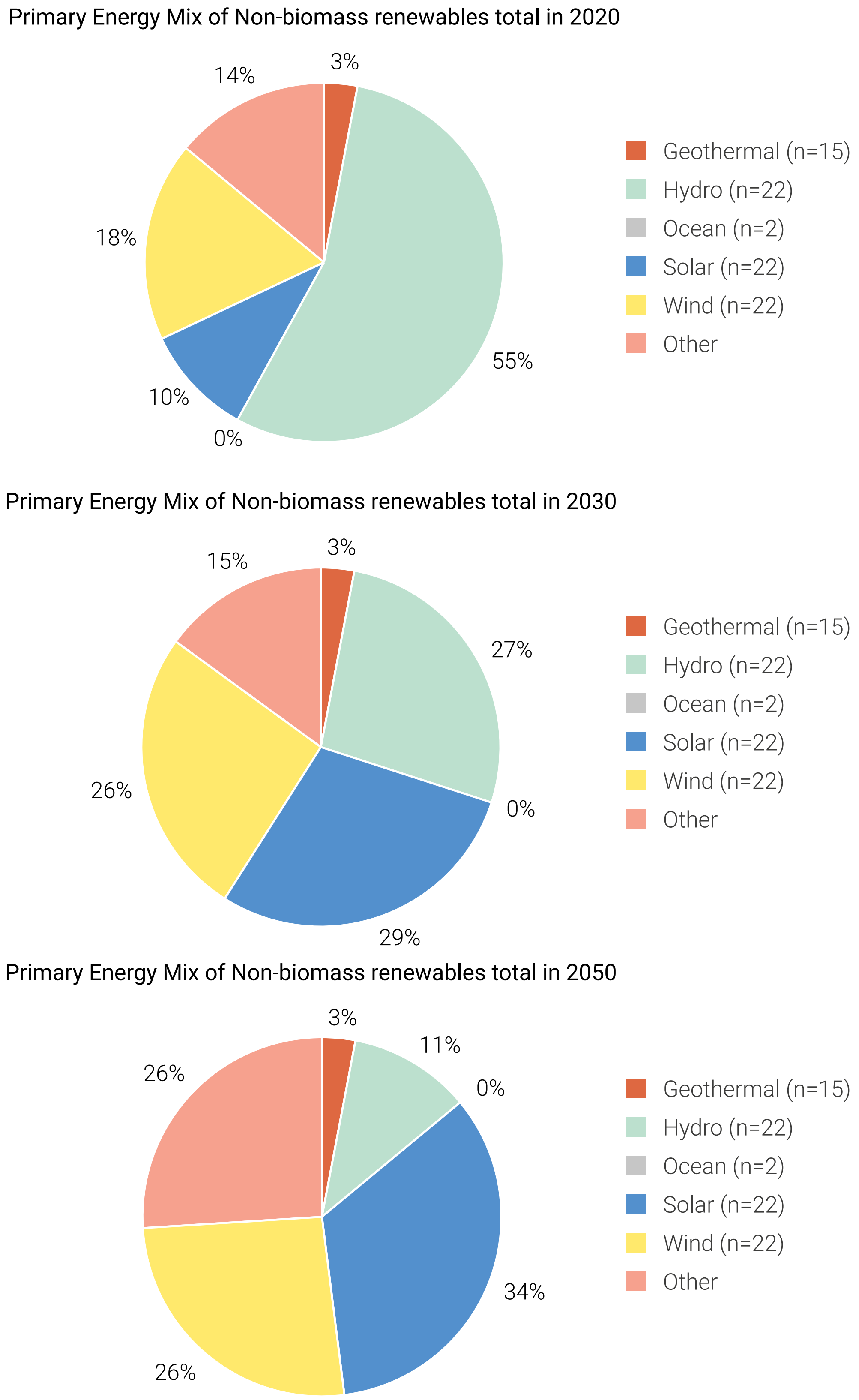
[47] Scenarios that show the ocean as a non-biomass renewable energy source report almost nothing in primary energy from the energy type.



Primary Energy Mix of Non-biomass renewables total in 2020

Primary Energy Mix of Non-biomass renewables total in 2030

Primary Energy Mix of Non-biomass renewables total in 2050

Figure 42: Global shift in the primary energy mix of non-biomass renewables from 2020 to 2030 and 2050[48]

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[48] Data on renewables as a source of primary energy were available in 94 of the 97 scenarios.

Solar and wind

In the past years, solar and wind energy deployment and price declines have exceeded the expectations of the majority of energy analysts. In 2022, solar experienced the greatest increase in electricity generation among all renewable technologies, measured in absolute terms. The IEA estimates that between 2022 to 2027, global solar PV capacity will triple and surpass coal as the largest source of power capacity globally. Over the same period, wind capacity is expected to double (IEA, 2023c; IEA, 2022b).

1.5°C scenarios with no or limited overshoot report a significant increase in solar energy, especially from 2025 to 2040 (Figure 43). Two main solar technologies are used to produce energy—photovoltaics (PV) and concentrating solar power (CSP). PV is the most well-known and fastest-growing sector of solar technology. PV devices generate electricity from sunlight through an electric process that occurs naturally in certain materials. Groups of PV cells can be configured into modules and arrays to generate electricity. CSP plants are utility-scale generators that can produce electricity using mirrors to concentrate energy from the sun (Planete Energies, 2022).

1.5°C scenarios with no or limited overshoot report a large increase in solar energy, especially from 2025 to 2040, with primary energy from solar growing by 746% from 2020 to 2030 and 148% from 2030 to 2040 (Figure 43).

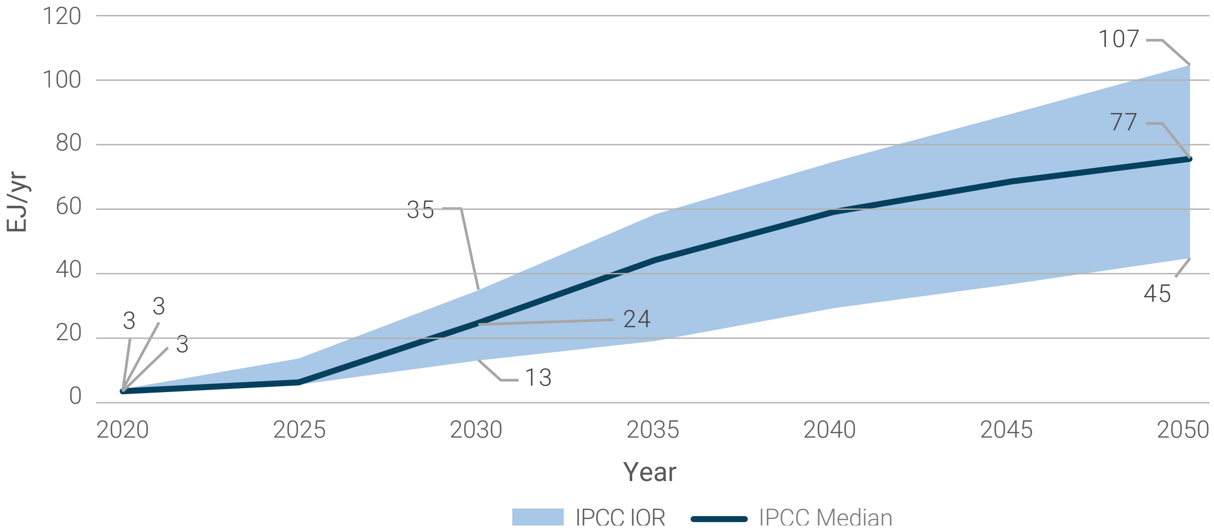
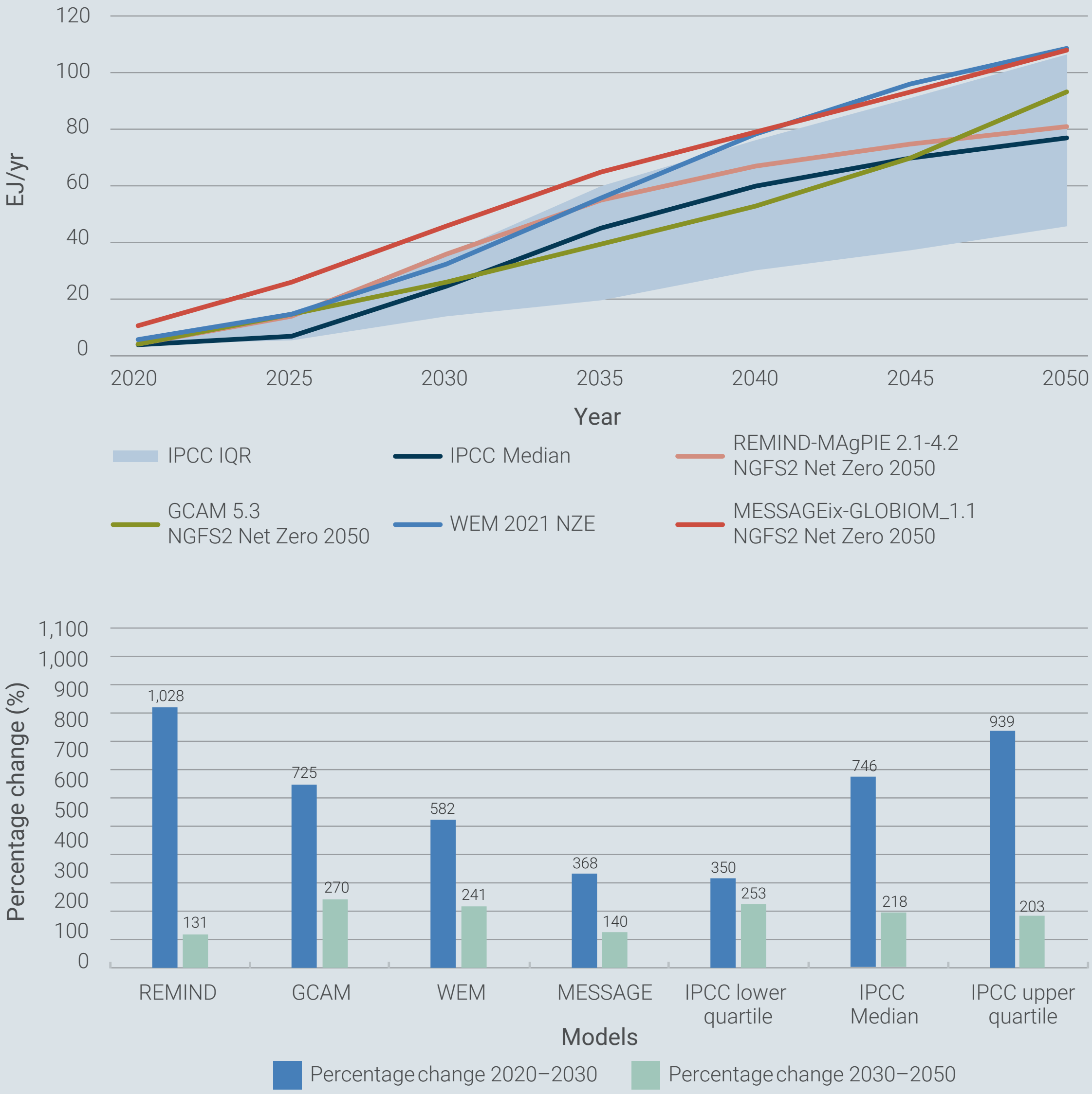


Figure 43: Global primary energy generated from solar shown in the IPCC-assessed 1.5°C with no or limited overshoot

Box 19: (a) Primary energy from solar shown in the IEA and the NGFS net-zero scenarios compared to the IPCC-assessed 1.5˚C scenarios with no or limited overshoot (b) Percentage change during 2020–2030 and 2030–2050 of primary energy from solar reported by different models

All NGFS scenarios shown are Net Zero 2050.



The MESSAGE pathway reports the highest values of solar primary energy from 2020 to 2040, with on average, 5.7 EJ/yr more than the upper quartile of the IPCC-assessed dataset. The IEA's NZE pathway shows a large increase in solar primary energy from 2020 to 2050, slightly higher than the upper quartile of the IPCC-assessed scenario dataset with an average difference of around 0.5 EJ/yr. By 2050, MESSAGE and the IEA NZE show similar levels of solar primary energy. The REMIND pathway also shows a rapid rise in solar primary energy from 2020 to 2035, following which the growth rate of solar primary energy slows down but remains higher than the median (on average 6.4 EJ/yr higher). The solar primary energy reported in the pathway for 2050 is almost 1.8 times larger than the lower quartile of the IPCC-assessed scenario dataset. Though the GCAM pathway shows the greatest increase in solar primary energy from 2020 to 2050, the pathway also shows a slower rate of increase from 2025 to 2040, following which the pathway reports higher solar primary energy than the median of the IPCC-assessed scenario dataset.

In all pathways, a significant increase in primary energy occurs between 2020 and 2030. REMIND reports the highest percentage increase of 1028% by 2030. MESSAGE reports the smallest percentage increase in solar primary energy (368%) between 2020 and 2030, close to the percentage increase of the lower quartile of the IPCC-assessed scenario dataset (350%).

Data source: AR6 scenario explorer

There are two main types of wind energy—offshore and onshore. Onshore wind energy requires large installations of wind turbines on land to generate energy. In contrast, offshore wind energy requires large installations of wind turbines to be located in bodies of water. Onshore and offshore wind energy have their trade-offs, with onshore wind farms being more common at present (ArcGIS, 2019).

1.5°C scenarios with no or limited overshoot report a large increase in wind energy, especially from 2025 to 2040, with primary energy from wind growing by 323% from 2020 to 2030 and 103% from 2030 to 2040 (Figure 44).

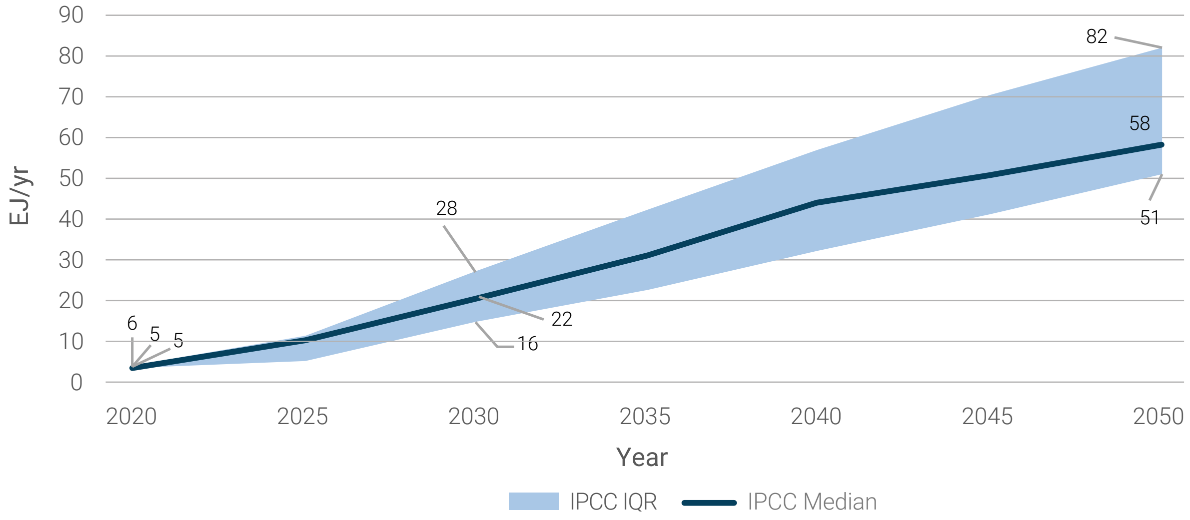
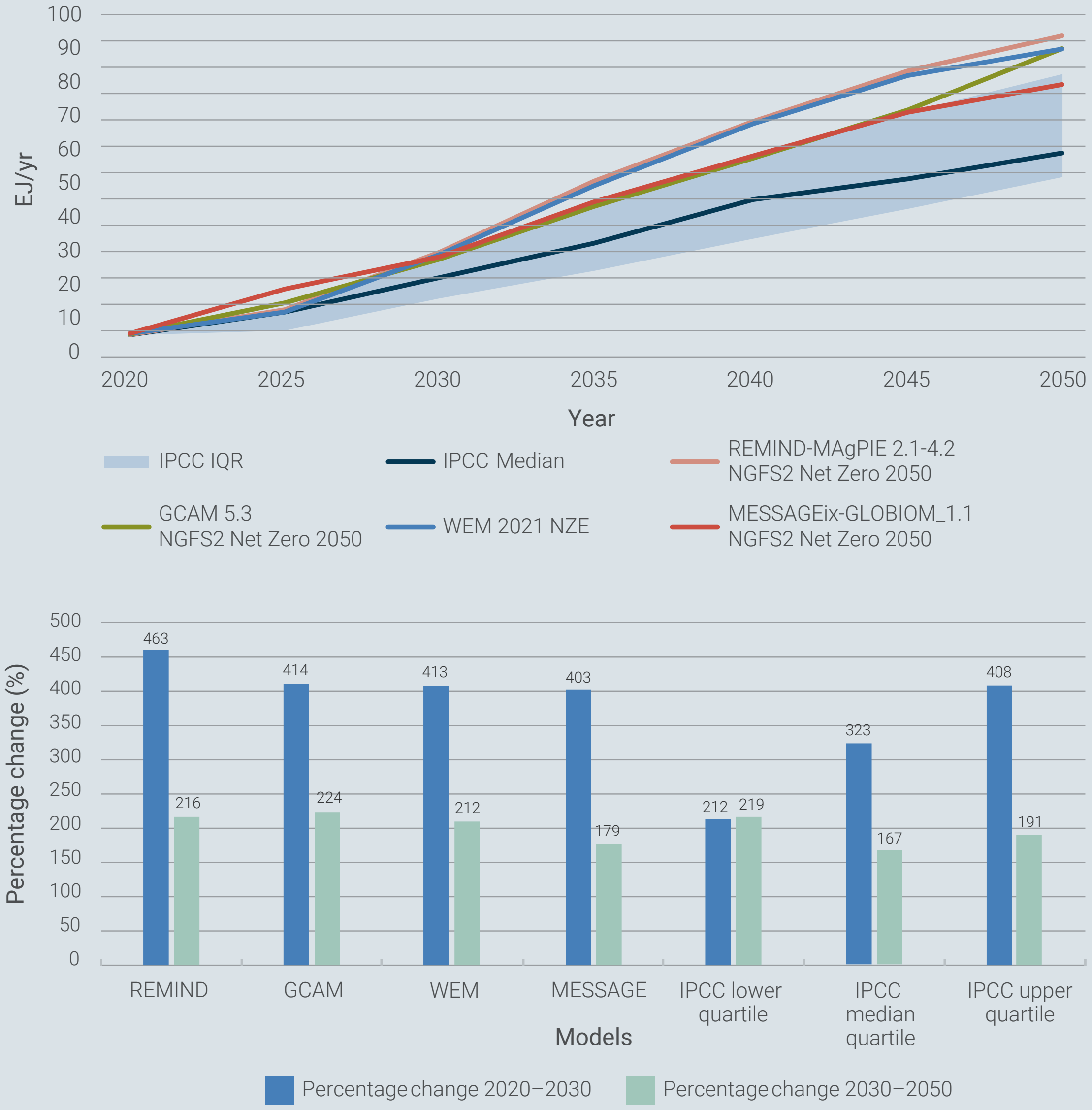


Figure 44: Global primary energy generated from wind shown in the IPCC-assessed 1.5°C with no or limited overshoot

Box 20: (a) Primary energy from wind shown in the IEA and the NGFS net-zero scenarios compared to the IPCC-assessed 1.5°C scenarios with no or limited overshoot (b) Percentage change during 2020–2030 and 2030–2050 of primary energy from wind reported by different models

All NGFS scenarios shown are Net Zero 2050.



The MESSAGE, REMIND, GCAM and the IEA NZE pathways show a higher increase in wind primary energy than the interquartile range of the IPCC-assessed scenario dataset. Out of the four pathways, MESSAGE shows the lowest amount of wind primary energy, close to the upper quartile of the IPCC-assessed scenario dataset. GCAM, REMIND, and the IEA NZE pathways all show wind primary energy higher than the upper quartile of the IPCC-assessed scenario dataset and are on average 15.2 EJ/yr higher than the median level of IPCC-assessed scenario dataset. By 2050, REMIND shows the highest amount of primary energy from wind.

In all pathways, a significant increase in wind primary energy occurs between 2020 and 2030. REMIND reports the highest percentage increase between 2020 and 2030, reaching to around 450%. GCAM (414%), MESSAGE (403%), and the IEA NZE scenario (413%) report similar levels of percentage increase in wind primary energy from 2020 to 2030. These are in line with the percentage increase (498%) of the upper quartile of the IPCC-assessed scenario dataset.

Data source: AR6 scenario explorer

Solar and wind energy growth in the 1.5°C scenarios with no or limited overshoot follows the S-curve model in which there is slow initial adoption of the technology, followed by rapid adoption and then levelling-off once the technology becomes mature. In the S-curve model, new technology reaches a catalytic tipping point of about 5–10% of the market share and then rapidly achieves a high market share of more than 50% within a few years. The S-growth of solar and wind energy means that fossil fuels are pushed out at an increasing rate (Carbon Tracker, 2023).

The key reason for the rapid expansion of solar and wind energy is the immediate reduction in cost over the last decade, supported by the implementation of robust policies to incentivise deployment. Utility-scale solar PV and onshore wind have become the cheapest option for new electricity generation in the majority of countries (IEA, 2022c). The cost of solar is now lower than fossil fuels, nuclear, and even wind. This is for a variety of reasons. Most notably, the cost of solar power generation has decreased by 90% since 2009 (Solar Power, 2022). Costs for solar and wind technologies have declined due to positive feedback loops. The significant amount of solar and wind that has been implemented has enabled these technologies to become cheaper thanks to economies of scale and the increased competitiveness of supply chains. In turn, decreased costs have resulted in greater deployment. The costs of solar and wind are expected to continue to fall in the coming decades. For example, wind power experts expect wind energy costs to decrease by 17%–25% by 2035 and by 37%-49% by 2050, compared to a 2019 baseline. This will be driven by advancements such as larger, more efficient wind turbines, as well as by lower capital and operating costs (Wiser *et al.*, 2021). As solar and wind technologies are standardised, technological advancements and cost reductions have been able to be easily duplicated across different regions (WRI, 2021). Anticipated innovations will allow solar to reach a level cost of energy in many regions with which fossil fuels will not be able to compete. Examples of such innovations include a reduction in the number of high cost materials used in solar cell manufacturing, the development of modules that capture solar energy from both sides of a panel (known as ‘bifacial modules’), and improvements to the integration of solar into power systems (World Economic Forum, 2020).

Near-term estimates for renewable capacity have been revised significantly upward just in the last year. The revision in expansion due to the implementation of existing policies and reforms, as well as new measures adopted in response to the energy crisis, such as China’s 14th Five-Year Plan, REPowerEU, and the US Inflation Reduction Act (IEA, 2022b).

As mentioned earlier in the context of shifting away from fossil fuels, concerns for energy security have also driven solar and wind energy growth. The global energy crisis in 2022, sparked by the Russian invasion, resulted in even faster growth of solar and wind power (IEA, 2022c). Security concerns represent a major cause behind the rapid current expansion of the EU's renewable electricity capacity, which is expected to double between 2022 and 2027 (IEA, 2022b). Despite recent inflationary pressures leading to cost increases for raw materials and for the shipping of solar and wind energy, energy produced by coal and natural gas has seen even greater price spikes since the Russian Federation's invasion of Ukraine (IEA, 2022d).

However, many challenges remain in the further expansion of wind and solar energy. Obstacles to the growth of solar energy include poor grid connection and flexibility, a limited number of skilled workers, and unfavourable policy frameworks. Additional scalability of solar will also depend on technological innovations, like utility-scale battery storage, peer-to-peer electricity trading, and demand-side management. Wind energy similarly faces limited grid connections and supporting infrastructure, a shortage of skilled labour, a lack of progress regulatory frameworks, and supply chain uncertainties. Land availability, opposition to wind farms, and high capital costs, as well as negative impacts on marine and avian life, are also impacting the growth of wind power (IRENA, 2022).

6.1.5 Near-term progress in decarbonising the primary energy mix

Table 20: Percentage differences of primary energy variables between latest global level and median of IPCC-assessed 1.5°C scenarios with no or limited overshoot levels (Energy Institute Statistical Review of World Energy, 2023)

	Primary energy variable type	2022 real primary energy consumption (EJ/yr) (a)	IPCC Median level 2020 (EJ/yr) (b)	Percentage difference between (a) and (b)	IPCC Median level 2025 (EJ/yr) (c)	Percentage difference between (a) and (c)
Fossil fuels	Oil	190.7	187.5	1.7%	182.7	-4.2%
	Coal	161.5	150.0	7.7%	84.7	-47.6%
	Gas	141.9	132.3	7.3%	127.9	-9.9%
Renewables	Solar	12.4	2.9	327.6%	6.0	-51.6%
	Wind	19.8	5.2	280.7%	12.1	-38.9%

While progress has been made on scaling up primary energy sourced from wind and solar, which has increased at a faster speed than shown in the IPCC-assessed 1.5°C scenarios with no or limited overshoot, current efforts to reduce fossil fuel primary energy fall short to limit warming to 1.5°C.

Coal

The IPCC-assessed 1.5°C scenarios with no or limited overshoot report 150 EJ/yr (median) of coal primary energy in 2020. However, latest available data show that globally in 2022 average primary energy sourced from coal was 161.5 EJ/yr. This is 7.7% higher than the median value for the scenarios in 2020. For 2025, the scenarios report a median value of 84.7 EJ/yr. In order to be in line with the 1.5°C scenarios by 2025, primary energy sourced from coal will need to decrease by 47.6% between 2023 and 2025.

Oil

For oil primary energy, the IPCC-assessed 1.5°C scenarios with no or limited overshoot report 187.5 EJ/yr (median) of oil primary energy in 2020. However, latest available data show that in 2022 the global average primary energy sourced from oil was 190.7 EJ/yr, 1.7% higher than the median value for the scenarios in 2020. For 2025, the scenarios report a median value of 182.7 EJ/yr. In order to be in line with the 1.5°C scenarios by 2025, primary energy sourced from oil will need to decrease by 4.2% between 2023 and 2025.

Natural Gas

For natural gas primary energy, the IPCC-assessed 1.5°C scenarios with no or limited overshoot report 132.3 EJ/yr (median) of gas primary energy in 2020. However, latest available data show that in 2022 the global average primary energy sourced from gas was 141.9 EJ/yr, 7.3% higher than the median value for the scenarios in 2020. For 2025, the scenarios report a median value of 127.9 EJ/yr. In order to be in line with the 1.5°C scenarios by 2025, primary energy sourced from gas will need to decrease by 9.9% between 2023 and 2025.

Solar

For solar primary energy, the IPCC-assessed 1.5°C scenarios with no or limited overshoot report 2.9 EJ/yr (median) of oil primary energy in 2020. However, latest available data show that in 2022 the global average primary energy sourced from solar was 12.4 EJ/yr. This is already 327.6% higher than the median value for the scenarios in 2020. For 2025, the scenarios report a median value of 6 EJ/yr. This means that the global average value of primary energy sourced from solar in 2022 is already 51.6% greater than the median primary energy level reported by in the 1.5°C scenarios in 2025.

Wind

For wind primary energy, the IPCC-assessed 1.5°C scenarios with no or limited overshoot report 5.2 EJ/yr (median) of oil primary energy in 2020. However, latest available data show that in 2022 the global average primary energy sourced from wind was 19.8 EJ/yr, which is already 280.7% higher than the median value for the scenarios in 2020. For 2025, the scenarios report a median value of 12.1 EJ/yr. As such, the global average value of primary energy sourced from wind in 2022 is already 38.9% greater than the median primary energy level reported by in the 1.5°C scenarios in 2025.

6.1.6 Energy Efficiency

Energy efficiency reduces the need for additional generation capacity and makes it easier to retire high-emitting assets. Supporting climate goals while meeting growing energy needs as the global economy increases in size will require a transformation of the traditional energy system. Energy efficiency can help a net-zero future with low energy costs and support global growth and development. Increased energy efficiency allows the same level of energy services to use less energy, which can significantly reduce CO_2 emissions, thus allowing countries to decouple GDP growth from the growth of CO_2 emissions. Improvements in energy efficiency can be influenced by technological advancements (such as high-efficiency appliances, industrial equipment and LED lighting), government policies (such as energy efficiency standards, green public procurement and building codes), consumer behaviour and energy-saving habits, and the cost of energy. 1.5°C scenarios with no or limited overshoot report constant energy efficiency of 34% to 36% (median) for electricity generated from coal with CCS from 2020 to 2050.

Utilities companies are concerned that energy efficiency will decrease sales, which can result in lower revenue for utilities. Implementing a decoupling mechanism would dissociate utility revenue from its sales, thereby improving the sector's ability to take up energy efficiency. Decoupling will periodically compare commission-authorised revenue to actual revenue, with customers being surcharged when sales are low and a refund when sales are higher than expected, hence removing the link between utility sales and revenues and incentivising energy efficiency (ACEEE, 2020).

End-user focused product and sector market transformation programmes such as the UNEP led United for Efficiency initiative, which uses an integrated policy approach to accelerate the adoption of energy-efficient lighting, appliances and equipment, have been successfully implemented in the major developed economies since the 1990's and are a proven, relatively fast and low cost policy measure to decouple GDP growth from the growth of CO_2 emissions. These strategically planned programmes include financial mechanisms such as incentives and public procurement measures to completely change the structure of end user product and service markets to higher energy performance standards.

6.1.7 Strategies and challenges for decarbonisation

Strategies for decarbonising the energy sector (UCL, 2022; UNEP, n.d.):

- Electrification and generation of electricity from renewable sources and nuclear with a shift away from fossil fuels.
- Advancing CCS technologies to install CCS at fossil fuel power plants at the commercial level to capture large amounts of CO_2.
- Improving energy efficiency of energy production, distribution, and consumption.
- Upgrading transmission networks and storage capacity and improving grid flexibility to enable the deployment of clean energy.
- Changes in lifestyles to reduce energy demand.

Challenges for decarbonising the energy sector (WRI, 2021; Eaton, n.d.; IEA, 2021c):

- Supply chain shortages of critical minerals needed in the manufacturing of certain clean energy technologies, such solar panels, can slow down the transition from fossil fuels to renewables.
- Massive subsidies for fossil fuels continue to be available.
- Intermittency issue of renewable sources as they cannot produce energy consistently. For example, solar panels can only generate energy when the sun is shining.
- Despite a rapid decrease manufacturing costs of renewable energy technologies, costs for installation and maintenance continue to be high.
- Availability of renewable energy sources is dependent on the geographical location and its weather.
- Environmental concerns of mining of critical minerals required for batteries and clean energy technologies.
- Countries continue to invest in power plant infrastructure which can result in carbon lock-ins as the lifetime of the infrastructure can span decades. A study by Tong *et al.* (2019) found that emissions from existing and proposed infrastructure could use up the entire carbon budget for limiting warming to 1.5°C.
- Large amounts of investments are needed to advance technologies and build the required infrastructure.

Table 21: Recommended scenario variables to use for assessing decarbonisation of the energy sector in pathways (AR6 scenario explorer)

Variable	Unit	Definition	Additional information
Primary Energy	EJ/yr	Primary energy input of primary energy consumption of an energy source.	Further variables are available for different energy types, such as coal, oil, gas, non-biomass renewables, nuclear, etc.
Final Energy	EJ/yr	Final energy consumption. Depending on the final energy variable chosen, this can exclude the use or transmission of feedstock or distribution losses (*adapted by the author*).	Variables are available for different types of energy, such as solar.

Capacity Additions	GW/yr	Additional capacity added annually	Further variables are available for the installed capacity of electricity from different energy sources.
Capacity	GW (Energy-related)	Total installed capacity	Further variables are available for the installed capacity of electricity from different sources and the installed capacity of power plants.
Efficiency	%	Conversion efficiency (electricity produced per unit of primary energy input) of a new power plant. The efficiency should refer to the plant type(s) for which capital costs have been reported. If capital cost for more than one plant type has been reported, modellers should report efficiency should be reported for additional plant types by adding variables.	Further granular variables are available for electricity, gases, hydrogen and heating, with or without CCS.

Questions for readers:

- What alternatives to fossil fuels do you identify as opportunities for your institution?
- In your opinion, are the decarbonisation pathways for energy shown in scenarios feasible for scenario analysis?
- Which methods have you identified as realistic for decarbonisation?
- What are the significant differences in modelling assumptions between the IPCC-assessed scenarios and modelling assumptions made in-house at your institution?
- What aspects of the energy pathways would you change to make them more applicable for use?

Switching from fossil fuels to electricity in end-use sectors

6.2 Transport

Fossil fuels are the dominant source of energy for the transport sector. Globally, the sector is responsible for about 60% of total oil demand (IEA, 2021b). Despite an expected growth in transport demand in the coming years, scenarios that limit warming to 1.5°C with no or limited overshoot require emissions from the sector to rapidly decrease by 2030. Final energy from oil for freight transportation is shown to decrease by 74% (median) from 2025 to 2050 in the scenarios. Decarbonisation of the transport sector will depend on the transition away from fossil fuel use towards rapid electrification, improvements in energy efficiency, and the commercialisation of low-carbon fuels, as well as shifts in public policy and consumer behaviour that encourage low-carbon travel alternatives.

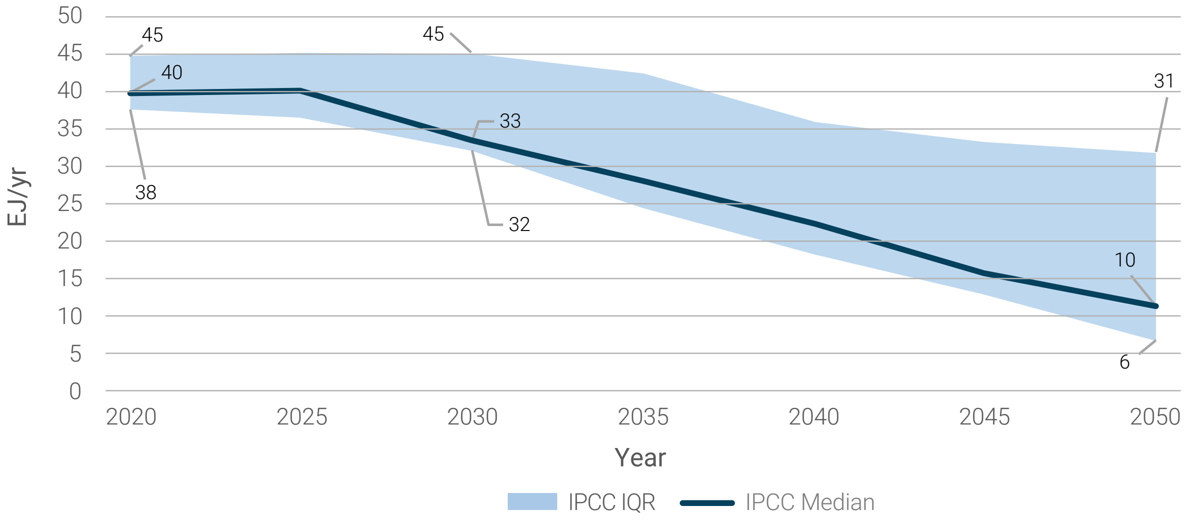


Figure 45: Global final energy from oil for freight transportation from 2020 to 2050 in the IPCC-assessed 1.5°C scenarios with no or limited overshoot

6.2.1 Electrification

EVs are one of the most important technologies for decarbonising the transport sector as they offer an alternative to conventional, carbon-intensive fossil fuels. A switch to electricity, especially for road transport, will reduce the sector's reliance on oil, thus reducing CO_2 emissions. Two methods will need to be deployed for the electrification of vehicles; storage batteries, and fuel synthesis (Tamor and Stechel, 2022). According to the International Council on Clean Transportation (ICCT), sales of EVs will need to account for 35% of the global market in 2030 and even higher levels for major markets if the 1.5°C climate target is to be met (ICCT, 2021). Should the growth in EVs experienced in the last two years continue, CO_2 emissions from cars will align with the IEA's Net Zero Emissions by 2050 scenario. However, there is a disparity in sales between developed and developing countries, with growth in sales being lower in developing and emerging countries due to higher purchase costs and limited access to charging infrastructure (IEA, 2022e). However, some emerging markets have shown signs of significant growth, for example, EV sales in India, Thailand and Indonesia tripled in 2022 from 2021 levels due to the policy schemes implemented by their governments (IEA, 2023d).

The expansion of EVs will need to continue at a rapid pace. 1.5°C scenarios with no or limited overshoot show final energy generated from electricity for the transport sector increasing from 1.8 EJ/yr (1.6–2.0 EJ/yr) in 2020 to 22.8 EJ/yr (19.2–27.0 EJ/yr) in 2050. The electricity used by the transport sector will need to be generated from low-carbon sources. To further incentivise both the production and adoption of EVs, government policies will need to provide fiscal incentives, infrastructure investments, and consumer information (ICCT, 2021). A number of countries have announced goals to phase out fossil fuels from the sector. Most European countries have announced measures to become a major force in the EV market. Paris authorities have announced a ban on the sale of new petrol and diesel cars as early as 2030 (S&P Global, 2020; Reuters, 2017). Many USA state governments have also announced goals to reduce national vehicle emissions to zero by 2050 ([Zhang and Fujimori, 2020]). Japan has announced its intention to sell only EVs by 2035 ([International Trade Administration, 2021]), while China plans to phase out vehicles powered by fossil fuels by 2035 ([Wood Mackenzie, 2021]).

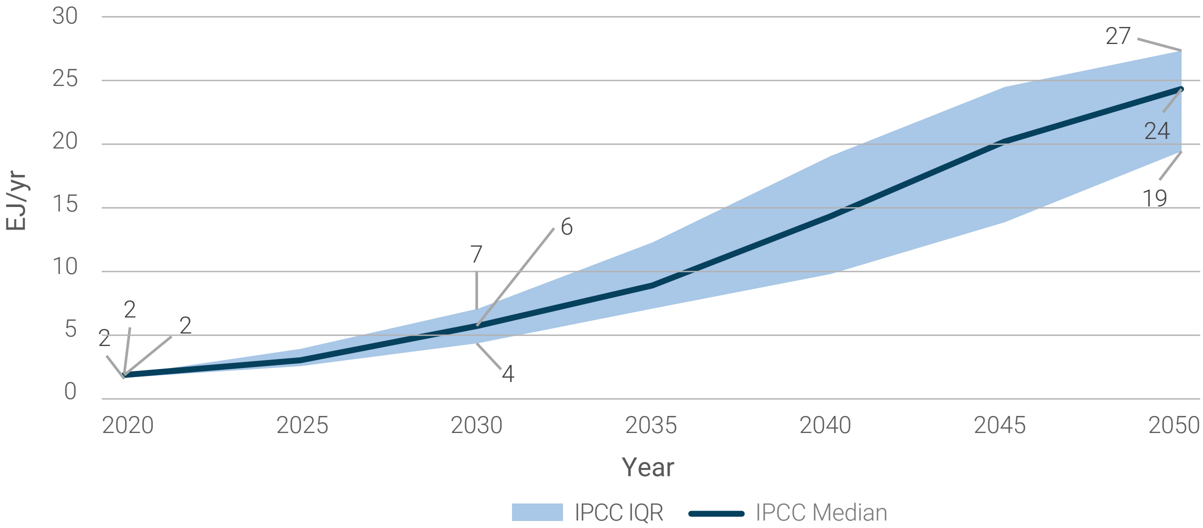
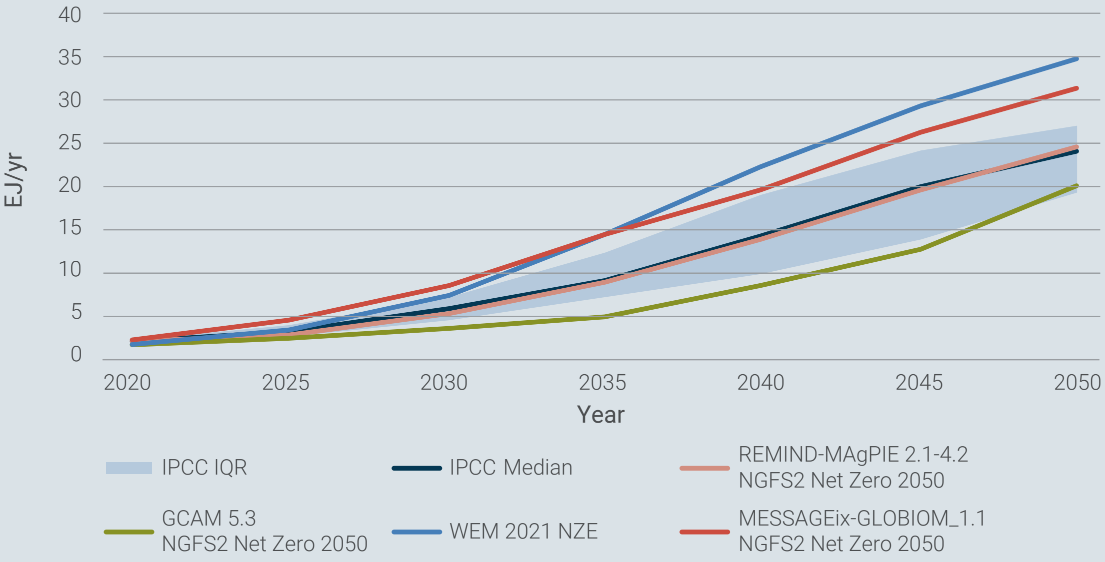
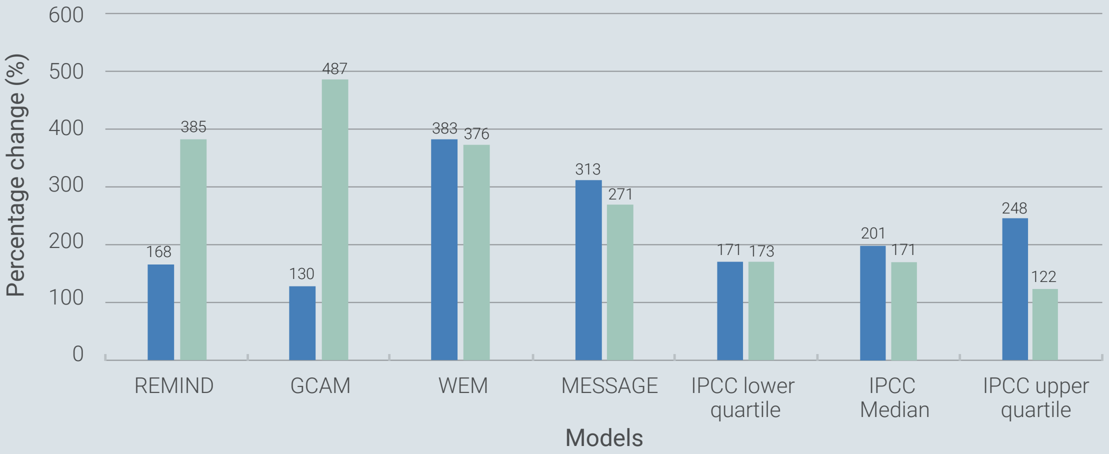


Figure 46: Global final energy generated from electricity for the transportation sector in the IPCC-assessed 1.5°C scenarios with no or limited overshoot

Box 21: (a) Final energy generated from electricity for the transportation sector shown in IEA and the NGFS net-zero scenarios compared to the IPCC-assessed 1.5˚C scenarios with no or limited overshoot, (b) Percentage change during 2020–2030 and 2030–2050 of final energy generated from electricity for the transportation sector reported by different models

All NGFS scenarios shown are Net Zero 2050.





The MESSAGE and the IEA NZE scenarios show the highest increase in final energy generated from electricity for the transportation sector, greater than the upper quartile of the IPCC-assessed scenario dataset. The IEA NZE scenario's increased rate for electrification from 2020 to 2050 is almost double that of the median rate of the scenario dataset. Final energy generated from electricity for the transportation sector shown in REMIND is similar to the median of the IPCC-assessed scenario dataset. GCAM reports the lowest values for final energy generated from electricity, falling below the lower quartile of the IPCC-assessed scenario database from 2025 until 2050 (on average 0.79 EJ/yr lower).

GCAM and REMIND report a substantial increase in final energy generated from electricity between 2030 to 2050, in comparison to 2020 to 2030. In the REMIND model, final energy generated from electricity increases by 385% from 2030 to 2050. GCAM reports highest percentage increase of 487% from 2030 to 2050, which is more than double the median percentage increase reported by the scenarios during the same period. The IEA NZE and MESSAGE scenarios both show similar percentage increases between 2020–2030 and 2030–2050.

Data source: AR6 scenario explorer

A major determinant of the share of EVs in the global market will be the cost of EV batteries. From 2010 to 2020, the costs of EV batteries decreased by 90% and are projected to further decline by half during this decade. In light of the current trend in cost decline, ICCT estimates that the upfront cost of battery-electric passenger cars will meet the price of internal-combustion engine (ICE) vehicles within this decade and may eventually become cheaper (ICCT, 2021). The energy density of batteries for EVs will also need to continue to rise to ensure that EVs can travel further distances for the same battery size. High-performing battery cells can now reach the energy density of 300 Watt-hour per kilogram (Wh/kg), a rise from 100–150 Wh/kg a decade ago (IEA, 2022e).[49] It will also be essential to reduce the need for critical metals to expand EV supply as supply chain constraints of semiconductors and lithium processing can slow down the growth of the EV market (IEA, 2022f).

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[49] Some of the latest battery technologies have claimed to reach an energy density of 500 Wh/kg.

Concerns of EVs expansion

However, the expansion of EVs also creates environmental and human rights concerns. Lithium-ion batteries common in EVs rely on various critical minerals like lithium, nickel, manganese, and cobalt. However, some lithium and cobalt mines have been accused of using child labour and abusing indigenous rights (Business of Human Rights Resource Center, n.d.). Current lithium mining practices also harm the environment as the extraction of lithium requires large amounts of water. The lithium mining process also causes water, soil and air pollution as toxic chemicals used in mining, like hydrochloric acid, leach from evaporation pools and contaminate the surroundings (Institute for Energy, 2020). With the rapid expansion of EVs, growing battery waste is an urgent challenge to address as current battery chemistries complicate efforts to recycle. Batteries may differ in their chemistry and construction, which also makes it difficult to develop a streamlined recycling system. Therefore, at present it is cheaper for battery producers to use newly mined metals rather than recycled materials (Science, 2021). This supply chain will need to grow significantly more circular in the future. Some countries have begun developing recycling plans for batteries.

Hydrogen fuel cells

Along with vehicles being powered by electricity stored in batteries, heavy duty EVs can also be powered by hydrogen fuel cells that produce electricity through chemical reactions between hydrogen and oxygen. Hydrogen fuel cells have a greater energy storage density than lithium-ion batteries, which means they can cover a greater range. However, there are technical challenges to powering EVs with fuel cells, especially the production of 'clean' hydrogen and the utilisation of hydrogen as an energy source (Jones and Nielson, 2021).

6.2.2 Energy efficiency

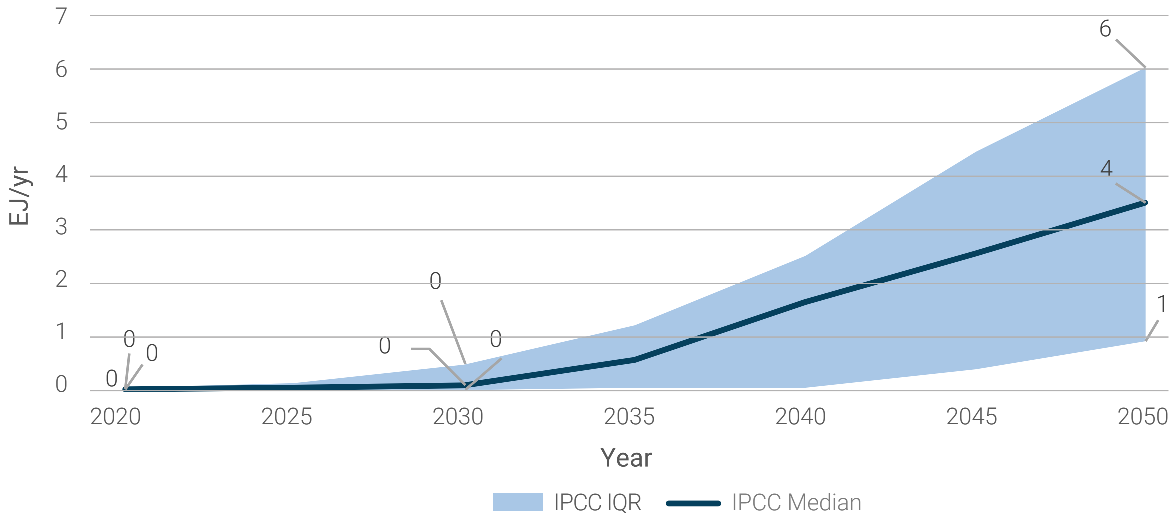
While the transition to EVs unfolds, improved efficiency and fuel standards for remaining ICE vehicles will cut emissions. If such vehicles are designed to be more energy efficient, they could provide the same amount of energy services (such as vehicle mileage) using less fuel, which can help reduce CO_2 emissions. It is estimated that 38Gt of CO_2 emissions could be saved were ICE vehicles to be produced to stricter efficiency standards (ICCT, 2021).

In 2021, the fuel consumption of cars and vans was estimated to be 6.7 litres gasoline-equivalent per 100 kilometres (LGE/100 km). In the past, improvements in engine, powertrain, and vehicle technology have led to improvements in fuel efficiency. Yet improvement in fuel efficiency has slowed down over recent years. This is partly attributed to the increase in vehicle size as well as to the slower adoption of more fuel efficient powertrains (IEA, 2022g). From 2017 and 2019, the average global fuel consumption improved only 0.9%, compared to 2.6% annually from 2010 to 2015. According to the IEA, global average fuel consumption of new light-duty vehicles in 2030 will need to be twice what is was in 2020. Along with electrification, fuel efficiency can be driven by hybridisation[50] and light weighting[51] for heavy trucks, new airframes[52] and engine designs in aircrafts, and slow steaming[53] and wind assistance technologies[54] in ships (IEA, 2021d).

6.2.3 Alternative fuels

A number of segments of the transport sector will remain hard to electrify. Notable examples here include heavy-duty vehicles, shipping, and aviation. As such, alternative fuel types such as hydrogen and biofuel will need to be scaled up. Potential alternative fuels to traditional fossil fuels for the transport sector include biofuels with high-energy density, low-emission hydrogen, and synthetic and e-fuels. The production of sustainable fuels is expected to increase to 46 Mt by 2025 with sufficient investments (McKinsey, 2022a).

The IPCC-assessed 1.5°C scenarios with no or limited overshoot project energy-related hydrogen use by the transport sector to increase from almost nothing in 2020 to 3.6 EJ/yr (0.9 EJ/yr–6.1 EJ/yr) in 2050. Similarly, the scenarios report an increase in biofuel energy consumed by passenger and freight vehicles from 1.3 EJ/yr (1.2–4 EJ/yr) in 2020 to 13 EJ/yr (10 EJ/yr–16 EJ/yr) by 2050.



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50 Hybrid electric architecture of heavy trucks using ICEs in conjunction with an electric motor.

51 Building trucks that are less heavy.

52 Changes to the basic structure of an airplane, such as wings.

53 Reducing travel speed to reduce fuel consumption (Degiuli et al., 2021).

54 Use of wind capture devices to reduce fuel consumption. These can be retrofitted into existing ships (International Windship Association, n.d.).

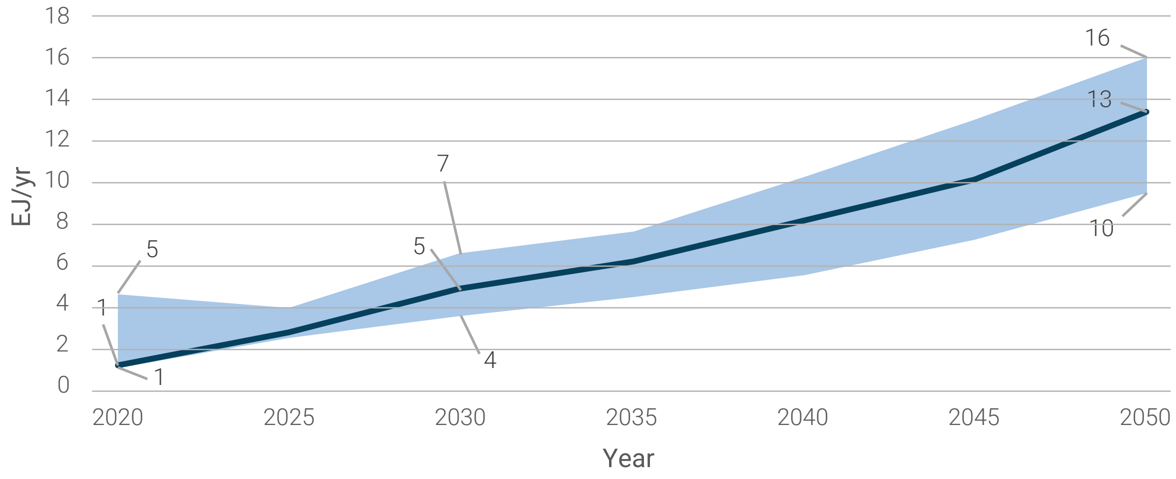
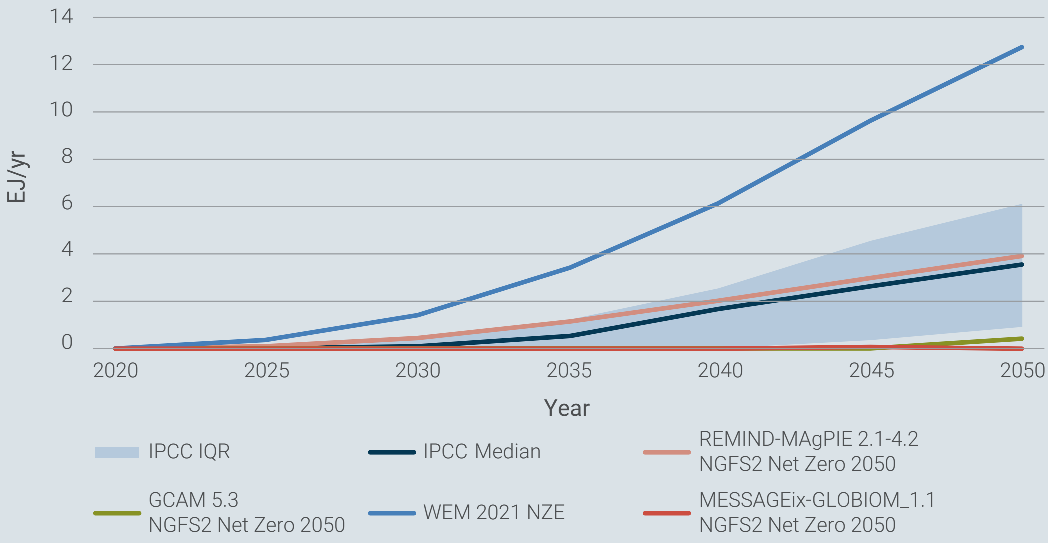


Figure 47: Global final energy consumption by the transportation sector of **(a)** hydrogen **(b)** biofuels in 1.5°C pathways with no or limited overshoot from 2020 to 2050

- Alternative fuel types will vary by sub-sector, including:
- Road vehicles: Hydrogen fuel cells are being seen as an emerging option as an energy source for land-based transport, such as heavy-duty vehicles, which may be challenging to electrify due to battery limitations (IPCC, 2022h).
- Aviation: Hydrogen power, biofuels, and other sustainable aviation fuels (SAFs) (IEA, 2022h).
- Shipping: Hydrogen, ammonia, biofuels, and other synthetic fuels are potential alternatives (IEA, 2022h).

Box 22: (a) Final energy generated from hydrogen for the transportation sector shown in the IEA and NGFS net-zero scenarios compared to the IPCC-assessed 1.5°C scenarios with no or limited overshoot

All NGFS scenarios shown are Net Zero 2050.

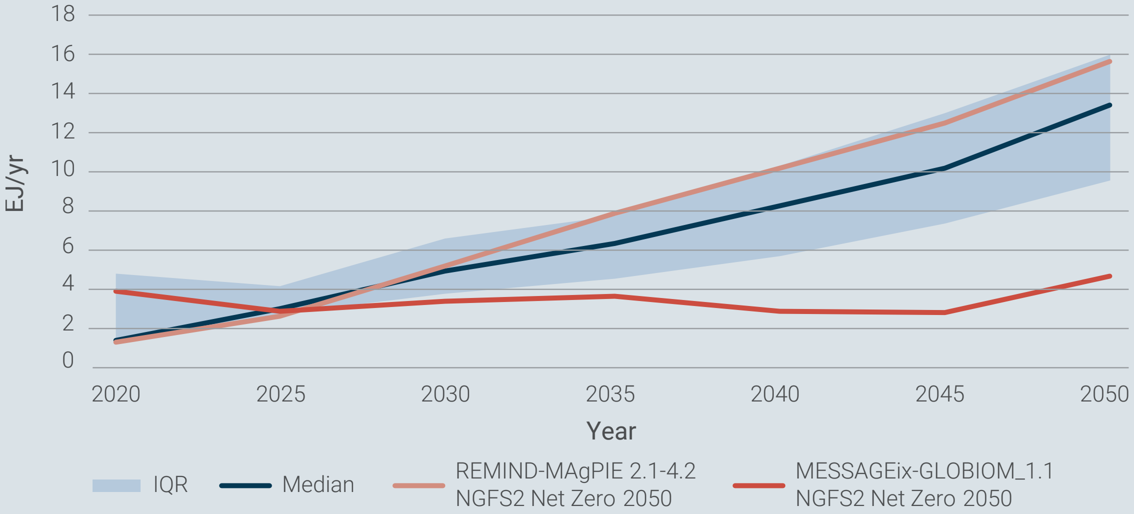


The IEA NZE scenario shows substantially higher levels of final energy generated from hydrogen for the transportation sector from 2025 to 2050, in comparison to the IPCC-assessed scenario dataset, including the NGFS net-zero pathways of REMIND, GCAM, and MESSAGE. In 2050, final energy generated from hydrogen shown in the IEA NZE scenario is 3.6 times the IPCC median level. REMIND reports similar levels of final energy generated from hydrogen as the median of the IPCC-assessed scenario dataset. Between 2020 and 2045, MESSAGE and GCAM reports near zero levels of final energy from hydrogen. GCAM reports a slight increase in 2050 but remains lower than the lower quartile of the IPCC-assessed scenario dataset.

Data source: AR6 scenario explorer

Box 23: Final energy generated from bioenergy for the transportation sector shown in the IEA and NGFS net-zero scenarios compared to the IPCC-assessed 1.5˚C scenarios with no or limited overshoot

All NGFS scenarios shown are Net Zero 2050.



MESSAGE shows low levels of final energy generated from bioenergy, reporting less than the lower quartile of the IPCC-assess scenario dataset from 2025 to 2050. In comparison, REMIND shows higher levels of final energy generated from bioenergy, reporting similar values to the upper quartile of the IPCC-assess scenario dataset from 2035 to 2050.

Data source: AR6 scenario explorer

6.2.4 Strategies and challenges for decarbonisation

Strategies for decarbonising the transport sector (ICCT, 2021; Brookings, 2020; UK Government, 2021; UNEP, n.d.):

- Electrification across the sector, especially for smaller vehicles and vehicles that travel short distances with a lighter load; a shift from ICE vehicles to EVs.
- Improved performance of batteries used in EVs.
- Development of fast charging infrastructure across countries: charging infrastructure for heavy vehicles will need grid upgrades to include clean energy sources; charging stations will need to be available for long-distance travel.
- Stringent standards for improving energy efficiency of ICE vehicles.
- Encourage the buying of used EVs.
- The powering of heavy-duty EVs with hydrogen fuel cells by utilising clean hydrogen as an energy source.
- Transition away from fossil fuels and the adoption of alternative fuels, such as sustainable biofuels, e-fuels, and hydrogen.
- Technology-based improvements of aviation and shipping to improve fuel efficiency.
- Improved designing of cities to reduce the need for transportation.
- Increased cycling and walking networks within cities.
- Improved accessibility and infrastructure of public transportation.
- Expansion of the capacity of rail networks to meet increasing passenger and freight use as demand shifts from air to rail travel.
- Expansion of the capacity of rail networks to meet increasing passenger and freight use as demand shifts from air to rail travel.
- Lifestyle changes such as flexible working arrangements and avoiding travel by air where possible.

Challenges for decarbonising the transport sector (Clean Air Task Force, 2022; Maritime Executive, 2021; OECD, 2020):

- Human rights and environmental concerns linked to EVs.
- Availability of charging infrastructure can vary by area.
- EVs have higher upfront costs than ICE vehicles, while costs will need to decrease in order to become affordable for many consumers, new ways of financing EVs are also needed for consumers.
- Supply chain limitations of critical minerals needed to produce batteries can slow down the expansion of EVs.
- The use of biofuels from waste as an alternative energy source for sub-sectors such as aviation has not yet been proven as viable at the commercial scale needed to meet demand.
- Use of a biofuel at a massive scale can have land use impacts, such as increasing food insecurity and creating risks for biodiversity.
- Transporting alternative fuels, such as biofuels, can be costlier than transporting fossil fuels.
- Significant investments are needed in sustainable synthetic fuels and hydrogen to reduce costs.

- Net-zero technologies that can be applied at a large scale to decarbonise hard-to-abate sub-sectors do not exist yet.
- Need for large capacity of fuel storage for long-distance travel.
- Providing public transport in areas with a low population density can be costly.
- Designing cities with greater cycling and walking paths may require repurposing existing infrastructure.
- Areas with a high dependency on cars will require a change in societal behaviour to shift from cars to alternative modes of transport, such as public transport, cycling and walking.

Table 22: Recommended scenario variables to use for assessing decarbonisation of the transportation sector in pathways (AR6 scenario explorer)

Variable	Unit	Definition	Additional information
Final Energy	EJ/yr	Final energy consumption. Depending on the final energy variable chosen, this can exclude the use or transmission of feedstock or distribution losses (*adapted by the author*)	Further granular variables are available for sub-sectors, including aviation, freight, rail, road, and other forms of passenger transport.

Questions for readers:

- What alternatives to carbon-intensive modes of transport do you identify as opportunities for your institution?
- In your opinion, are the decarbonisation pathways for transportation shown in scenarios feasible for scenario analysis?
- Which methods have you identified as realistic for decarbonisation?
- What are the significant differences in modelling assumptions between the IPCC-assessed scenarios and modelling assumptions made in-house at your institution?
- What aspects of the transportation pathways would you change to make them more applicable for use?

6.3 Agriculture

Estimates suggest that food production will need to increase by 60% to feed the global population by 2050, with future population growth and rising income being the key drivers (Dijk *et al.*, 2021). However, based on current trends, the increase in demand for specific food types will comprise a more important factor than the increase in the total quantity of food produced. For example, increased economic growth and rising incomes can lead to rising demand in developing and emerging markets for improved nutrition, including meat and dairy products. Similarly, urbanisation will also impact food demand with a rise in consumption of perishable goods due to improved infrastructure. However, urbanisation and the rising use of biofuels will also compete with food production for land (Michigan State University, 2018). The excess need for nutrient-rich food will have to be offset with a decrease in meat consumption.

1.5°C scenarios with no or limited overshoot report an increase in demand for per capita calories from 2,946 kcal per capita per day (kcal/cap/day) (median) to 3,025 (kcal/cap/day) (median) from 2020 to 2050. However, traditional carbon-intensive food production practices will need to be rethought if the growing demand for food is to be met while also decreasing CO_2 emissions. Primary sources of CO_2 emissions from the agriculture sector come from the cutting down of forests to expand farmland, the use of fossil fuels on farms, manure management, and the burning of crops (UN, n.d.). Even if all emissions from fossil fuels were eliminated at once, emissions from the global food system would make limiting warming to 1.5°C extremely difficult (Clark *et al.*, 2020).

To reduce CO_2 emissions to limit warming to 1.5°C, diets will need to shift towards less carbon-intensive sources, such as diets that are plant-rich and protein-rich with less saturated fat and cholesterol. Animal-based foods will need to be consumed less (Ivanovich, 2023; UN, n.d.). Alternative proteins like plant-based meat, cultivated meat, and dairy substitutes are growing in demand and are attracting technological innovation and investments. For remaining animal products, new methods will need to be introduced (UN, n.d.). Along with changing diets, reductions in food waste are necessary to decarbonise the sector, as about 17% of all food available globally is wasted. According to the UN's Food and Agriculture Organisation, if food waste were a country, it would be the third largest GHG emitter in the world (FAO, n.d.).

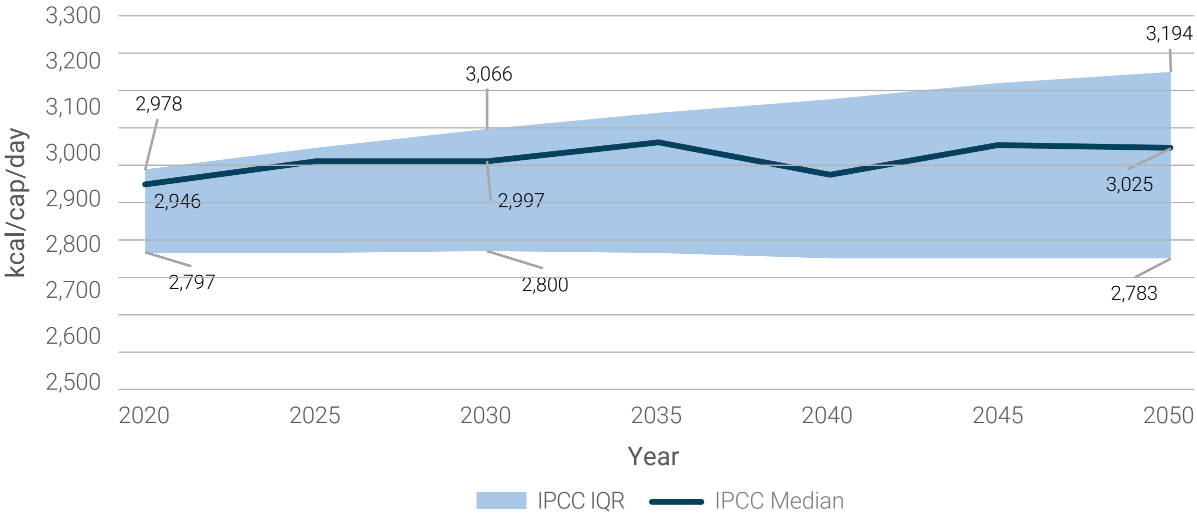


Figure 48: Global per capita calories demanded shown in the IPCC-assessed 1.5°C scenarios with no or limited overshoot

6.3.1 Electrification

Electrification of tractors, cultivators, ploughs, and other machinery involved in agricultural activities will be necessary to reduce demand for fossil fuels from the sector. Machinery accounts for about 43.5% of total energy inputs in farming (Soofi *et al.*, 2022). In the future, such machinery could be powered by hydrogen. Older machinery that is less efficient could be used less. Minimum tillage practices can reduce emissions through decreased use of fossil fuels to prepare fields for cultivation. Such practices can also increase carbon sequestration in soil. Maintaining temperatures such as in milk tanks also requires large amounts of energy. Traditional infrastructure relies on fossil fuels as most glasshouses use gas-fired boilers. Such infrastructure can be replaced with low-carbon and renewable alternatives (Soofi *et al.*, 2022; WWF, 2021).

6.3.2 Bioenergy

Bioenergy is a renewable energy source that can be used in all sectors. It can be operated using existing transmission and distribution systems as well as end-user equipment (IEA, 2021). Biodiesel from agriculture products is less carbon-intensive than fossil fuels. Agriculture biomass as an energy source is typically prevalent in developing countries due to its availability. Globally, about 30% of household energy is powered from agricultural biomass for use in heating, cooking, and lighting (Saleem, 2022).

However, there are trade-offs to using bioenergy, especially in relation to conflicts with other land uses, such as food production and the conservation of biodiversity. Sustainable bioenergy also comprises a crucial alternative to fossil fuels for the agriculture sector. Therefore, in 1.5°C scenarios with no or limited overshoot, the shift of bioenergy to sustainable sources is important. Similarly, a change away from traditional solid biomass for cooking is necessary. Shifting bioenergy sources from food crops to advanced short-rotation wood crops from marginal lands and pasture lands could sequester about 190 Mt of CO_2 by 2050. This would reduce the sector's CO_2 emissions by 140 Mt relative to 2021 levels (IEA, 2021e).

Capacity addition of electricity from biomass is reported with uncertainty in 1.5°C scenarios with no or limited overshoot pathways assessed in AR6, with initial median annual capacity addition remaining the same in 2020 and 2030 (3.5 GW/yr) and decreasing to 1.4 GW/yr in 2050. Annual capacity additions of electricity from biomass suggest that climate models are relatively dependent on biofuels, especially by 2030.

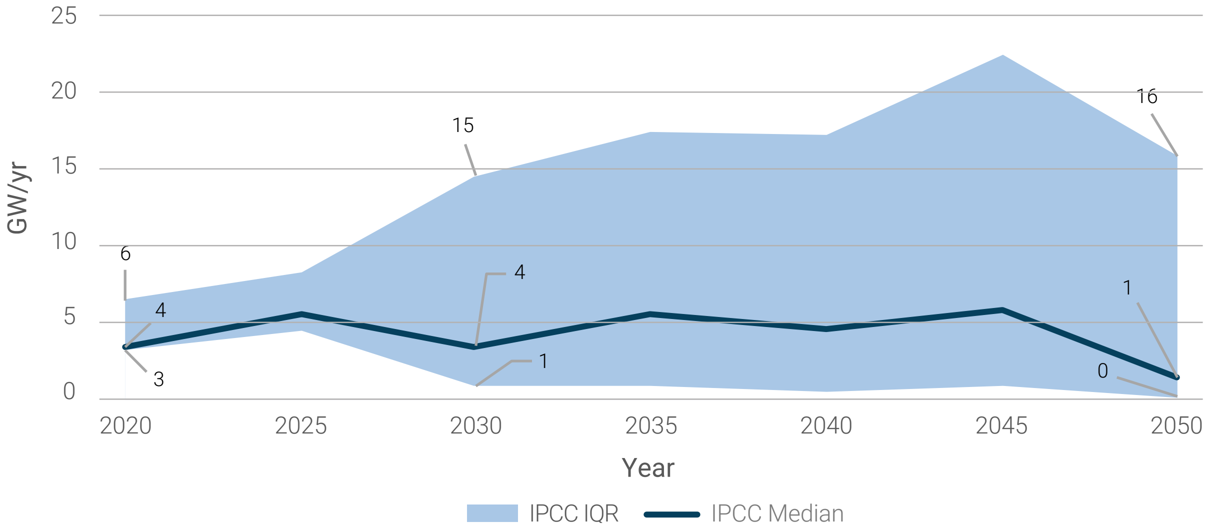
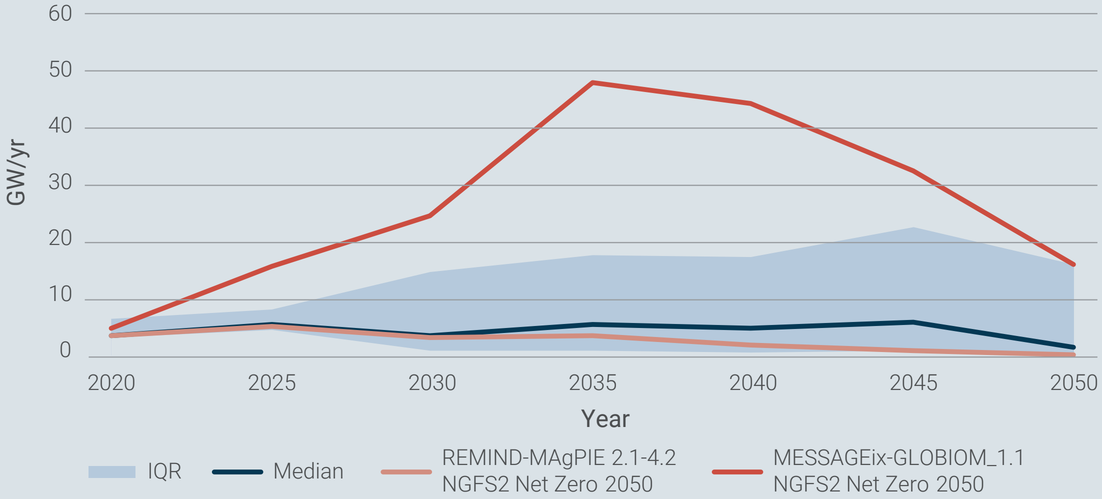


Figure 49: Global additional capacity of electricity from biomass in the IPCC-assessed 1.5°C scenarios with no or limited overshoot

Box 24: Global additional capacity of electricity from biomass in the NGFS net-zero scenarios compared to the IPCC-assessed 1.5°C scenarios with no or limited overshoot



GCAM reports much higher values of additional capacity of electricity from biomass compared to the upper quartile of the IPCC-assessed scenario dataset and the REMIND model. Due to hard-to-abate residual emissions, like non-CO_2 emissions, in GCAM, the model requires negative emissions through BECCS to limit warming. To constrain the application of BECCS, a ceiling is implemented in the model for biomass availability but is still higher than other models. In comparison, REMIND reports lower levels of additional capacity of electricity from biomass, closer to the lower quartile of the IPCC-assessed scenario dataset.

Data source: AR6 scenario explorer

6.3.3 Strategies and challenges for decarbonisation

Strategies for decarbonising the agriculture sector (c2es, 2018; McKinsey, 2023; Rose and Gabrielli, 2023; UNEP, n.d.):

- Electrification of on-farm energy use.
- Production of electricity directly on farmlands; installations of wind turbines and solar PV panels are becoming common on agricultural lands ('agrivoltaics' is the use of land for both solar panels and agriculture).
- Use of ethanol, biodiesel, and biogas as alternatives to fossil fuel use.
- Replacement of traditional tractors with smaller and light electric machinery can improve energy efficiency due to improved precision and automation technology.
- Digitalisation of agricultural practices, such as with sensors and artificial intelligence, can improve energy and resource efficiency.
- Conservation tillage, organic agriculture, and crop rotation can decrease energy use and reduce the use of fertilisers and pesticides.
- Adoption of smart irrigation technologies, including soil moisture sensors and controllers, can boost irrigation efficiency and reduce energy consumption.
- Use of CCS can help decarbonise fertilisation production processes.

- Innovative technologies and adoption of processes can reduce carbon emissions from fertilisation production processes; example include electrochemical synthesis, plasma-activated processes, biochemical processes, water electrolysis by less fossil-fuel free electricity, electrified heat pumps, and biological nitrogen fixation.
- Greater efficiency of fertiliser supply chains.
- Improved feed quality and livestock management, including feed additives to livestock diets and animal breeding to utilise feed more efficiently; gene editing techniques are being explored.
- Reduction in food loss and food waste by better connecting supply chains, improving preservation of food, and changing purchasing behaviours.
- Shift in dietary habits by increasing consumption of alternative proteins and locally produced food.
- Adoption of nature-based solutions, such as forest restoration and improved soil management for carbon sequestration.

Challenges for decarbonising the agriculture sector (European Environment Agency 2022; Rose and Gabrielli, 2023):

- Energy efficient technological alternatives require higher initial investments and are costlier than traditional fossil-fuel based technologies.
- Processes and technologies to produce net-zero fertilisers require lots of investments and have high operating costs in comparison to traditional production methods.
- Certain decarbonisation methods can have environmental trade-offs, such as exacerbating land and water scarcity; for example, the use of water electrolysis to produce net-zero ammonia requires 25 times more energy, land, and water than traditional production.
- Knowledge gaps in animal health and quality can impact mitigation strategies for reducing emissions from livestock.
- High capital costs for improving infrastructure, especially for smaller farms.
- Limited awareness of agricultural producers on sources of emissions and their impact.
- Policies on production maximising can conflict with mitigation incentives.

Table 23: Recommended scenario variables to use for assessing the decarbonisation of the agriculture sector in pathways (AR6 scenario explorer)

Variable	Unit	Definition	Additional information
Agriculture demand	Million tonnes dry matter per year (million t DM/yr)	Total demand for food, non-food, and feed products (crops and livestock) and bioenergy crops (1st & 2nd generation).	Further variables available for crops and livestock.
Agriculture production	million t DM/yr	Production of agriculture for bioenergy or non-energy uses (adapted by authors).	Further variables available for energy and non-energy.
Capacity Additions	GW/yr	Additional capacity added annually.	Variable available for capacity addition of biomass.
Food demand	kcal/cap/day	All food demand in calories.	Further granular variables are available for crop-related and livestock-related food demand in calories.

Questions for readers:

- What alternatives to carbon-intensive agricultural practices and diets do you identify as opportunities for your institution?
- In your opinion, are the decarbonisation pathways for agriculture shown in scenarios feasible for scenario analysis?
- Which methods have you identified as realistic for decarbonisation?
- What are the significant differences in modelling assumptions between the IPCC-assessed scenarios and modelling assumptions made in-house at your institution?
- What aspects of the agriculture pathways would you change to make them more applicable for use?

6.4 Industrials

Most direct emissions from the industrial sector come from the consumption of fossil fuels for energy. Emissions are produced by burning fuel for power or heat in chemical reactions or leaks from industrial processes. Many activities in the sector are perceived as difficult to decarbonise and will require significant advancement in infrastructure and technological innovation, however more efficient standard industrial equipment in widespread usage such as motors, pumps, lighting, heating systems and power transformers can all be more easily upgraded. Efforts to reduce CO_2 emissions will include switching from fossil fuels, improving efficiency, and capturing CO_2 emissions (American Progress, 2022). The decarbonisation of three sub-sectors—steel, cement and ammonia—is explored below.

6.4.1 Steel

1.5°C scenarios with no or limited overshoot show a massive decrease of 69% (median) in the carbon intensity of steel production from 2020 to 2030 and 84% (median) by 2050. To do so, traditional fossil fuel-reliant production processes will need to shift towards alternatives. The source of electricity and fossil fuel-based feedstocks will need to be changed. New methods that are less carbon-intensive will need to be implemented to produce high heat (American Progress, 2022). Conventional steel is delivered through two main processes; blast furnace or basic oxygen furnace, and electric arc furnace (EAF). Electrification of the steelmaking process is crucial for decarbonising the steel sub-sector. One way to do this would be the continued scale-up of EAF use during steel production. Steel produced by EAF can reduce carbon intensity by up to 75% compared to traditional blast furnace steelmakers (Wright, 2022). Scrap-based EAF production using 100% renewable electricity is a potential solution for low-emission steel (World Economic Forum, 2022c). Climate Action 100+ estimates that an annual emissions could be reduced by 51% compared to a business-as-usual scenario were the proportion of steel made from scrap-EAF to be increased from 23% to 60% by 2050 (Climate Action 100, 2021). Electricity is needed to reduce and melt iron ore, which, if produced using renewable energy, could eliminate the steps in crude steelmaking that require fossil fuels. Green hydrogen and direct reduced iron (DRI) and gas-based hydrogen will need to be utilised in the production process to reduce the emission intensity of steel. In the iron-reducing process of DRI, green hydrogen can replace natural gas. Using green hydrogen will substantially reduce the emissions produced from the steelmaking process, apart from process emissions and potential hydrogen leaks (American Progress, 2022). Electricity and hydrogen produced from renewable electricity can reduce the emission intensity of steel by 95% (Climate Action 100, 2021). For CO_2 emissions that cannot be abated, CCS will need to be deployed at steelmaking plants to capture CO_2 emissions.

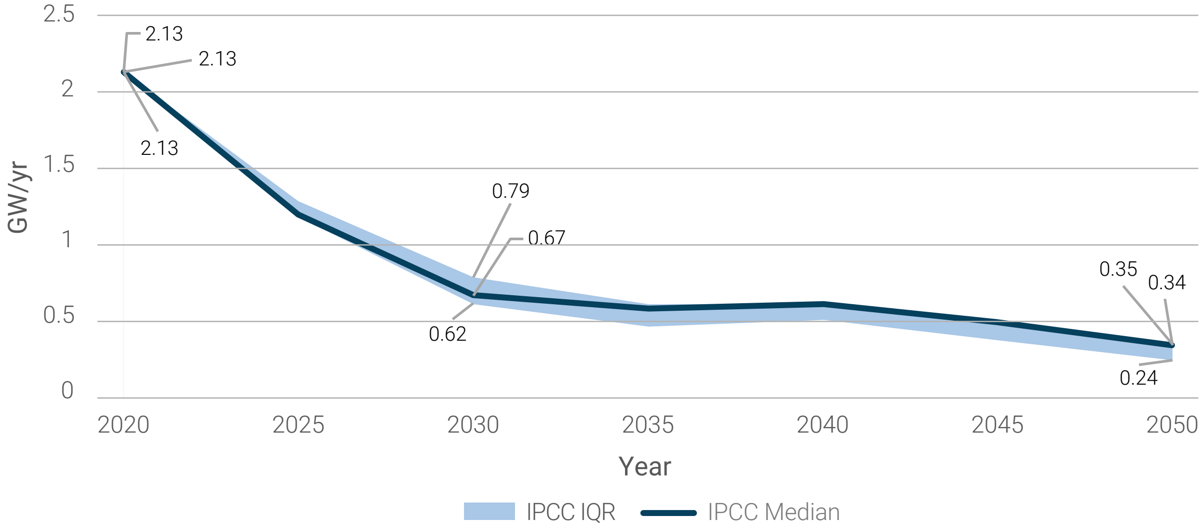


Figure 50: Global carbon intensity of steel[55] in the IPCC-assessed 1.5°C scenarios with no or limited overshoot

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[55] Only six scenarios provide data for this variable. All six scenarios are modelled using the REMIND-MAgPIE model. The REMIND-MaGPIE model, developed by the Potsdam Institute for Climate Impact Research (PIK), is an integrated assessment model and is used by the NGFS to generate its climate scenarios.

According to the latest data provided by the World Steel Association, global average carbon intensity for crude steel in 2023 reached a value of 1.92 $MtCO_2eq/Mt$. To align with the IPCC-assessed 1.5°C scenarios with no or limited overshoot, a reduction of 37.5% in real carbon intensity is necessary by 2025. Carbon intensity will need to decrease even more significantly and by 65.1% this decade to be in line with the median steel carbon intensity reported in the scenarios for 2030 (Table 24). Accomplishing this ambitious target will demand concerted efforts from all steel-producing nations, ranging from those exhibiting the lowest carbon intensity, such as Italy, to those with the highest, such as Ukraine (Figure 51). These nations will need to collectively embrace and implement measures geared towards decarbonising the sub-sector.

Table 24: Current global average steel carbon intensity compared to the 1.5°C scenarios with no or limited overshoot

Real average global CO_2 intensity of crude steel cast in 2023 ($MtCO_2eq/Mt$) (World Steel Association, 2024)	Median CO_2 intensity reported in 1.5°C scenarios with no or limited overshoot in 2025 ($MtCO_2eq/Mt$)	Percentage difference between 2022 and 2025 (%)	Median CO_2 intensity reported in 1.5°C scenarios with no or limited overshoot in 2030 ($MtCO_2eq/Mt$)	Percentage difference between 2022 and 2030 (%)
1.92	1.20	-37.5	0.67	-65.1

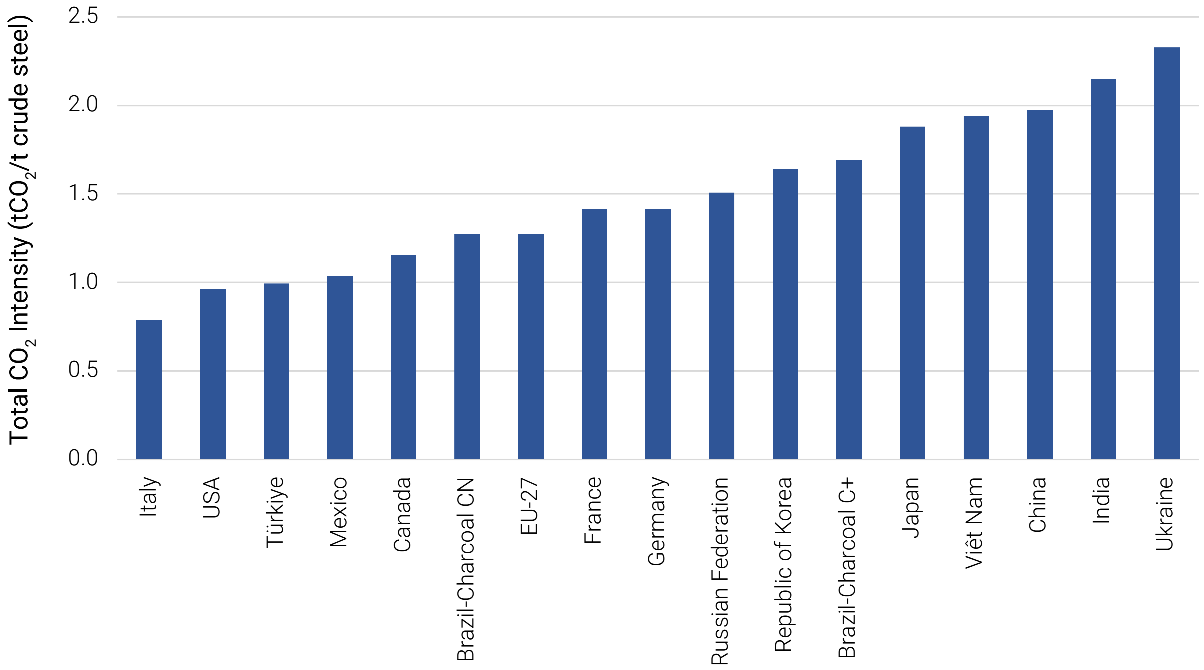

Figure 51: Carbon intensity of steel production by country in 2019 (Global Efficiency Intelligence, 2022)

6.4.2 Cement

1.5°C scenarios with no or limited overshoot show carbon intensity of cement production rapidly decreasing from 1.07 $MtCO_2eq$ /Mt in 2020 to 0.71 $MtCO_2eq$/Mt in 2030 (a decrease of 34%) and to 0.2 $MtCO_2eq$ /Mt in 2050 (a decrease of 81% (Figure 52)). Such a decrease in carbon intensity will require huge changes to how traditional cement is produced. New methods (such as clinker substitutes), the replacement of fossil fuels, carbon capture, electrification, and hydrogen will need to be integrated in order to decarbonise the sub-sector (McKinsey, 2022b). The use of clinker will need to decrease, on the one hand, while alternatives will need to be adopted, on the other. Substances like blast-furnace slag and fly ash can substitute a portion of clinker. Cement production requires large amounts of heat. This means large amounts of energy are needed for electricity and through a fuel source. The use of electricity for cement production will need to be decarbonised, such as by using renewable energy. Fuel sources will need to be replaced by alternatives like green hydrogen to produce the heat required (American Progress, 2022). A suitable alternative to conventional cement is bio-concrete. Bio-concrete is an innovative building material that contains clay pellets. The material is more durable and environmentally friendly than conventional cement (UNEP FI, 2023).

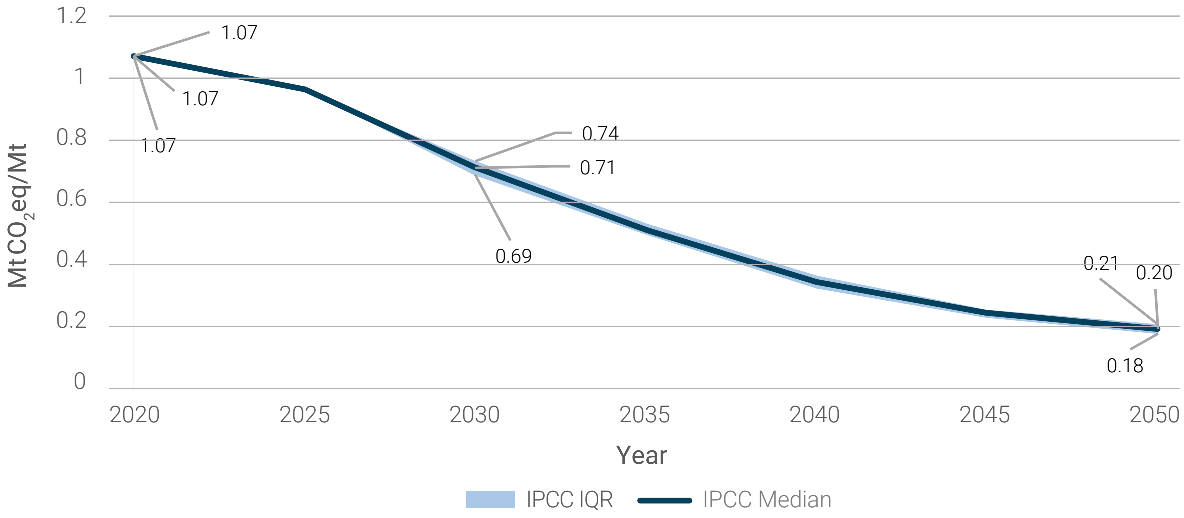

Figure 52: Global carbon intensity of cement production[56] in the IPCC-assessed 1.5°C scenarios with no or limited overshoot

According to the latest data provided by the IEA, global average carbon intensity for cement in 2022 reached a value of 0.58 $MtCO_2eq$ /Mt. This carbon intensity of cement is already 55.2% lower than the median carbon intensity of cement (0.97 $MtCO_2eq$/Mt) reported by the IPCC-assessed 1.5°C scenarios with no or limited overshoot for 2025. However, in the scenarios a steep reduction in carbon intensity of cement occurs after 2025 to reach 0.20 $MtCO_2eq$/Mt (median) in 2030. To be aligned with the scenarios, the global average cement carbon intensity will therefore need to decrease by 65.5% in the next seven years (Table 25). Achieving such an ambitious goal will require the deployment of technologies that are not currently available at a commercial level. It will also

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[56] Only two scenarios provide data for this variable. Both scenarios are modelled using the REMIND-MAgPIE model. The REMIND-MaGPIE model, developed by the Potsdam Institute for Climate Impact Research (PIK), is an integrated assessment model and is used by the NGFS to generate its climate scenarios.

require concerted efforts from key cement producers such as China, India, Vietnam, and the USA (Figure 53). These nations will need to collectively embrace and implement measures geared towards decarbonising the sub-sector.

Table 25: Current global average cement carbon intensity compared to the 1.5°C scenarios with no or limited overshoot

Real average global CO_2 intensity of cement in 2022 ($MtCO_2eq/Mt$) (IEA, n.d.)	Median CO_2 intensity reported in 1.5°C scenarios with no or limited overshoot in 2025 ($MtCO_2eq/Mt$)	Percentage difference between 2022 and 2025 (%)	Median CO_2 intensity reported in 1.5°C scenarios with no or limited overshoot in 2030 ($MtCO_2eq/Mt$)	Percentage difference between 2022 and 2030 (%)
0.58	0.97	67.2	0.20	-65.5

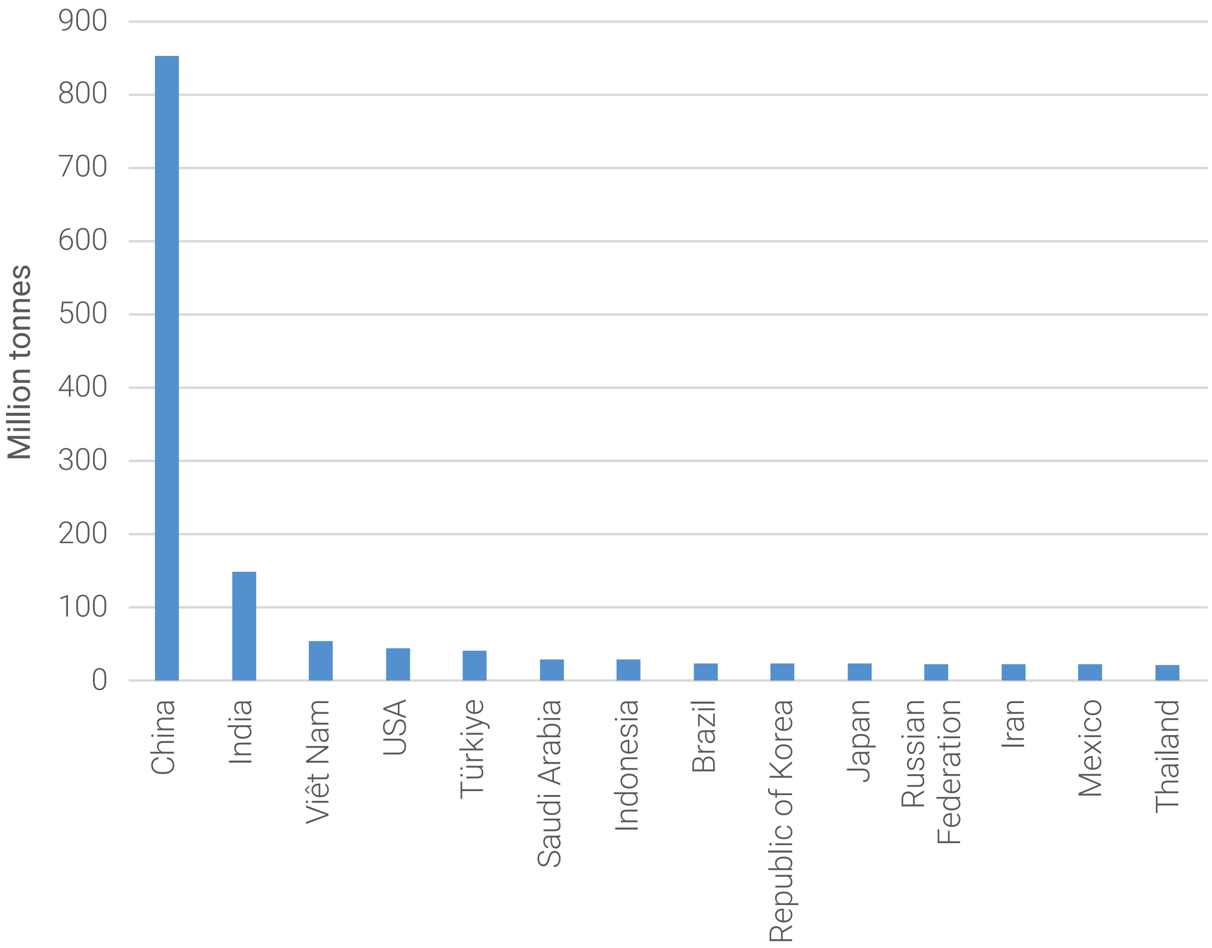

Figure 53: Annual CO_2 emissions from cement production by country in 2022 (Our World in Data, 2022).

6.4.3 Ammonia

1.5°C scenarios show the final energy for ammonia decreasing from 1.2 EJ/yr (median) in 2020 to 0.4 EJ/yr (median) in 2050, a 68% (median) decrease. At 1.4%, the increase in final energy for ammonia between 2020 and 2030 is only slight. This suggests that the decrease in final energy consumption by the ammonia sub-sector occurs after 2030 in the scenarios. Conventional ammonia is produced from a fossil fuel-intensive process called Haber-Bosch. To reduce emissions from the sub-sector, an alternative to conventional ammonia is green ammonia. This involves ammonia being produced using renewable energy. Green ammonia plants have already been installed in a number of countries to produce hydrogen and energy for chemical reactions. Along with the urgent need to tackle emissions from the sector to limit warming to 1.5°C, high fertiliser costs and energy security can drive countries to shift to green ammonia (UNEP FI, 2023).

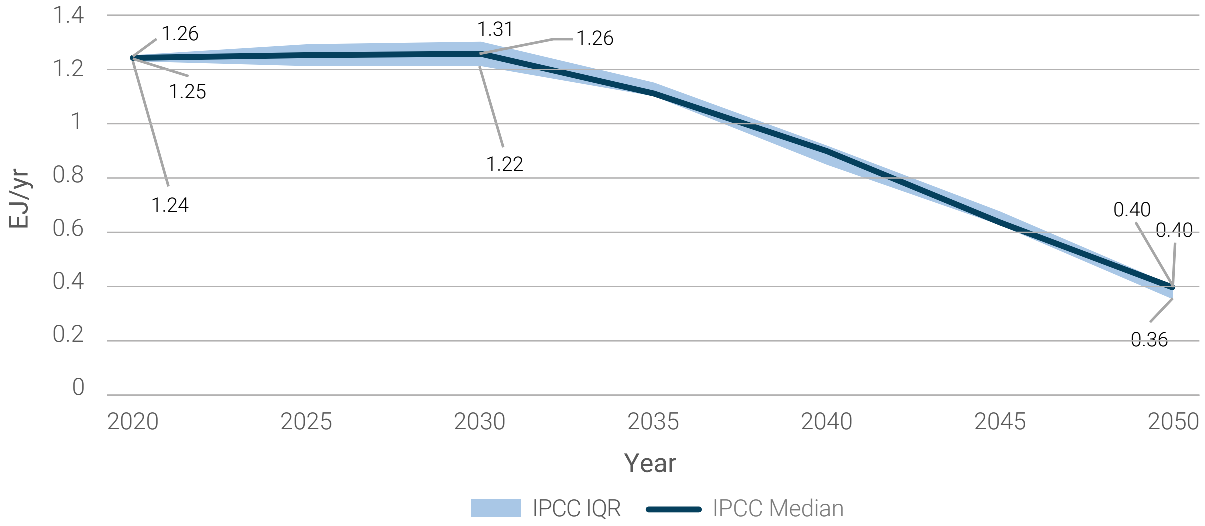

Figure 54: Global final energy consumption by the industrial ammonia gas sub-sector[57] in the IPCC-assessed 1.5°C scenarios with no or limited overshoot

The technology needed to decarbonise industrials is still in its early stages. Substantial technological innovations are required in order to be able to deploy the technology at the commercial scale needed and at costs needed to be competitive with traditional industrial processes.

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[57] Seven scenarios provide data for this variable. All seven scenarios are modelled using the IMAGE 3.2 model, an integrated assessment model developed by Netherlands Environmental Assessment Agency (PBL).

6.4.4 Strategies and challenges for decarbonisation

Strategies for decarbonising the industrials sector (DOE, n.d.; Energy sector Management Assistance Programme, n.d.; UNEP, n.d.)

- Expansion of direct electrification, such as the generation of heat.
- Piloting of innovative decarbonisation technologies such as:
    - Near-zero-carbon hydrogen as a heat source or reduction agent
    - Biomass as an energy source for heat generation
    - Use of solar, thermal, and geothermal technologies for low and medium temperature heat generation.
- Use of CCUS.
- Material efficiency and increase in the circular use of materials.
- Reduction in demand for carbon-intensive products through reuse, remanufacturing, recycling, and the improved utilisation of existing materials.
- Improvement to energy efficiency across the production process by replacing equipment and improving management.
- Reduction in waste during industrial processes.
- Supplementation of carbon-intensive materials with low carbon materials during industrial processes; or example, supplement clinker and other materials with low-carbon binding materials and natural cementitious materials to lower-carbon intensity.

Challenges for decarbonising the industrials sector (US Department of Energy, 2022; EDF, 2020; Muslemani, 2021; McKinsey, 2018):

- Industrial facilities have long lifetimes, between 25–50 years and high capital intensity, thus making it difficult to retire or retrofit carbon-intensive facilities during the timeline needed to limit global warming to 1.5°C.
- Facilities for less carbon-intensive production processes take many years to build and production of the materials can have long lead times.
- Industrial products need to comply with safety regulations and meet a strict quality criteria; with currently available technology, reducing the carbon content of steel, cement, and similar industrial products could impact quality.
- Limited local availability of less carbon-intensive energy sources, innovative technologies, CCS, and infrastructure can hinder decarbonisation.
- Significant initial investment and long-term investment is required for decarbonisation.
- Advanced technology needed to decarbonise the sector is costly, with CCS being one of the lower-cost decarbonisation options.
- Commercial deployment of the technologies are limited and lack business models to support them.
- Though biomass is a financially attractive alternative for fuel and feedstock, sustainably produced biomass is limited globally.

Table 26: Recommended scenario variables to use for assessing decarbonisation of the industrials sector in pathways (AR6 scenario explorer)

Variable	Unit	Definition	Additional information
Final Energy	EJ/yr	Final energy consumption. Depending on the final energy variable chosen, this can exclude the use or transmission of feedstock or distribution losses (*adapted by the author*).	Further granular variables are available for different types of energy sources.
Carbon Intensity	$MtCO_2eq/Mt$	CO_2eq carbon intensity of production	Further variables are available for different industrial processes, such as for cement, chemicals, and steel.

Questions for readers:

- What alternatives to traditional industrial processes do you identify as opportunities for your institution?
- In your opinion, are the decarbonisation pathways for industrials shown in scenarios feasible for scenario analysis?
- Which methods have you identified as realistic for decarbonisation?
- What are the significant differences in modelling assumptions between the IPCC-assessed scenarios and modelling assumptions made in-house at your institution?
- What aspects of the industrial pathways would you change to make them more applicable for use?

6.5 Real estate

As the global population continues to grow, demand for housing and its related energy demand is expected to rise in the coming decades. However, to limit warming to 1.5°C with no or limited overshoot, scenarios show a substantial decrease in energy consumption and fossil fuel use in the buildings sector, with a shift to clean energy. To decarbonise the sector, existing buildings will need to be retrofitted, and new buildings constructed will need to be made net zero. Buildings will need to reduce both their operational[58] and embodied[59] emissions.

Retrofitting existing buildings involves large-scale building alterations to reduce CO_2 emissions. Some common retrofitting strategies include: daylight-based zoning and shading for visual comfort; insulation and openings for thermal comfort and ventilation; efficient lighting systems and controllers; on-site renewable energy sources; optimised building materials; and the optimisation of heating, ventilation, and air conditioning

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[58] Operational carbon footprint is defined as the amount of carbon emissions that are generated directly from building operations.

[59] The embodied carbon footprint is defined as the amount of carbon emissions that are associated with the production of building materials, transport, and construction processes.

(HVAC) systems for energy consumption (Biloria and Abdollahzadeh, 2021). New buildings that are constructed will need to be energy efficient by minimising energy use through the building design.

6.5.1 Electrification and renewable energy

1.5°C scenarios with no or limited overshoot report an increase in electricity consumed in residential buildings from 38% (25%–145%) from 2020 to 2050. Electricity is already used in buildings for appliances, including refrigerators and lighting. However, to reduce the energy consumption of fossil fuels, electricity will need to be integrated into thermal energy services such as heat pumps. Traditional boilers and furnaces are highly carbon-intensive. Therefore, heat pumps comprise an important alternative to conventional boilers to reduce emissions as they are about three times more energy efficient than gas furnaces. To reduce CO_2 emissions generated from energy consumption in the sector, energy sourced from fossil fuels, such as coal and gas, will need to shift to energy produced from renewable sources, such as solar PV. Buildings will also need to be updated to allow for on-site production of energy, such as PVs on the roof, solar water heating, and wind turbines. The IPCC-assessed 1.5°C scenarios with no or limited overshoot report a significant reduction of about 60% (median) in gas consumption for energy in residential buildings from 2020 to 2050 (Figure 56).

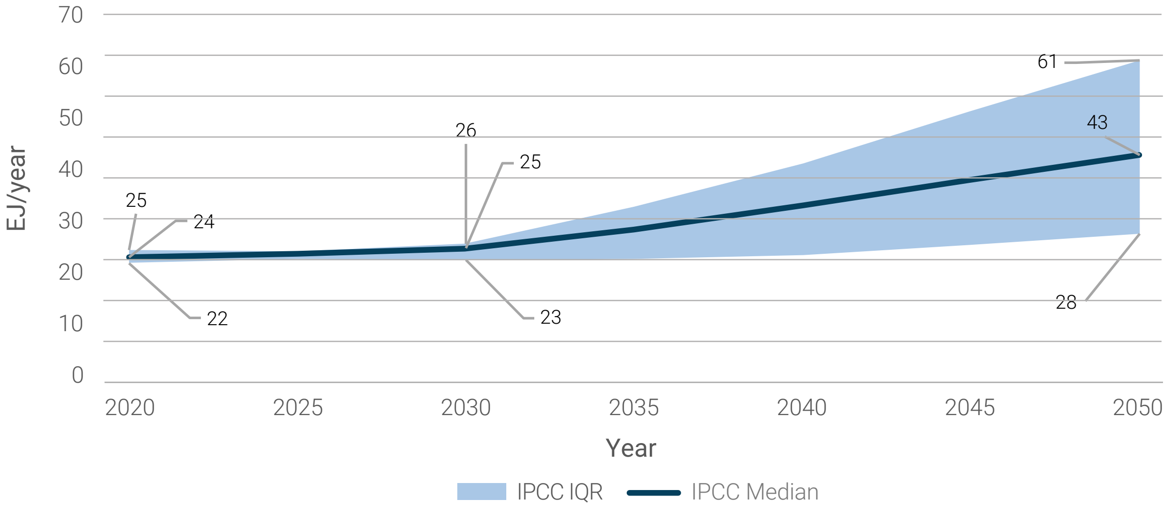
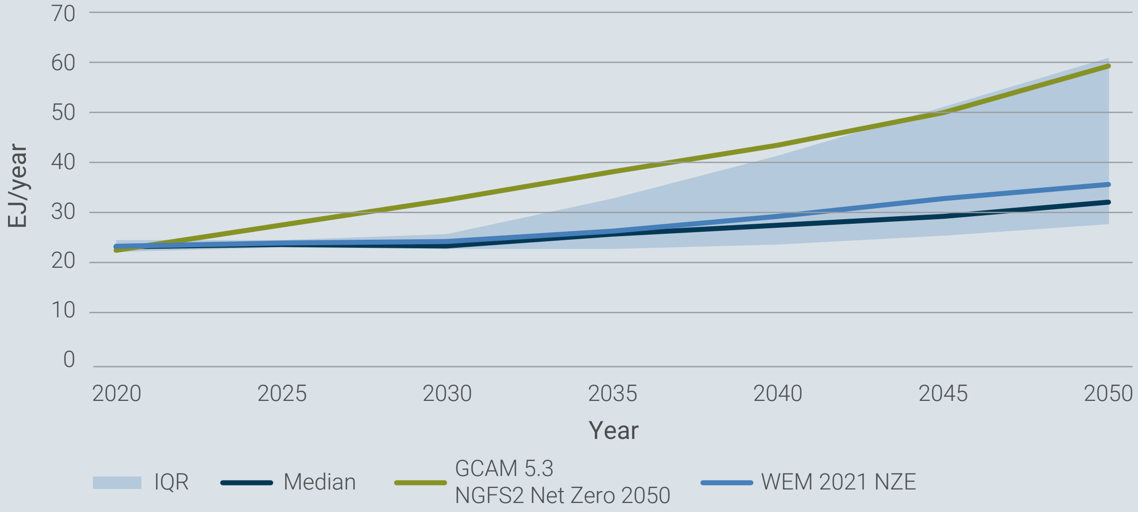


Figure 55: Global final energy consumption of electricity of residential buildings in the IPCC-assessed 1.5°C pathways with no or limited overshoot from 2020 to 2050

Box 25: Final energy consumption of electricity of residential buildings in the IEA and NGFS net-zero scenarios compared to the IPCC-assessed 1.5°C scenarios with no or limited overshoot



GCAM reports a significant increase in the final energy consumption of electricity by residential buildings, showing the final energy levels to be higher than the upper quartile of the IPCC-assessed scenario dataset. In comparison, the IEA NZE scenario reports a smaller rise in final energy, with the values shown to be closer to the median of the IPCC-assessed scenario dataset.

Data source: AR6 scenario explorer

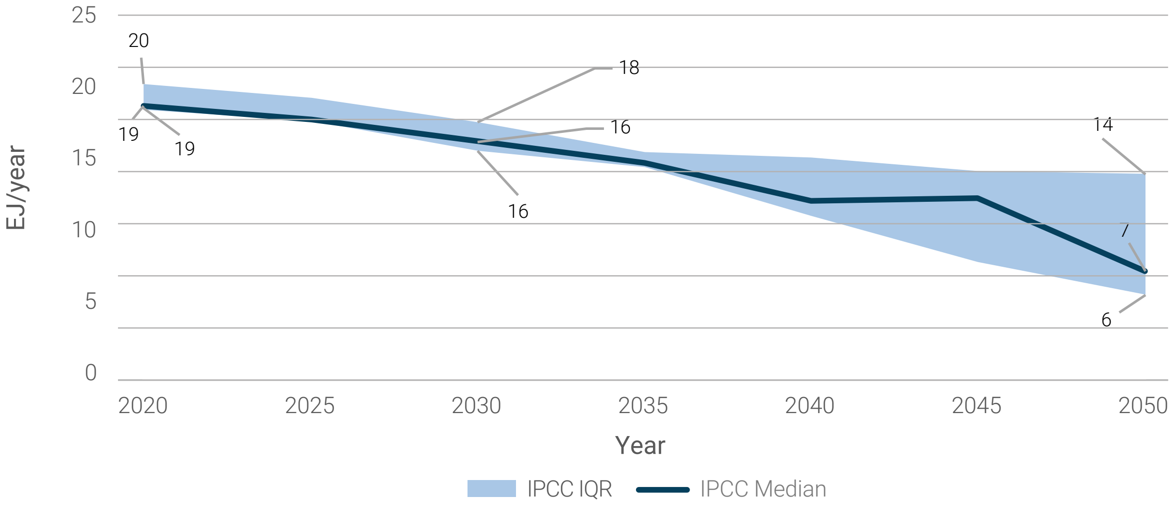


Figure 56: Global final energy consumption of gas in residential buildings in the IPCC-assessed 1.5°C pathways with no or limited overshoot from 2020 to 2050

6.5.2 Operational and embodied carbon emissions

A net-zero building has no net-carbon emissions during construction and operation. Emissions are reduced and balanced by renewable energy and carbon offsets. A net-zero building needs to be highly energy efficiency and powered through renewable energy, either on-site or off-site (WSP, n.d.). Digitalisation, as used in 'smart' equipment and appliances, is key to reducing the operational emissions of net-zero buildings by enabling energy efficiency of buildings through energy optimisation, advanced sensing and controls, and system integration (WEF, 2021). Along with operational emissions, embodied carbon emissions of buildings need to be drastically reduced. Measures to achieve this include (Global Alliance for Buildings and Construction, n.d.; American Institute of Architects, n.d.; UNEP, n.d.):

- Renovations and reuse of buildings instead of the construction of new buildings; this can save 50 to 75% of embodied carbon emissions, especially when preserved foundations and structures are reused.
- Design of lower-carbon concrete mixes using fly, ash, slag, calcined clay and, where feasible, lower-strength concrete.
- Limits to the use of carbon-intensive materials, such as aluminium, plastics, and foam insulation.
- Selection of lower carbon-intensive alternatives, such as wood structures instead of steel and concrete.
- Selection of carbon-sequestering materials, such as hemp insulation.
- Reuse of materials like brick, metals, wood, and broken concrete; reusing materials can have a lower carbon footprint than newly manufactured materials.
- Use of high-recycled content materials.
- Maximisation of structural efficiency using wood framing that employ optimum value engineering methods, as well as efficient structural sections and slabs.
- Use of fewer finished materials, such as polished concrete slabs for flooring, can reduce the carbon footprint from carbon or vinyl flooring; unfinished ceilings can also reduce embodied carbon.
- Minimisation of waste, especially in wood-framed projects.
- Increase the amount of green spaces, street trees and green roofs in urban cities.
- Improve energy efficiency in urban planning and building appliances.
- Implement enhanced building and energy management systems for operational efficiency.
- Integrate on-site renewables and prioritise green power procurement for clean energy sources.
- Provide access to electricity and clean cooking.

6.5.3 Decarbonisation challenges

Decarbonisation of the real estate sector faces two challenges: (1) the scalability of technological solutions; and (2) the cost of adopting less carbon-intensive measures. Expanding industry adoption will be a challenge due to the following factors:

1. **High upfront costs**, such as for building retrofits, which requires substantial upfront investments that can be challenging for building owners to pay back, especially older buildings that require more extensive retrofits.
2. **Beneficiary of retrofits** is often different from the owner and most likely a tenant who benefits from lower energy costs. Split incentives can make it difficult to reach a consensus on retrofitting decisions.
3. **Lack of standardisation** in terms of technology, processes and financing mechanisms across the industry.
4. **Limited awareness** among building owners on the benefits that retrofits can provide.
5. **Existing building codes and other regulations** can pose an obstacle for the scaling-up of retrofitting projects.

Table 27: Recommended scenario variables to use for assessing decarbonisation of the real estate sector in pathways (AR6 scenario explorer)

Variable	Unit	Definition	Additional information
Final Energy	EJ/yr	Final energy consumption. Depending on the final energy variable chosen, this can exclude the use or transmission of feedstock or distribution losses (*adapted by the author*).	Further granular variables are available for different types of energy sources for residential and commercial buildings.

Questions for readers:

- What alternatives to traditional building designs do you identify as opportunities for your institution?
- In your opinion, are the decarbonisation pathways for real estate shown in scenarios feasible for scenario analysis?
- Which methods have you identified as realistic for decarbonisation?
- What are the significant differences in modelling assumptions between the IPCC-assessed scenarios and modelling assumptions made in-house at your institution?
- What aspects of the real estate pathways would you change to make them more applicable for use?

6.6 Scenario limitations

Scenarios assessed in AR6 that limit warming to 1.5°C with no or limited overshoot are limited in their pathways, reporting changes in energy production and consumption. Some of the key limitations of the scenarios are highlighted below.

- **Socio-political feasibility of scenarios for a rapid phase-out of fossil fuels across regions**: The IPCC-assessed scenarios limiting warming to 1.5°C with no or limited overshoot show a rapid decline in coal. However, they show that countries strongly dependent on coal, like China, India, and South Africa, phase out coal at twice the rate of that historically achieved for any other power technology, thus raising questions about the socio-political feasibility of the scenarios. The coal phase-out of 2030 for rich nations and 2050 for developing countries will be more feasible. According to Muttitt *et al.*, 2023, model estimates tend to be generated by experts from wealthy nations with a subconscious bias. Scenarios hardly consider the challenges faced by developing countries in decarbonisation, such as the difficulties in shutting down a coal power plant. Instead, oil and gas reductions, which tend to be produced and used more by wealthy countries, are slower in scenario pathways. If socio-political realities are taken into consideration, then pathways will need to require CO_2 emissions reductions from developed countries to be 50% faster.
- **Model biases can influence the final energy mix in the pathway till 2050**: Figure 57 shows how the share of electricity generation in 2050 can differ by model type. For example, solar accounts for the largest share of electricity generation in REMIND, gas with CCS for the largest share of electricity generation in MESSAGE, and wind for the largest share of electricity generation in GCAM. When considering model biases, two types of biases need to be considered; selection bias, and compound bias. Models can influence scenario pathways either because they start with a set of different assumptions or because they combine the same set of assumptions in different manners. Therefore, the model selected for a 1.5°C scenario with no or limited overshoot can influence the energy mix of the pathway.

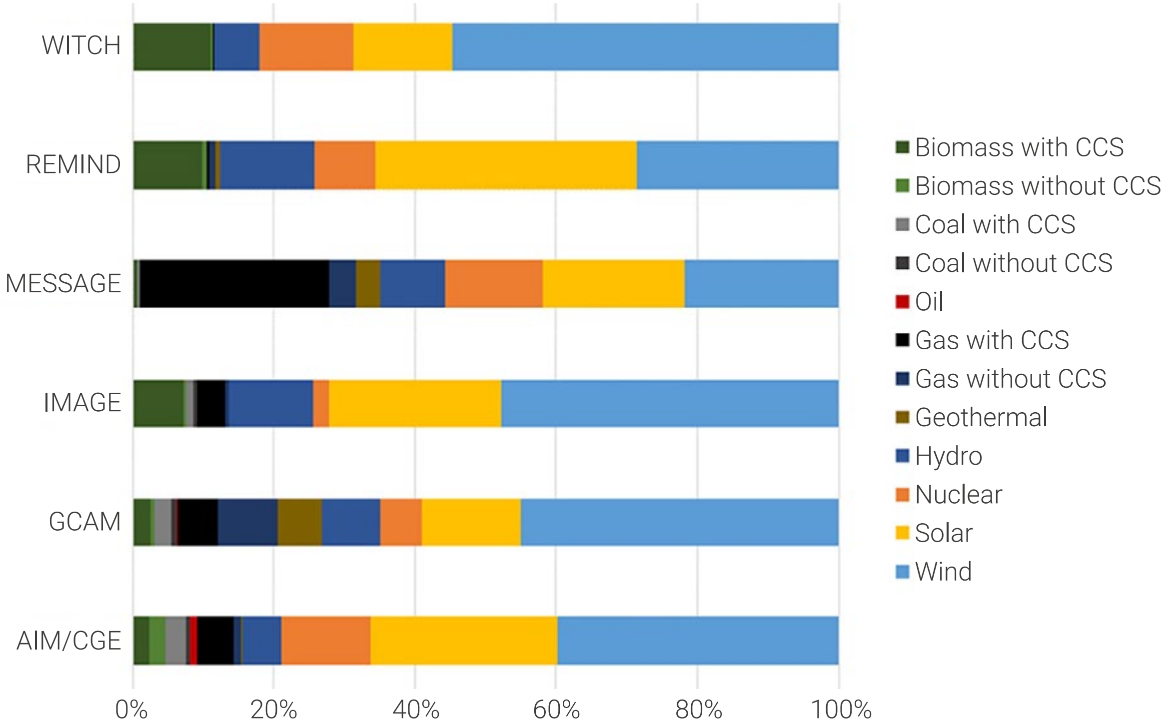


Figure 57: Share of electricity generation in 2050 by model type (Gambhir and Lempert, 2023)

- **Limited variables and metrics available to represent global energy systems:** Scenarios only include a limited number of metrics and variables to characterise changes in the energy system. Scenario pathways simplify technological innovations and their adoption. Due to the global nature of integrated assessment models (IAMs), they are unable to represent energy systems at detailed geographic and temporal scales. For example, variable granularity is limited in terms of the breakdown of energy types and alternatives. The failure of most models to recognise the breakdown of hydrogen into 'grey', 'blue' and 'green' types of hydrogen is a case in point. Similarly, different types of retrofits and transport technologies are often overlooked due to the generic categorisations that models employ (Gambhir *et al.*, 2019).
- **Lack of interaction between energy goals and other policy goals:** Scenario pathways do not take into consideration the impact of other policy goals, economic conditions, or geopolitical tensions on the decarbonisation of the energy system despite the influence that such factors can exert on turning the transition to a low-carbon economy into a reality.
- **Keeping up with rapid technological changes in the real economy that can influence energy demand and generation:** IAMs have a low-cost objective and are designed to keep up with gradual changes to the energy system. They are not good at capturing rapid technological advances. For example, IAMs have difficulty keeping up with the rapid uptake of solar PVs and EVs, which is happening much faster in the real economy than previously assumed (Climate Analytics, 2018).

- **Limited integration of changes in social norms for energy consumption:** The inclusion of assumptions regarding social norms is limited in IAMs. An illustrative example is the norm of social conformity, which makes it more likely that individuals will adopt a practice such as shifting to renewable energy or reducing energy consumption when those around them do so. Social affirmation is also a factor. People are more prone to adopt practices that are seen as less carbon-intensive practices when these are viewed by others as socially desirable. Quantifying the influence of such assumptions is difficult, hence their limited integration into IAMs.
- **Consideration of other risks in decarbonisation of sectors:** Current climate scenarios do not consider a just transition and are constrained in including biodiversity loss.

CHAPTER 7:

Financing the transition to net zero

Key insights into emissions reduction

- Financial institutions can support the transition through lending, investing, and underwriting.
- Financial institutions need to rapidly decrease investments in fossil-generated electricity energy and shift investments from fossil fuels to renewables as shown in the IPCC-assessed 1.5°C scenarios with no or limited overshoot for investments in new power generation:

Energy type	Median 2020 investments	Median 2030 investments
Coal	USD 58.2 billion	USD 12.7 billion
Oil	USD 0.05 billion	USD 0.01 billion
Gas	USD 59.9 billion	USD 30.8 billion
Solar	USD 132.7 billion	USD 427.5 billion
Wind	USD 102.6 billion	USD 391.6 billion

- A substantial increase in investments in non-biomass renewables like solar, wind, hydro, and geothermal is needed with opportunities for financial institutions for financing in emerging markets.
- Significant financing by financial institutions is needed to upgrade and expand transmission networks and storage capacity and the digitalisation of energy systems to improve energy efficiency.
- Investments are also needed for EVs, battery technology, charging infrastructure, and alternative fuel types to decarbonise the transportation sector.
- Financial institutions need to consider annual investments in sustainable agricultural practices and investments that address heightened demand and minimise food waste. This includes exploring investment opportunities in technologies such as those related to disease resistance and sustainable farming practices.
- To decarbonise the industrial sector, investments by firms are required for less carbon-intensive power generation, green hydrogen production, and specialised equipment. For example, steel and cement sub-sectors require investments in clean technologies and innovative processes.
- Investment opportunities for financial institutions to decarbonise buildings include digitalisation, ‘green’ building materials, renewable energy, low-emissions building design and construction, material efficiency, and retrofits.

Suitability considerations of scenarios for exploring financing

Limited information and detail	Some information and detail	Good information and detail
▪ Limited sector granularity to identify investment opportunities for the buildings, AFOLU, and industrials sectors ▪ No information on adaptation finance ▪ No explicit modelling of the financial sector ▪ Breakdown of financing is not reported at the sectoral level (i.e. private or public) nor by institution type ▪ Information on the risks associated with specific investments & the capital and provision needed for investments is not provided ▪ Limited consideration of costs associated with capital spending ▪ The impacts of changing economic conditions on investments & availability of finance are not taken into account ▪ Lack of clear considerations of cost of capital in different regions, rendering the expected financial return from projects unclear.	▪ Information available on investment opportunities for the energy and transportation sector ▪ Some variables are only covered by certain integrated assessment models	▪ Show levels of financing needed and offer a broad view of potential allocations for limiting warming ▪ Able to identify investment opportunities and potential new markets for firms looking to accelerate the transition to a net-zero economy

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Suitability considerations of scenarios for exploring financing in the energy sector

Overall rating: average to good

Potential areas of greatest suitability: Risk analysis and stress testing, sensitivity analysis, client engagement, opportunity assessment, benchmark for target setting, internal strategy setting

Limited information and detail	Some information and detail	Good information and detail
▪ No explicit modelling of the financial sector ▪ Breakdown of financing is not reported at the sectoral level (i.e. private or public) nor by institution type ▪ Information on the risks associated with specific investments and the capital and provision need for investments is not provided ▪ Limited consideration of costs associated with capital spending ▪ The impacts of changing economic conditions on investments & availability of finance are not taken into account ▪ Lack of clear considerations of cost of capital in different regions, rendering the expected financial return from projects unclear.		▪ Show levels of financing needed and offer a broad view of potential allocations for limiting warming ▪ Able to identify investment opportunities and potential new markets for firms looking to accelerate the transition to a net-zero economy

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Suitability considerations of scenarios for exploring financing in the transportation sector

Overall rating: average to limited
Potential areas of greatest suitability: High-level risk analysis, client engagement, and opportunity assessment

Limited information and detail	Some information and detail	Good information and detail
▪ Limited view of investments needed for some of the transport sub-sectors, such as aviation and shipping. ▪ Lack of modelling covering the financing needs for alternative fuels ▪ No explicit modelling of the financial sector ▪ Breakdown of financing is not reported at the sectoral level (i.e. private or public) nor by institution type ▪ Information on the risks associated with specific investments & the capital and provision needed for investments is not provided ▪ Limited consideration of costs associated with capital spending ▪ The impacts of changing economic conditions on investments & availability of finance are not taken into account ▪ Lack of clear considerations of cost of capital in different regions, rendering the expected financial return from projects unclear.	▪ Information available on investment opportunities for the transportation sector ▪ Some variables available are only covered by certain integrated assessment models (e.g., investments in infrastructure and EVs)	▪ Offer a broad view of potential allocations of financing for the sector

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Suitability considerations of scenarios for exploring financing in the agriculture sector

Overall rating: limited

Potential areas of greatest suitability: High-level risk analysis and opportunity assessment

Limited information and detail	Some information and detail	Good information and detail
▪ No variables available that directly cover investment for the sector ▪ Sector granularity is highly limited and therefore pathways do not address the financing needs for the sector and cannot be used to be made definitive statements on investment opportunities for financial institutions	▪ Information available on changes in land use, agriculture production and demand which can be used to infer investment needs for the sector to decarbonise	

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Suitability considerations of scenarios for exploring financing in the real estate sector

Overall rating: limited

Potential areas of greatest suitability: High-level risk analysis and opportunity assessment

Limited information and detail	Some information and detail	Good information and detail
▪ No variables available that directly cover investment for the sector ▪ Sector granularity is highly limited and therefore pathways do not address the financing needs for the sector and cannot be used to be made definitive statements on investment opportunities for financial institutions	▪ Information available on changes in energy use for the sector, including electricity, heating and gas use of buildings. For example, energy use of appliances, cooking and cooling. These variables can be used to infer investment needs for the sector to decarbonise	

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

Suitability considerations of scenarios for exploring energy demand in the industrials sector

Overall rating: limited

Potential areas of greatest suitability: High-level risk analysis and opportunity assessment

Limited information and detail	Some information and detail	Good information and detail
▪ No variables available that directly cover investment for the sector ▪ Sector granularity is highly limited and therefore pathways do not address the financing needs for the sector and cannot be used to be made definitive statements on investment opportunities for financial institutions	▪ Information available on changes in energy use for the sector, including carbon intensity and final energy amount of various industrial processes and the use of carbon sequestration. These variables can be used to infer investment needs for the sector to decarbonise	

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

7.1 Importance of climate finance to drive decarbonisation

Finance has a critical role to play both in accelerating decarbonisation and advancing adaptation to the growing impacts of climate change. According to the Climate Policy Initiative (CPI), climate finance has doubled globally in the last decade. From 2011 to 2020, on average, USD 480 billion was committed to climate finance annually. In 2021/2022, the annual flows doubled compared to the previous year, reaching a total of USD 1.3 trillion. Despite its gradual growth, climate financing does not meet the required levels for the low and no overshoot 1.5°C pathways. By 2030, the CPI estimates that at least USD 5.9 trillion annually is needed for climate financing, this implies that the annual climate finance must grow by at least three times (CPI, 2023). The International Energy Agency (IEA)'s net-zero scenario requires energy investments to increase from 2% of global GDP annually from 2017–2021 to close to 4% by 2030 (IEA, 2023a). Reaching these ambitious mitigation and adaptation goals requires unlocking private climate finance (GFANZ, 2021). The growth in climate finance needs to be the fastest in the next 10–15 years to put the world on a net-zero trajectory (McKinsey, 2022a)

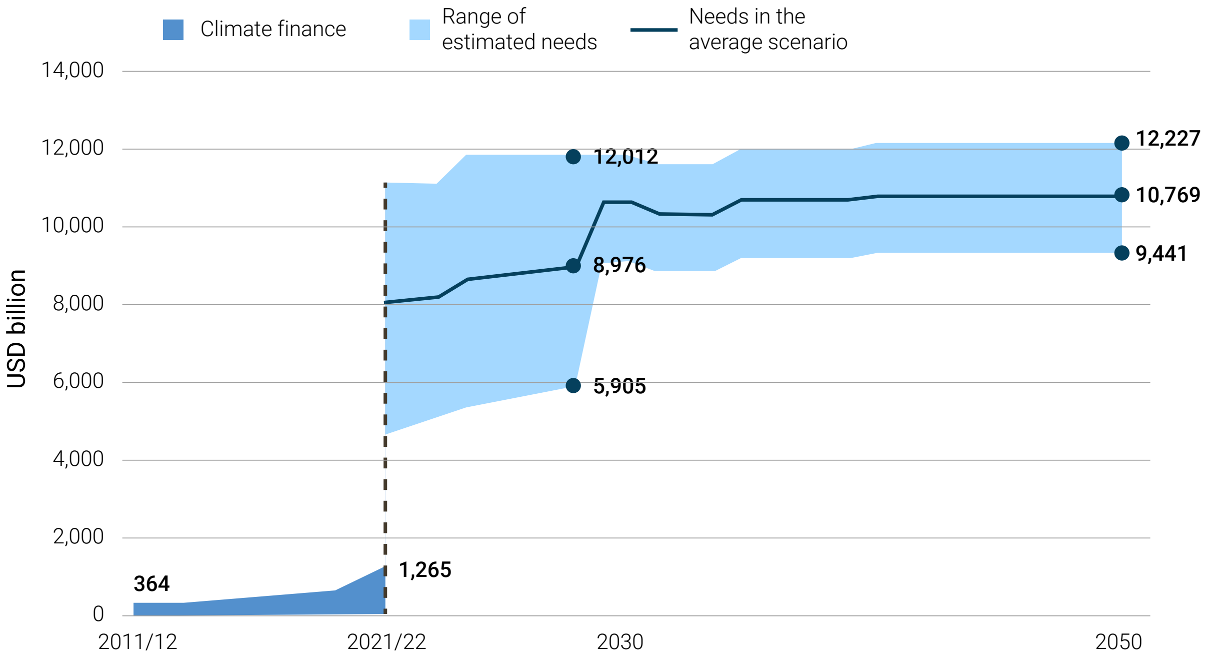


Figure 58: Tracked climate finance flows from 2011–2050 compared to the average estimated climate investment need till 2050 (CPI, 2023)

Financial institutions can support the transition to a low-carbon economy through lending, investing, and underwriting activities. These firms will need to steer their capital into businesses and technologies that can help reduce emissions. Given the diversified nature of many financial institutions, they have the potential to impact diverse sectors and regions across the global economy. Global management consultancy, McKinsey, estimates that private financial institutions could facilitate up to USD 3.5 trillion annually between now and 2050. Of this, commercial banks could facilitate the bulk share, of between USD 2 trillion to USD 2.6 trillion annually. Asset managers, private equity, and venture capital funds could facilitate the remaining USD 950 billion to USD 1.5 trillion (McKinsey, 2023).

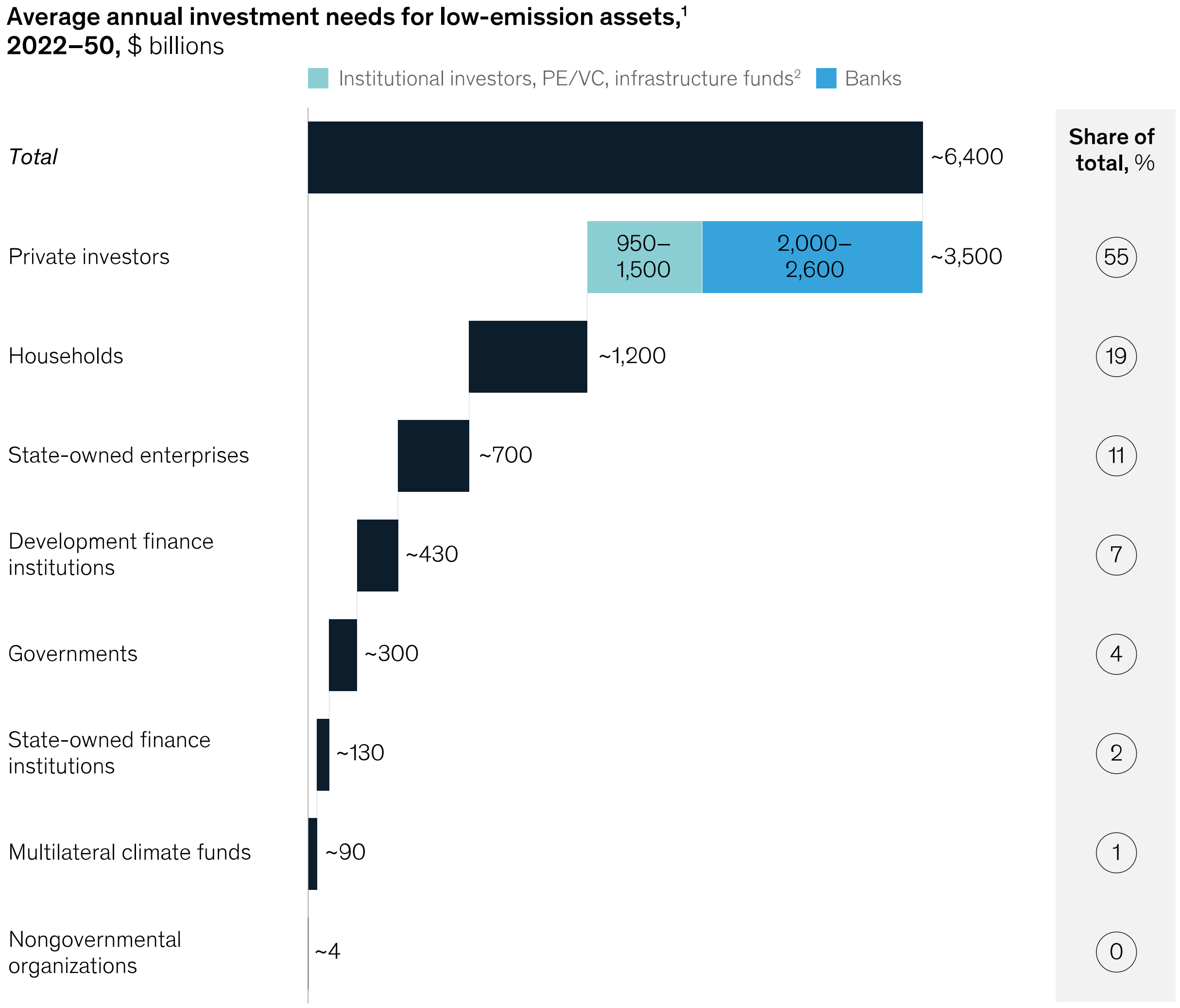
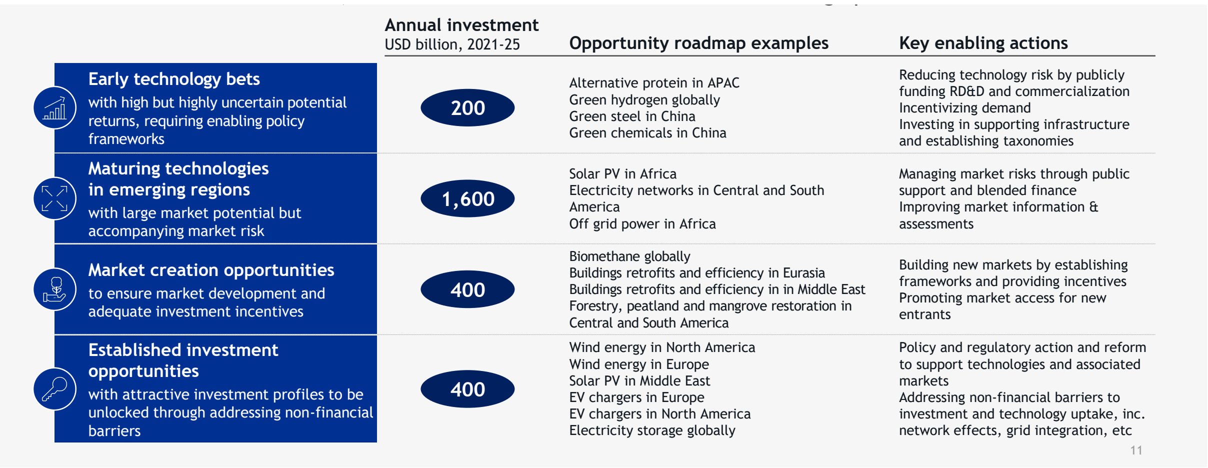


Figure 59: Breakdown of potential financing by private financial institutions (McKinsey, 2023)

Financial institutions must begin by aligning their financing to a science-based 1.5°C pathway. This will require reducing the financing of carbon-intensive activities and reallocating capital to mitigation and adaptation measures (IPCC, 2022). In doing so, they will also be able to take advantage of opportunities created by a decarbonising world. Such opportunities have been illustrated below (Figure 60) (GFANZ, 2021).



	Annual investment USD billion, 2021-25	Opportunity roadmap examples	Key enabling actions
Early technology bets with high but highly uncertain potential returns, requiring enabling policy frameworks	200	Alternative protein in APAC Green hydrogen globally Green steel in China Green chemicals in China	Reducing technology risk by publicly funding RD&D and commercialization Incentivizing demand Investing in supporting infrastructure and establishing taxonomies
Maturing technologies in emerging regions with large market potential but accompanying market risk	1,600	Solar PV in Africa Electricity networks in Central and South America Off grid power in Africa	Managing market risks through public support and blended finance Improving market information & assessments
Market creation opportunities to ensure market development and adequate investment incentives	400	Biomethane globally Buildings retrofits and efficiency in Eurasia Buildings retrofits and efficiency in in Middle East Forestry, peatland and mangrove restoration in Central and South America	Building new markets by establishing frameworks and providing incentives Promoting market access for new entrants
Established investment opportunities with attractive investment profiles to be unlocked through addressing non-financial barriers	400	Wind energy in North America Wind energy in Europe Solar PV in Middle East EV chargers in Europe EV chargers in North America Electricity storage globally	Policy and regulatory action and reform to support technologies and associated markets Addressing non-financial barriers to investment and technology uptake, inc. network effects, grid integration, etc

Figure 60: Different types of investment opportunities that enable climate action (GFANZ, 2021)

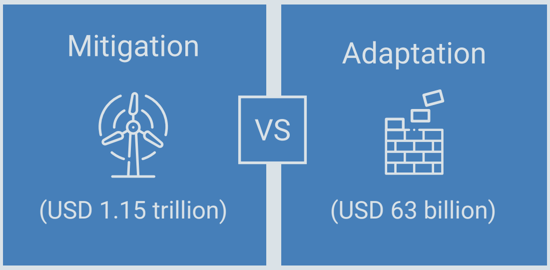
Low-carbon technologies can provide financial institutions with investment opportunities that offer long-term returns. By 2030, four-fifths of decarbonisation technology investments could be more valuable than their conventional competitors (GFANZ, 2021). Between 2016 and 2021, private investments in low-carbon technologies were the highest for mature technologies such as EVs, energy storage and solar energy. However, in an attempt to increase investment returns, financial institutions are increasingly investing in less mature technologies, such as fuel cells, hydrogen, and carbon capture (BCG, 2021).

Scenario pathways can help financial institutions identify investment opportunities and markets that can accelerate the capital scale-up needed to transition to net zero by 2050 and reach the 1.5°C climate goal. Investment assumptions in scenario pathways can provide insights into the potential investments that will provide the required emission reductions. While these scenarios can be useful in showing both the levels of financing needed and a broad view of potential allocations, they do not tend to focus on the specific financial products required to make that capital flow into the low-carbon economy. The models also do not break down the financing reported in scenario pathways down to the private and public sectors. Financial users cannot use climate scenarios to gain information on capital and provision for investments nor on the risk associated to specific investments. The specific products and terms are left to the financial institutions.

This section explores the scale-up in financing needed to limit warming to 1.5°C with no or limited overshoot based on the scenarios assessed in the IPCC's Assessment Report 6 (AR6) and the current financing gap.

Box 26: Current state of climate finance

1. Finance flows towards **mitigation** and **adaptation** (2021/2022 levels) (CPI, 2023)



Mitigation

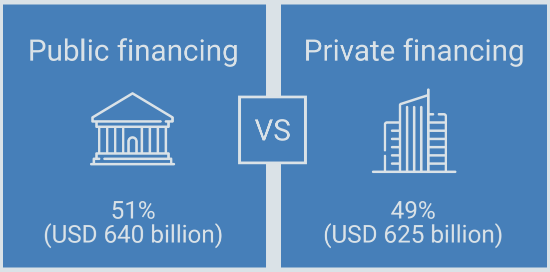
(USD 1.15 trillion)

VS

Adaptation

(USD 63 billion)

2. Finance flows from the **public** and **private sectors** (2021/2022 levels) (CPI, 2023)



Public financing

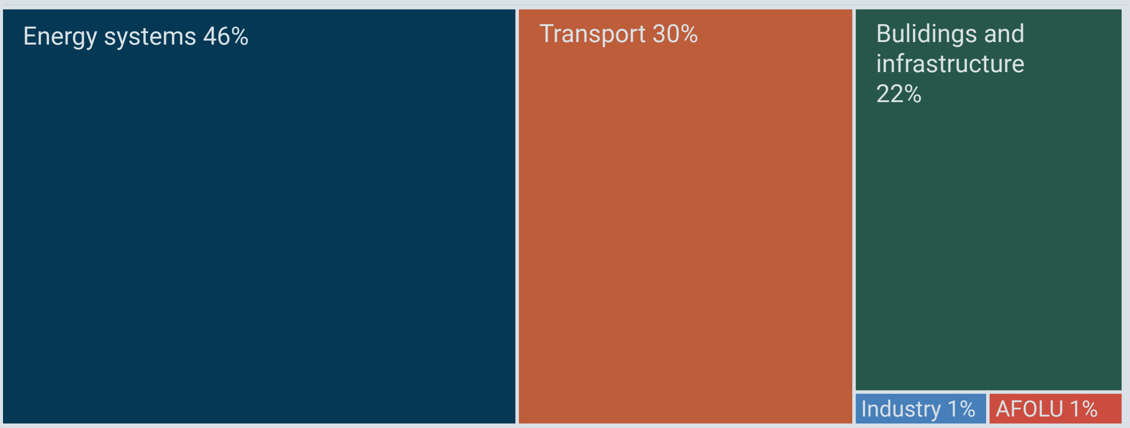
51%
(USD 640 billion)

VS

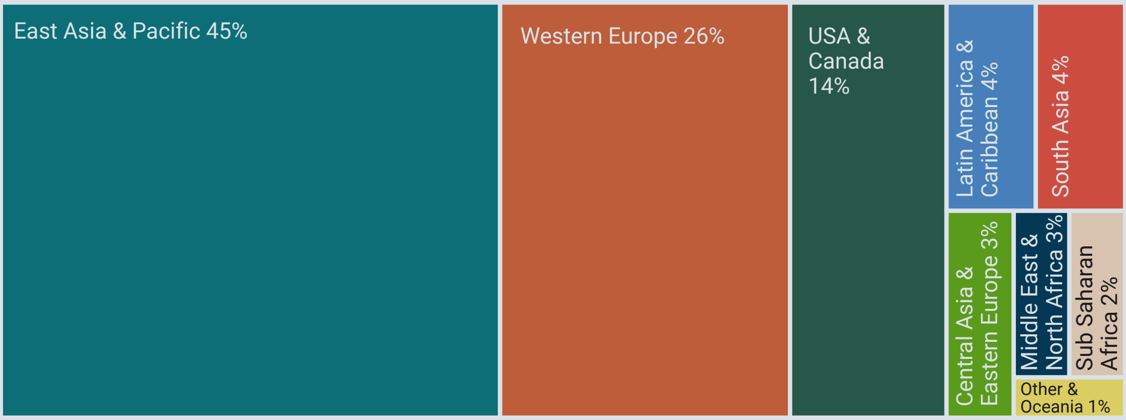
Private financing

49%
(USD 625 billion)

3. Landscape of climate finance by **sector** (2021/2022 levels) (CPI, 2023)



4. Landscape of climate finance by **region** (2021/2022 levels) (CPI, 2023)



7.2 Climate financing needs

Bloomberg's primary research service for energy, BloombergNEF, calculates in its net-zero scenario that the world will need to invest USD 4.55 trillion annually this decade to achieve net zero. This amounts to a total of USD 31.9 trillion in the next seven years (BloombergNEF, 2023a). The NGFS puts the figure at more than double this. Its Net Zero 2050 scenario[60] demonstrates that a total of USD 275 trillion in investment would be needed between 2021 and 2050 to reach net zero. This amounts to USD 9.2 trillion annually, which translates to a total of USD 64.4 trillion in spending between 2023 and 2030 (McKinsey, 2022a). Aligned with the IEA's Net Zero 2050 scenario (2021), the UNFCCC Race to Zero campaign estimates that USD 125 trillion of investment will be needed to transform the global economy to reach net zero by 2050, with USD 32 trillion in investment being required over the next decade across six key sectors. Of this USD 32 trillion, USD 16 trillion will be required for electricity generation, USD 5.4 trillion for transport, USD 5.2 trillion for buildings, USD 1.5 trillion for low-emission fuels, and USD 1.5 trillion for Agriculture, Forestry and Other Land-use (AFOLU) (GFANZ, 2021 [analysis conducted by Vivid Economics]) (Figure 61). BloombergNEF states that the biggest markets for investors will be EVs and low-carbon power (BloombergNEF, 2022a).

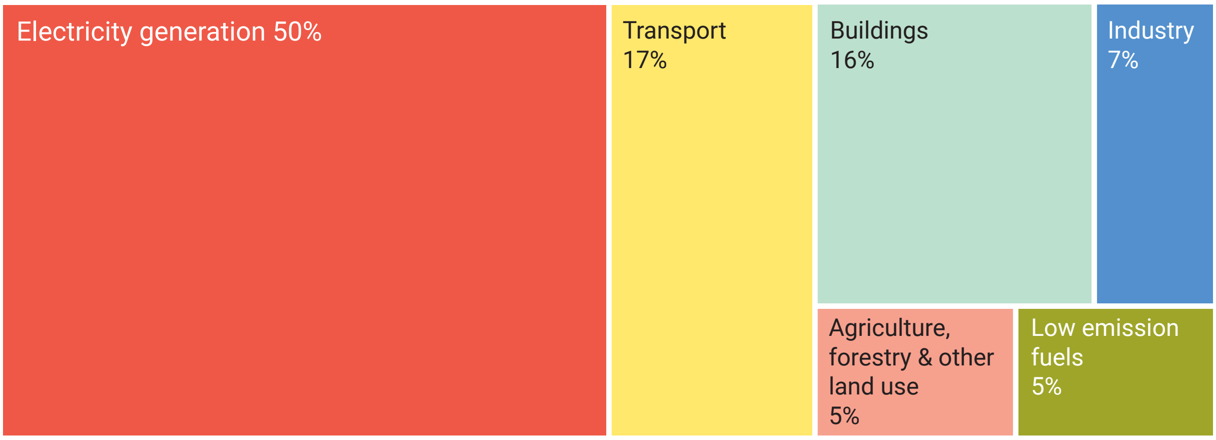


Figure 61: Climate financing needs from 2020 to 2030 by sector according to the UNFCCC Race to Zero campaign

Of the USD 32 trillion investment needs stated by the UNFCCC Race to Zero campaign in the 2020s, Asia Pacific requires USD 13.6 trillion, North America USD 5.9 trillion, Europe USD 6.6 trillion, Africa USD 1.7 trillion, Central and South America USD 1.5 trillion, and the Middle East USD 1.2 trillion (GFANZ, 2021 [analysis conducted by Vivid Economics]) (Figure 62).

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[60] 2021 version

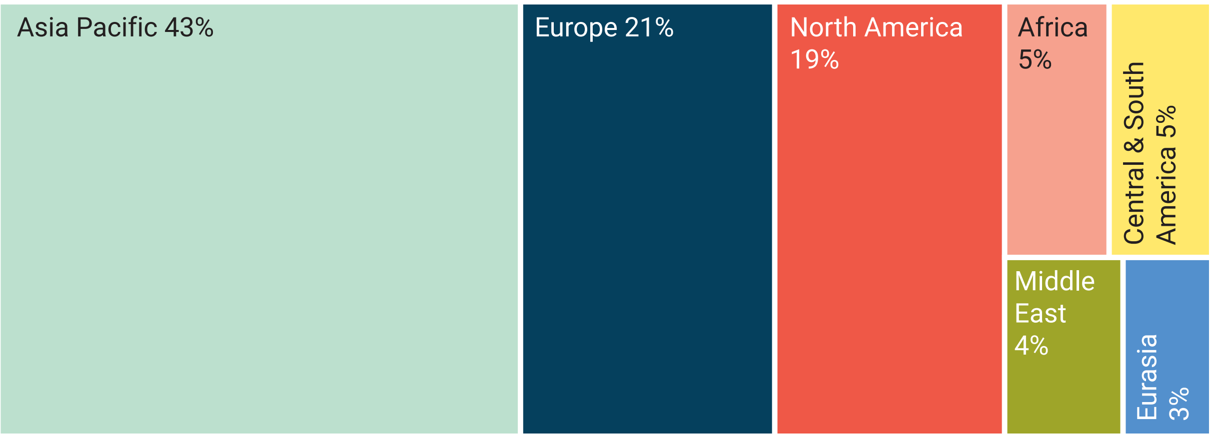

Figure 62: Climate financing needs from 2020 to 2030 by region

Financing can typically focus on sectors with technologies that are market-ready and mature or that are in the early stages of adoption (IEA, 2021a). At present, financing has become directed to specific technologies in the energy sector, such as those linked to solar and wind energy. A more balanced approach to financing is required, with more investment flowing to decarbonising solution in high-emitting sectors such as steel, and cement (IRENA, 2023). Decisions on financing for emission-intensive sectors over the next decade will play a role in determining the pathway to a net-zero economy. Either they will provide the necessary push for the advancement and integration of new technologies for decarbonisation, or they will potentially lock in emissions for future decades (IEA, 2021a).

7.3 Energy sector

1.5°C scenarios assessed by the IPCC show a consensus in rapidly shifting investments from fossil fuels to renewables. However, investment pathways in these scenarios vary in pace and scale. In 1.5°C scenarios with no or limited overshoot, electricity generation investments increase rapidly in the near term in order to support efforts to green the electricity generation sector. The scenarios also show a substantial increase in investments in non-biomass renewables such as solar, wind, hydro and geothermal. Investments in such renewables are projected to increase to more than USD 1 trillion in 2030, about three times more than the investments in renewables seen in the previous decade (IPCC, 2022). Table 28 summarises the global average annual investments from 2023–2032 for electricity supply shown in 1.5°C scenarios with no or limited overshoot assessed by the IPCC. Figure 63 shows the median investments reported by the scenarios for different fuel types between 2020 and 2050.

Table 28: Global average annual investments from 2023–2032 for electricity supply shown in 1.5°C scenarios with no or limited overshoot (IPCC, 2022)

Electricity supply subcomponents	Average annual investment (in USD billion) (IEA, 2023a)	Number of scenarios	Annual investments, IEA's NZE scenario 2030 (in USD billion) (IEA, 2023c)
Fossil	53 (34–115)	50	400
Nuclear	127 (85–165)	52	114
Non-biomass renewables	1190 (688–1430)	52	1080[61]
Solar (part of non-biomass renewables)	498 (292–603)	52	c.460
Wind (part of non-biomass renewables)	390 (273–578)	52	c. 500
Storage	221 (88–295)	39	c.170
Transmission and distribution	549 (422–787)	50	680

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[61] All renewables

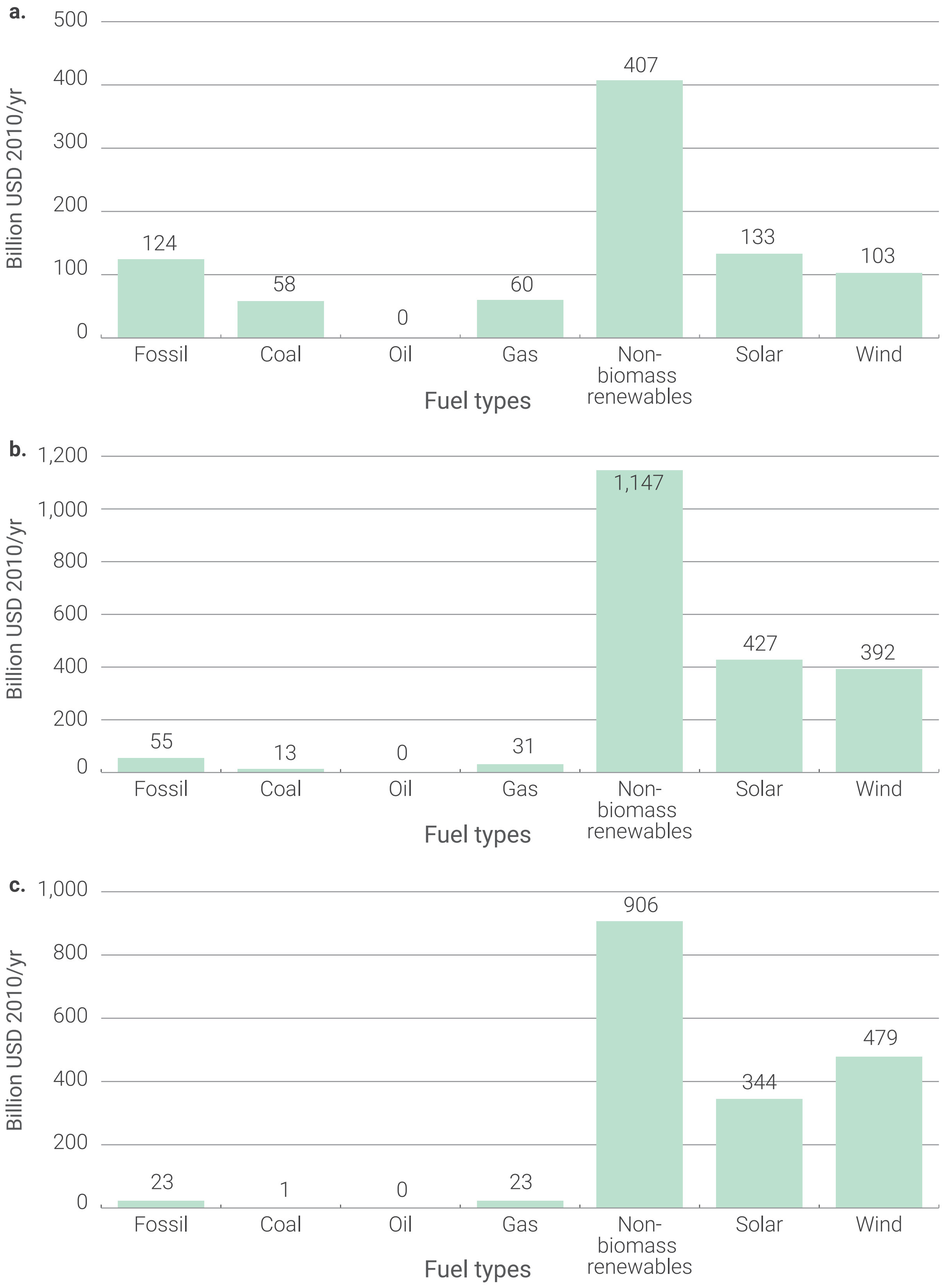

Figure 63: Global median investments in fuel types from 2020–2050, as reported in the IPCC-assessed 1.5°C scenarios with no or limited overshoot: (a) 2020, (b) 2030 and (c) 2050

The energy composition of a given scenario pathway will be dependent on its assumptions around the scale of financing as well as its assumptions on cost and deployment. For example, models that invest more in renewables will also assume a larger share of renewables in the future energy mix. Similarly, models with optimistic assumptions of energy production from nuclear through to 2050 will report different financing for renewables, fossil fuels, transmission and distribution, and energy efficiency due to their greater reliance on nuclear energy.

7.3.1 Fossil fuels

In scenarios limiting warming to 1.5°C with no or limited overshoot, investments in fossil fuels for the energy supply of electricity is shown to rapidly decrease from 2020 to 2050, as shown in Figure 63. The IPCC-assessed 1.5°C scenarios with no or limited overshoot show investments in fossil-generated electricity energy decreasing by 56% and 82% from 2020 to 2030 and 2050, respectively. As the largest contributors to GHG emissions, investments in fossil fuels can impede reaching global climate goals (United Nations, n.d.; IPCC, 2018).

7.3.2 Coal

1.5°C scenarios with no or limited overshoot in AR6 are nearly unanimous in requiring a rapid phase-out of coal. Reductions in primary energy from oil and gas are more scenario dependent, with most reductions taking place between 2030 and 2050 (see Chapter 6 on Energy Demand). As a result, the greatest decrease in investments in new power generation from fossil fuels in the 1.5°C scenario pathways is reported for coal; annual investments decrease by 78% (98%–65%)[62] from 2020 to 2030, and by 98% (97%–94%) from 2020 to 2050 (Figure 64a). A decrease in investments has already been signaled by various countries (most notably China) pledging to stop building coal-fired power plants overseas (IEA, 2022a).

7.3.3 Oil & gas

In comparison, investments in new power generation from oil are projected to fall slower in the pathways. For oil, annual investments in 1.5°C scenarios with no or limited overshoot decrease from USD 0.05 billion (USD 0.05–USD 18 billion)[63] in 2020 to USD 0.01 billion (USD 0–USD 4 billion) in 2030 and to USD 0.01 billion (USD 0.0–USD 6 billion) in 2050 (Figure 64b). The overall low investment numbers in the scenarios are due to the variable only covering oil power generation, which is not competitive at scale and is used in particular applications or when alternatives are unavailable, such as the use of backup generators. Some models assume that the share of applications of oil power generation will remain constant in the coming decades and foresee a decrease in investments. Other models do not allow for additional investments in their pathways for the future, which is more closely aligned with the reduction in battery costs, making backup battery systems combined with renewables a cheaper alternative to oil-fired generators.

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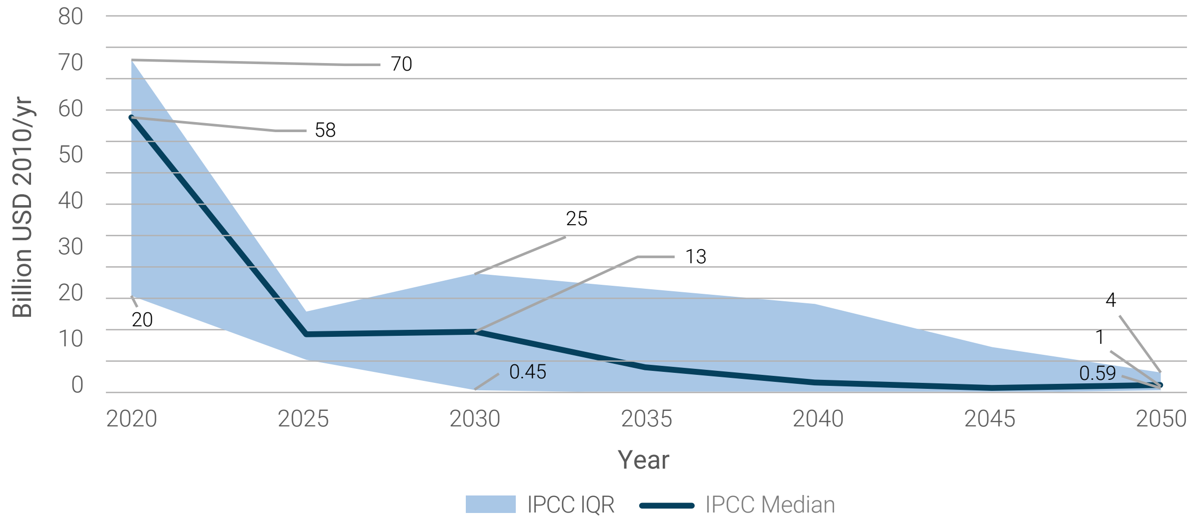
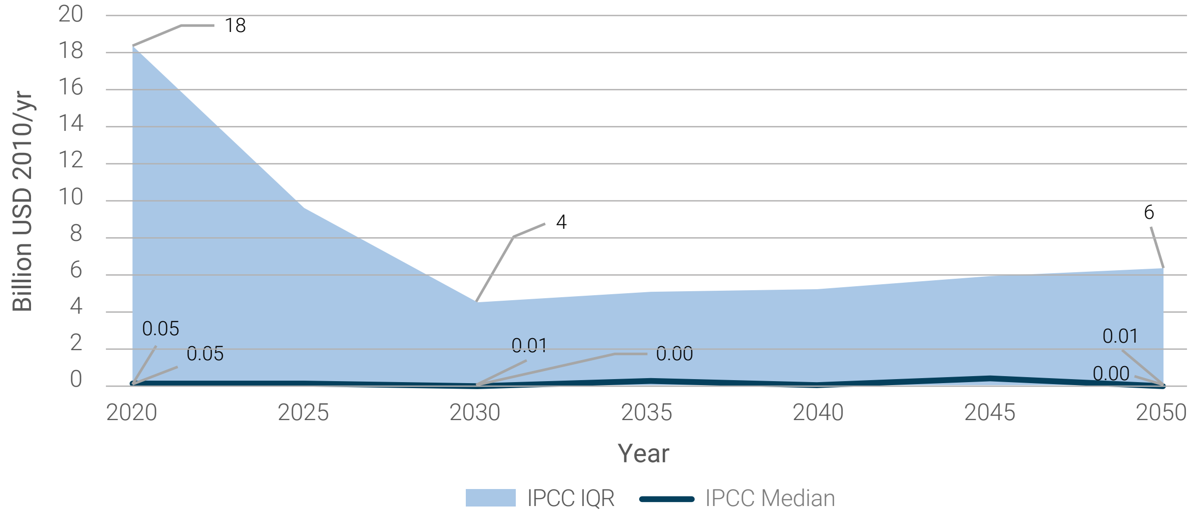
[62] Percentage change of median (percentage change of lower quartile—percentage change of upper quartile)

[63] Values in this chapter are represented as median (interquartile range)

In the near term, natural gas is seen as a potential source to replace higher-emitting sources such as coal. As a result, investments in natural gas are projected to fall much more slowly compared to coal investment. 1.5°C scenarios with no or limited overshoot show annual investments in natural gas decrease from USD 60 billion (USD 26–USD 113 billion) in 2020 to USD 31 billion (USD 17–USD 89 billion) in 2030 and USD 23 billion (USD 7–USD 63 billion) in 2050 (Figure 64c). Some scenarios, such as the IEA's Net Zero 2050 pathway, require no investments in new oil and gas fields from 2022. Though financing in oil and gas meets IEA estimates (see Appendix 3), the types of investment being directed into fossil fuels are important to understand. For example, financing could be directed towards maintaining production from existing fields or it could be used to support the exploration and exploitation of new reserves. Both have important impacts on long-term emission levels, although the latter carries particularly serious implications for the probable, lock-in of fossil fuel use.





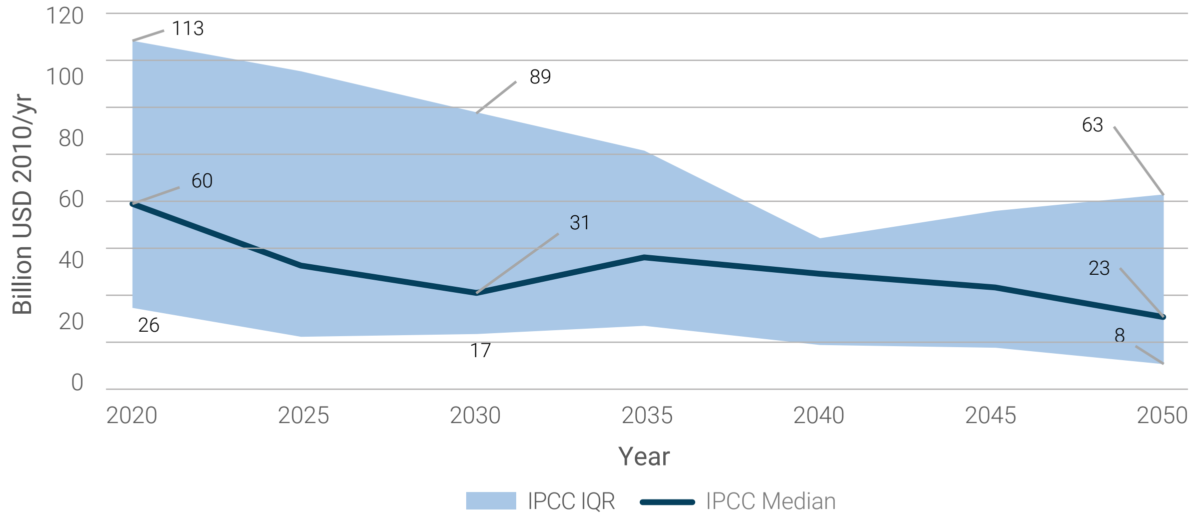
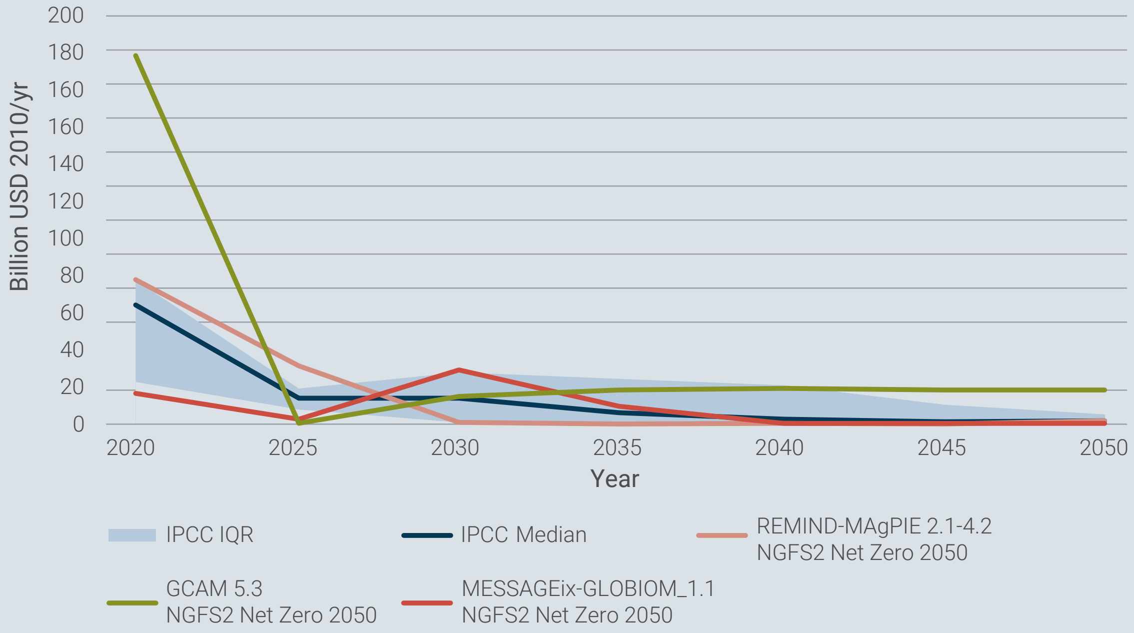


Figure 64: Investment in new power generation from (a) coal, (b) oil, and (c) gas in the IPCC-assessed 1.5°C pathways with no or limited overshoot from 2020 to 2050

Box 27: Investment in new power generation from coal in the NGFS net-zero scenarios compared to the IPCC-assessed 1.5°C scenarios with no or limited overshoot

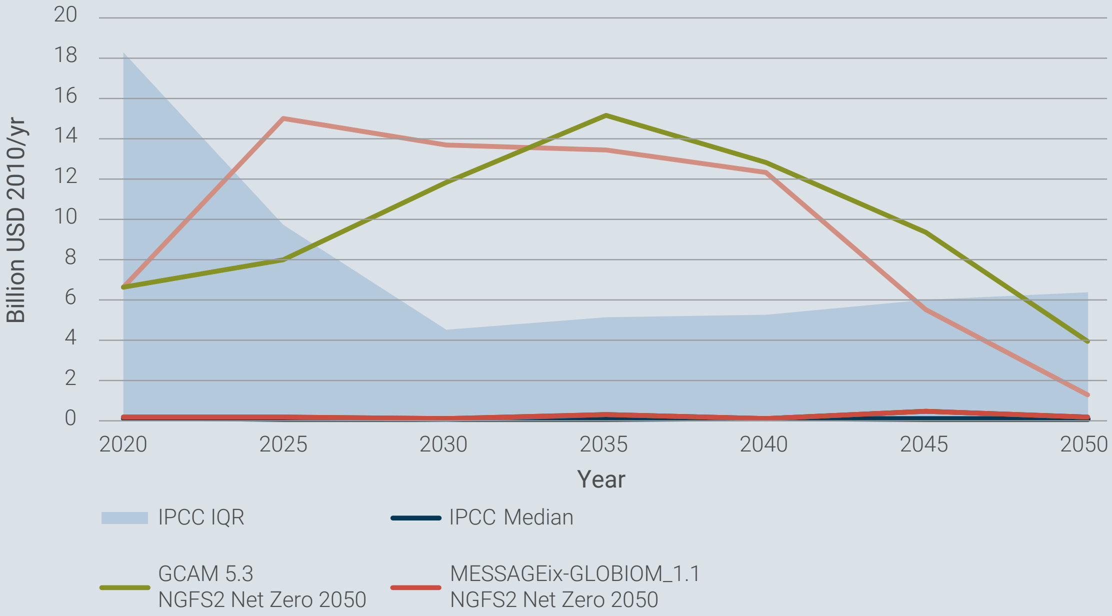
All NGFS scenarios shown are Net Zero 2050.



From 2020 to 2025, REMIND, GCAM, and MESSAGE report a decrease in coal investment for electricity energy generation. In comparison with other models, the GCAM pathway showcases more dramatic changes over the five-year period but also reports a slight increase in coal investment from 2025 to 2030. Between 2030 and 2050, REMIND and MESSAGE both fall within the lower quartile range of the IPCC-assessed scenario dataset. By 2050, only the GCAM pathway still reports coal investment levels in electricity energy generation more than four times greater than the upper quartile of the IPCC dataset.

Data source: AR6 scenario explorer

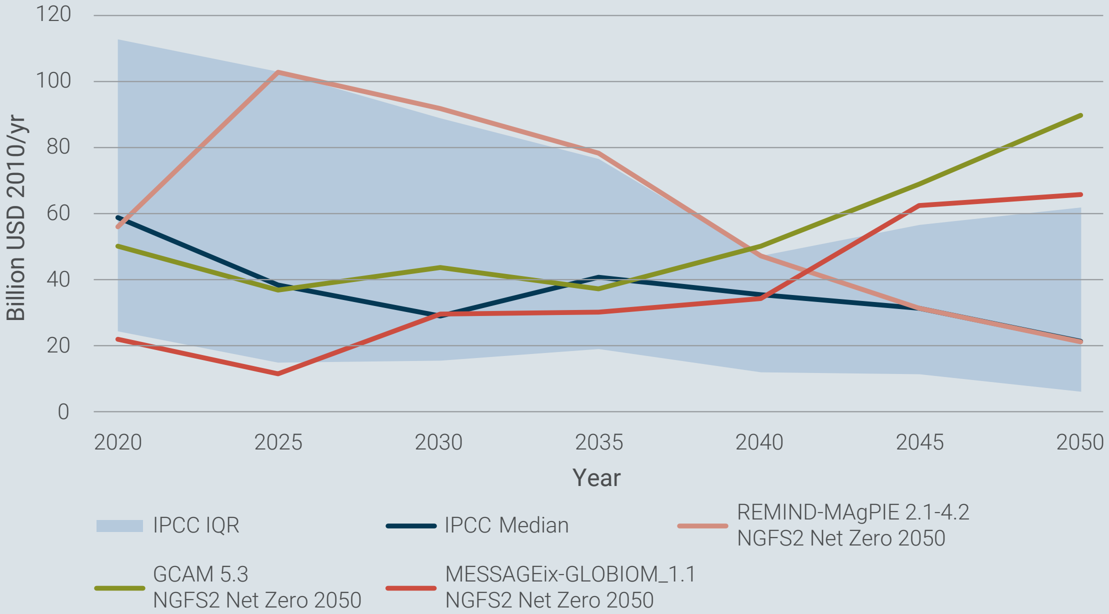
Box 28: Investment in new power generation from oil in the NGFS net-zero scenarios compared to the IPCC-assessed 1.5°C scenarios with no or limited overshoot



The MESSAGE Net-Zero 2050 scenario show similar values to the median of the IPCC-assessed scenario pathway, which is close to 0 USD 2010/yr of oil investment in electricity energy during 2020 to 2050. The GCAM Net-Zero 2050 scenario reports higher values than the upper quartile of the IPCC-assessed scenario dataset from 2025 to 2045. While the upper quartile data of the IPCC-assessed scenarios report a slight increase in oil investment from 2030, the GCAM models show a consecutive decrease in investments, especially after the year 2035. It is important to note that GCAM does not make additional adjustments for certain regions, such as the Middle East, having a high preference for oil electricity.

Data source: AR6 scenario explorer

Box 29: Investment in new power generation from gas in the NGFS net-zero scenarios compared to the IPCC-assessed 1.5°C scenarios with no or limited overshoot



The three NGFS models report uncertainty in investments in new power generation from gas. Between 2020 and 2025, REMIND shows an increase in investments, while GCAM, MESSAGE, and the median values of the IPCC-assessed dataset show a decrease in investments. From 2035, REMIND reports a massive decline in investments in gas, with investment levels in 2050 falling in line with the median investment level of the IPCC-assessed dataset. MESSAGE and GCAM report an increase in gas investment from 2035. By 2050, GCAM's value in gas investment significantly exceeds the upper quartile of the IPCC-assessed scenario dataset. GCAM reports an increase in investments as it starts to build out expensive gas with CCS in 2035.

Data source: AR6 scenario explorer

1.5°C scenarios assessed in AR6 with no or limited overshoot still show small levels of investments in fossil fuels by 2050. Despite a phase-out of fossil fuels to reach net zero by 2050, small levels of fossil-fuel use will remain for activities that cannot solely rely on renewable sources for electricity generation (Breakthrough Institute, 2022). As mentioned, carbon capture and storage (CCS) is a crucial feature of 1.5°C scenarios with no or limited overshoot (see section on CCS). Investments will also be needed in the research and development of CCS to further expand the deployment of such technology. In scenario pathways that show faster transitions, CCS makes up a larger share of investment in the energy sector (IEA, 2022b).

7.3.4 Renewables

To accelerate the transition from fossil fuels to clean energy, **significant investment is needed in non-biomass renewables, especially solar and wind**. Clean energy investment can also help reduce pressure of rising fossil fuel prices, increase the resiliency of clean energy supply chains, and improve national energy security for countries around the world (IEA, 2022c). Large increases in investments in non-biomass renewables for the energy supply of electricity are shown in scenarios limiting warming to 1.5°C with no or limited overshoot (Figure 65). Annual investments increase from USD 407 billion (USD 251–USD 470 billion) in 2020 to USD 1,147 billion (USD 675 billion–USD 1,390 billion) in 2030. From 2030 to 2050, the scenarios show a slight decrease in investments by 2050, at USD 906 billion (USD 772–USD 1,349 billion) annually. This highlights the urgency of scaling up financing in renewables over the next decade to limit global temperature rise to 1.5°C.

1.5°C scenarios with no or limited overshoot assume a decrease in capital and operational costs from 2020 to 2050 for renewable energy. For example, capital and operational costs for solar PV are assumed to decrease by 63% and 56% (median), respectively, from 2020 to 2050. Similarly, the capital cost of offshore wind is assumed to reduce by 39% (median) between 2020 and 2050, while operational costs for wind energy (offshore and onshore) are assumed to decrease by 65% (median) over the same period. For renewable energy, the rapid decrease in costs of clean energy technologies provides an opportunity for financing to expand the deployment of renewable technologies, especially in emerging markets. Technologies like wind and solar PV have low operating and fuel expenditures, which offset the high upfront investments required. Low financing costs will be important to accelerate the financing of energy systems (IEA, 2021a). The pace of such acceleration depends heavily on the adoption of policies and regulations that support energy transitions.

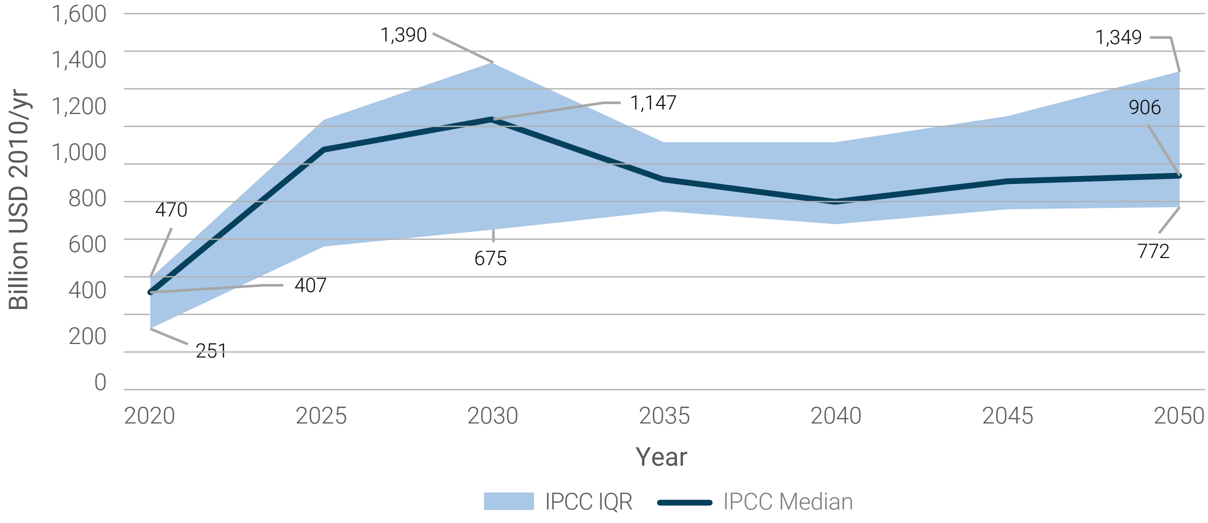
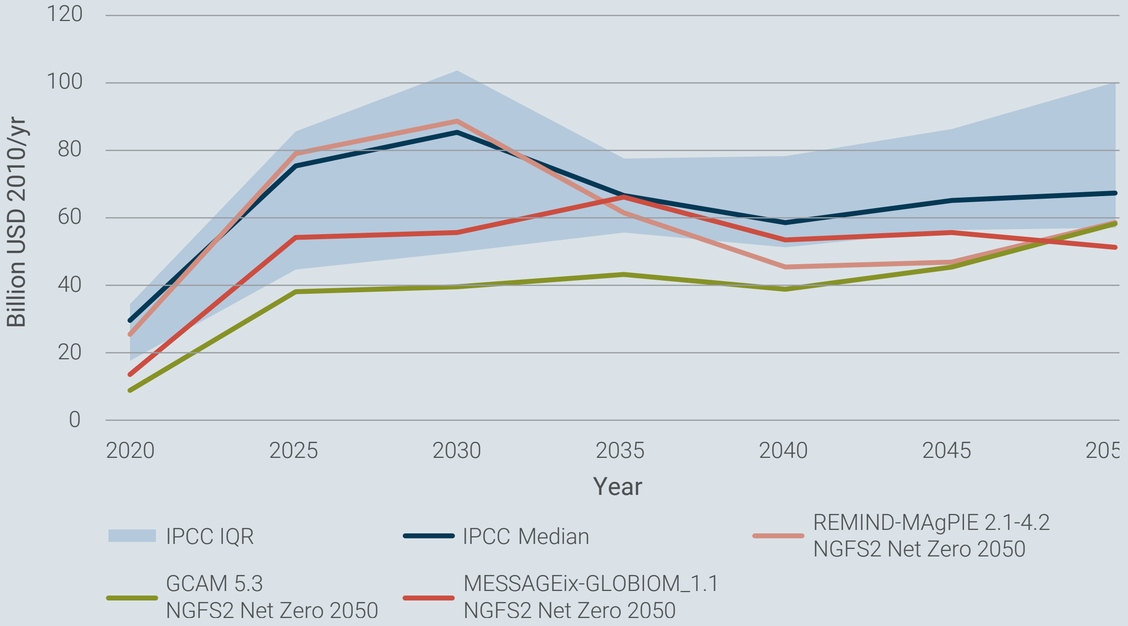


Figure 65: Investments in new power generation from non-biomass renewables in the IPCC-assessed 1.5°C pathways with no or limited overshoot from 2020 to 2050

Box 30: Investment in new power generation from non-biomass renewables in the NGFS net-zero scenarios compared to the IPCC-assessed 1.5°C scenarios with no or limited overshoot



The GCAM Net Zero 2050 pathway reports lower levels of investment in new power generation from non-biomass renewables than the lower quartile value of the IPCC-assessed scenario dataset, however, it shows a rapid increase in investments till 2025, aligned with the median level of investments in 2025, but then reports a stark decrease in investments to 2030. Between 2035 and 2050, investments increase, with GCAM Net Zero 2050 reporting investments higher than the lower quartile and lower than the median values of the IPCC-assessed scenario dataset. The REMIND Net Zero 2050 pathways show similar levels of investment to the median of the IPCC-assessed scenario dataset until 2030, a higher rate of decrease is observed in the REMIND scenario thereafter.

The REMIND pathway and the IPCC-assessed scenario dataset show investments peaking between 2025 and 2030 as this period corresponds to the rapid scaling up of non-biomass renewables, such as solar and wind. The unit costs are assumed to be lower post-2030 due to endogenous learning, where costs are assumed to be a function of previous investments (Ouassou *et al.*, 2021) and cost mark-ups during the rapid upscaling phase. Consequently, investment declines at a faster rate than installations of non-biomass renewable technologies, primarily due to the substantial replacement of fossil fuels with renewables by 2035.

Data source: AR6 scenario explorer

Investment in solar PV includes spending on developing battery technology, critical minerals, efficiency improvement, utility scale projects, and the distribution of solar PV systems (IRENA, 2021). In AR6, modeled pathways for limiting warming to 1.5°C with no or limited overshoot report an increase in annual investments in solar for electricity supply from USD 133 billion (USD 72–USD 156 billion) in 2020 to USD 427 billion (USD 320–USD 628 billion) in 2030, an increase of 221% (median) from 2020 levels. The majority of the rapid scale-up in the required investments in solar PV is shown to occur in the next several years, but the annual required investment rises to USD 344 billion (USD 274–USD 466 billion) by 2050 (Figure 66). The trend in investment reported by the IPCC-assessed scenarios from 2020 to 2050 align with new solar installations slowing down and costs declining after 2030. In the pathways, power generation from solar energy scales up rapidly in the short term to obtain a higher share of solar energy and reduce emissions. However, in the long-run demand, without substantial growth in demand, the utilisation of solar energy reaches its maximum potential within the energy system. This leads to a decreased need for new investments, primarily due to a greater emphasis on capacity replacement rather than widespread capacity expansion. Additionally, a decline in emission levels is facilitated by decreasing investment costs attributed to technological learning.

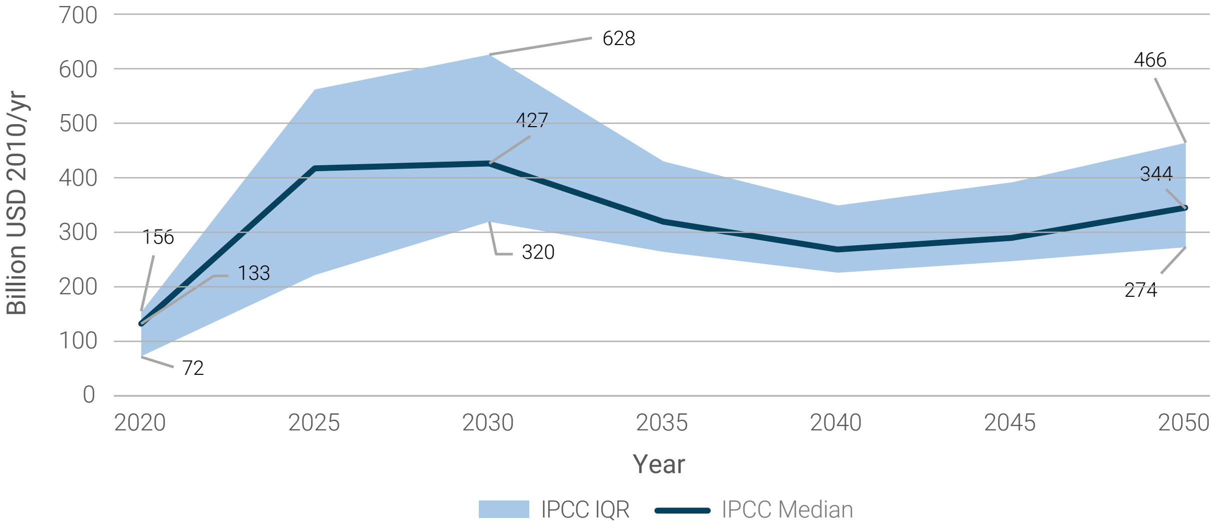
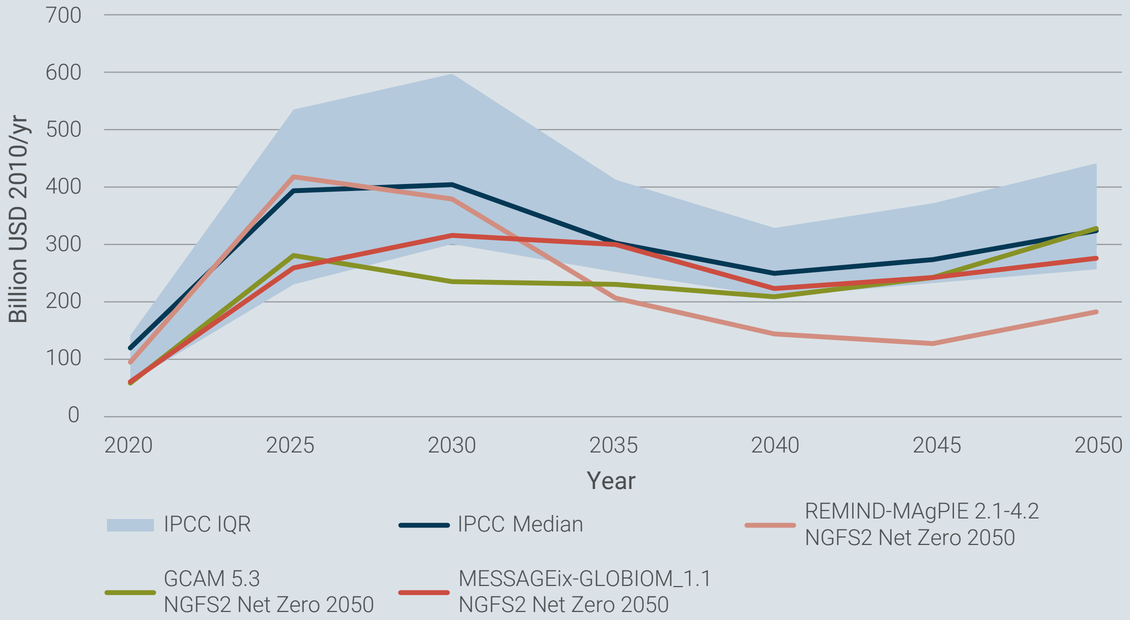


Figure 66: Investments in new power generation from solar in the IPCC-assessed 1.5°C pathways with no or limited overshoot from 2020 to 2050

Box 31: Investment in new power generation from solar in the NGFS net-zero scenarios compared to the IPCC-assessed 1.5˚C scenarios with no or limited overshoot



The REMIND pathway reports similar values as the median of the IPCC-assessed scenario dataset from 2020 to 2025. Thereafter, the levels of solar investment for power generation begin to decrease significantly, eventually becoming 0.7 times lower than the lower quartile of the IPCC-assessed scenario dataset by 2050. In comparison, the GCAM and MESSAGE models report investment values that remain between the median and lower quartile of the IPCC-assessed scenario dataset from 2040. By 2050, the GCAM reports a similar value to the median of the IPCC-assessed scenario dataset.

Data source: AR6 scenario explorer

After solar, wind projects take up a large proportion of new investments in renewable energy. **Investments in wind power include: a ramp-up of installation rates; an expansion of projects across new shores and new areas of the seabed; an advancement of technologies for improved efficiency and minimised costs; a scaling-up of projects to utility level; an expansion of the grid and of transmission networks; and the commercialisation of green hydrogen** (Global Wind Energy Council, 2022; Fortune Business Insights, 2021; McKinsey, 2022b). Scenario pathways limiting warming to 1.5°C with no or limited overshoot report a substantial increase in annual investments in electricity supply from wind; increasing from USD 103 billion (USD 73–USD 126 billion) in 2020 to USD 392 billion (USD 285–USD 613 billion) in 2030 and USD 479 billion (USD 302–USD 544 billion) in 2050 (Figure 67).

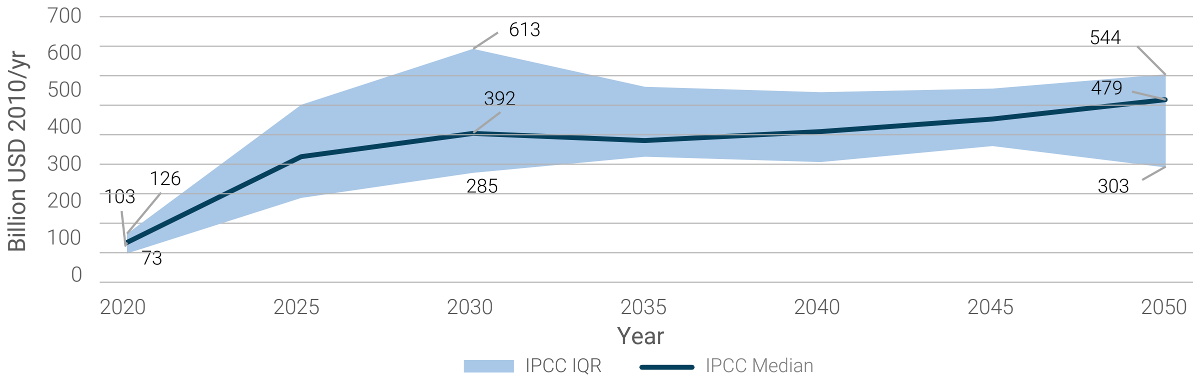
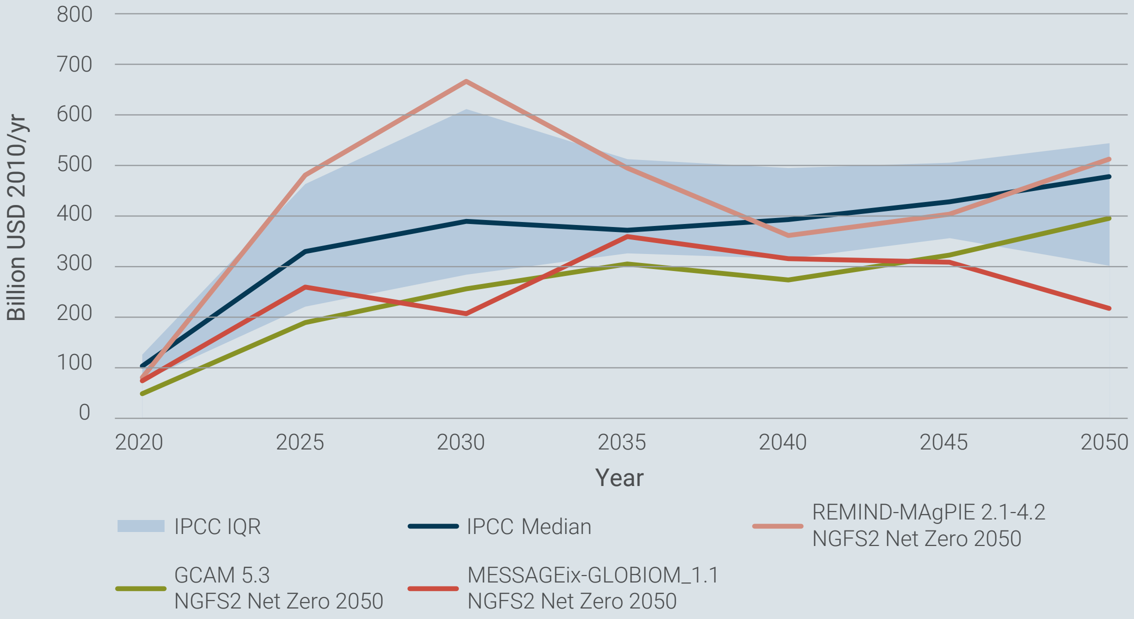


Figure 67: Investments in new power generation from wind in the IPCC-assessed 1.5°C pathways with no or limited overshoot from 2020 to 2050

Box 32: Investment in new power generation from wind in the NGFS net-zero scenarios compared to the IPCC-assessed 1.5°C scenarios with no or limited overshoot



The REMIND pathway reports significant fluctuation in investments in new power generation from wind from 2020 to 2040. At first, a rapid increase is modeled from 2020 to 2030, with investments exceeding the upper quartile values of the IPCC-assessed scenario dataset. This is followed by a decrease from 2030 to 2040, during which time investments fall below the median range of the IPCC-assessed scenario dataset. In comparison, the modelled pathways of GCAM and MESSAGE show values of wind investment for power generation that are close to the lower quartile of the IPCC-assessed scenario dataset. Post 2040, GCAM witnesses continuous growth above the lower quartile of the IPCC-assessed scenario dataset, while MESSAGE shows investments dipping below the lower quartile of the IPCC-assessed scenario dataset. Median level of investment for the IPCC-assessed scenario dataset is about two times higher than investments reported by the MESSAGE pathway in 2050.

Data source: AR6 scenario explorer

7.3.5 Transmission and distribution, plus storage capacity

To limit global warming to 1.5°C with no or limited overshoot, the IPCC assessed scenario pathways report annual investments of USD 549 billion in transmission and distribution of electricity over the next decade. **Countries' transmission networks and storage capacity need to be upgraded and expanded to improve grid flexibility and reliability so as to meet the warming target, which will require substantial investments from financial institutions**. Today's network of transmission lines were designed with the transportation of power from coal, natural gas, and hydroelectric generators in mind. However, to enable greater deployment of clean energy in the future, grids will need to be updated to ensure they have greater flexibility and wider geographical coverage. In this way, electricity from wind and solar resources can match local energy demand. Investments are required to guarantee that new transmission lines deliver energy from renewables over larger areas, while also being more resilient to local weather events (Yale, 2022). In AR6, scenarios limiting warming to 1.5°C with no or limited overshoot report an investment increase in the transmission and distribution of electricity from USD 355 billion (USD 291 billion–USD 411 billion) in 2020, and then to USD 780 billion (USD 446 billion–USD 1,007 billion) in 2030. In 2050, the figure is put at USD 891 billion (USD 774 billion–USD 1,238 billion) (Figure 68).

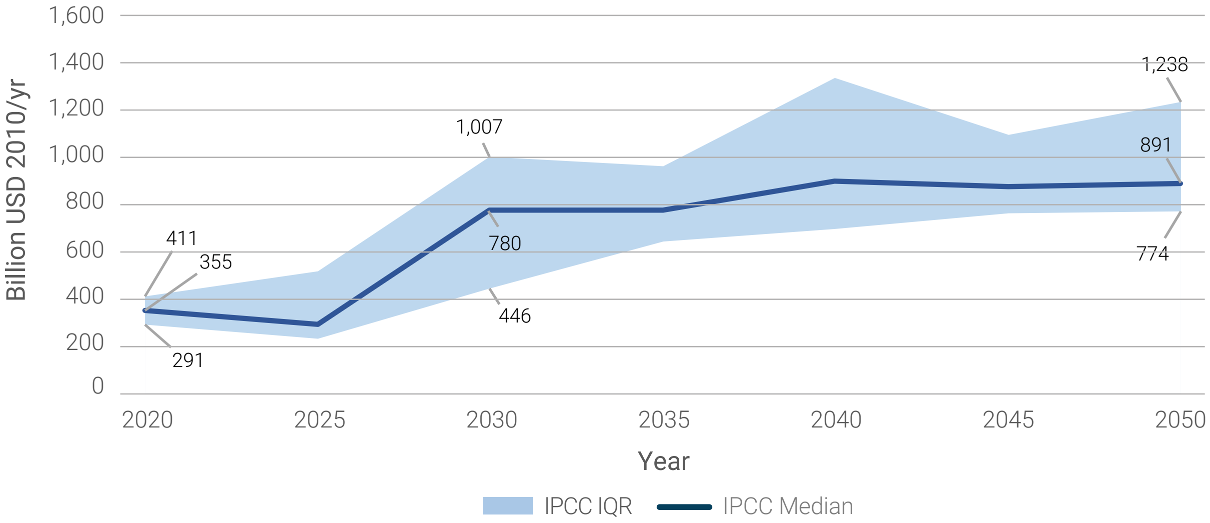
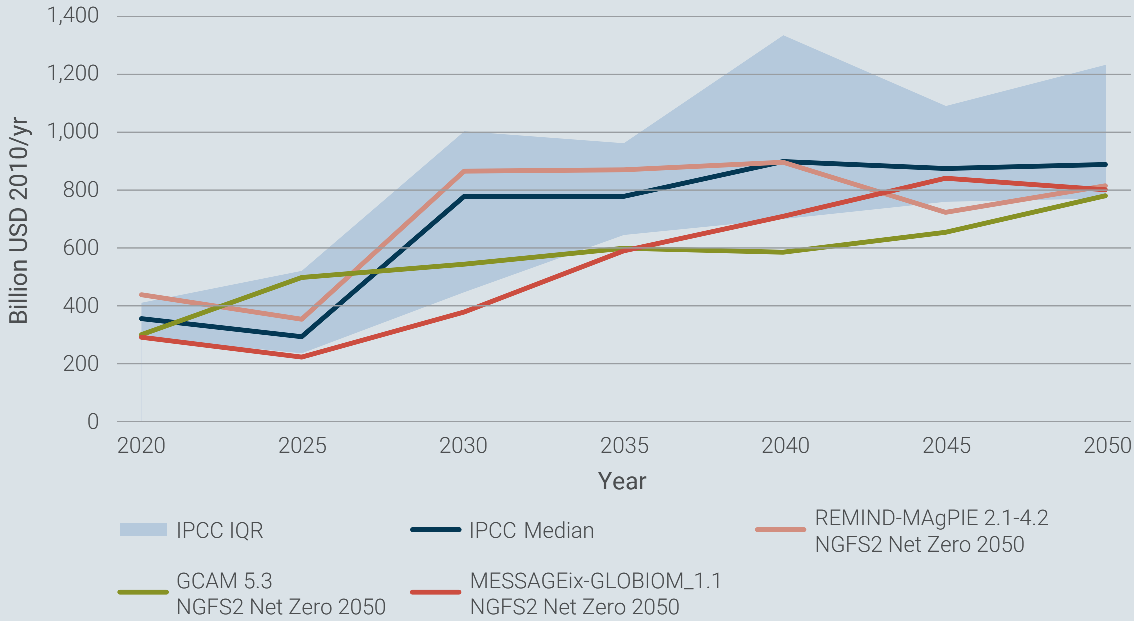


Figure 68: Investments in the transmission and distribution of energy in the IPCC-assessed 1.5°C pathways with no or limited overshoot from 2020 to 2050

Box 33: Investment in the transmission and distribution of energy in the NGFS net-zero scenarios compared to the IPCC-assessed 1.5˚C scenarios with no or limited overshoot



The net-zero pathways of all three NGFS models and the IPCC-assessed scenario dataset demonstrate an overall upward trend in investments in energy transmission and distribution from 2020 to 2050. However, the trajectory at which this occurs varies across models as the pathways report fluctuations in the investment levels. For example, the MESSAGE pathway shows a consistent rise in investments from 2025 to 2040 but shows a decline in investments before 2025 and after 2040. Similarly, the REMIND pathway also reports a decrease in investments from 2020 to 2025, followed by a rapid rise in investments from 2025 to 2030, after which investment levels both increase and decrease. The GCAM pathway shows an overall increase in investments, with a slight dip between 2035 and 2040. By 2050, the investment levels reported in the three NGFS pathways are lower than the median level of investments reported in the IPCC-assessed scenario dataset.

Data source: AR6 scenario explorer

7.3.6 Energy efficiency

Currently, there are cost-effective technologies that can improve energy efficiency. However, **investments will be needed to digitalise energy systems in order to further improve energy efficienc**y. Advancements in digital technologies can reduce energy losses during production and distribution, improve grid flexibility, and adapt to growing variables (IEA, 2021b; IEA, 2019). In AR6, the IPCC-assessed 1.5°C scenarios with no or limited overshoot all concur that investments in energy efficiency need to be increased. However, no such consensus exists on the number of investments needed by 2050 (Figure 69). The scenarios report investments in energy efficiency of USD 175 billion (USD 12–USD 362 billion) in 2030 and USD 362 billion (USD 15–USD 815 billion) in 2050.

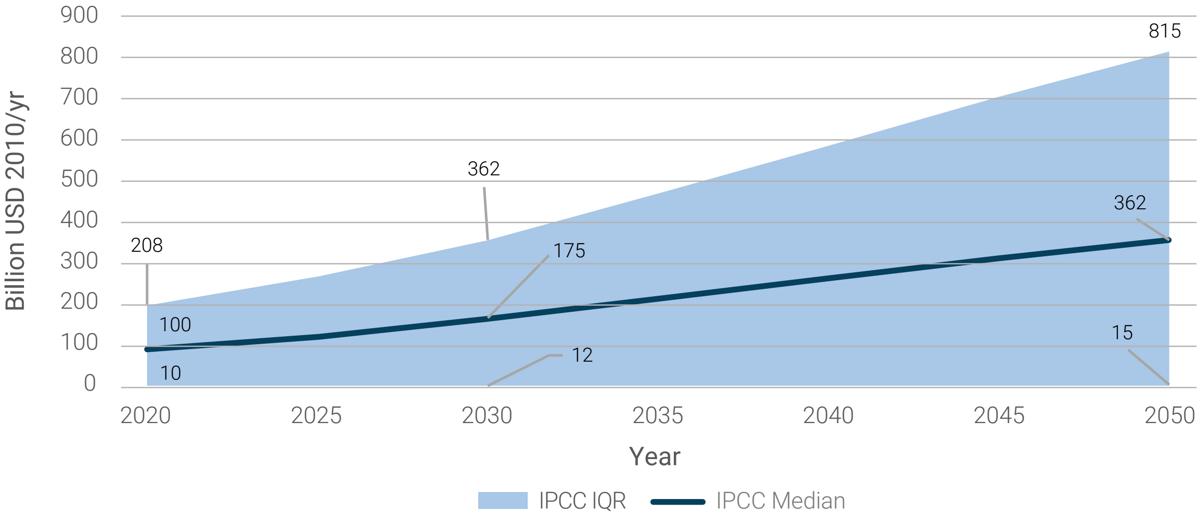


Figure 69: Investments in energy efficiency in the IPCC-assessed 1.5°C pathways with no or limited overshoot from 2020 to 2050

A large proportion of investments in the energy sector over the next decade will need to be directed towards medium and low-income countries in 1.5°C scenarios with no or limited overshoot. The focus here falls especially on countries in Asia, Latin America, the Middle East, and Africa as these regions have growing energy demand. Although this demand is still below the global average, it is expected to rise. This will present opportunities to reduce investments in fossil fuel infrastructures, such as coal-fired power plants, thereby reducing emissions and lessening the risk of additional carbon lock-in (IPCC, 2022). Figure 70 shows the percentage increase in investments in the electricity supply from wind for selected regions from 2020 to 2050 in the IPCC-assessed 1.5°C pathways. The scenarios report the greatest increase in investments in Asia, with North America some way behind and Europe even more so.

A number of obstacles are delaying new wind energy installation across various regions. Notable examples include permitting procedures and inflationary pressures. As a result, a gap is growing between the current rate of wind installations and power generation from wind energy assumed by 1.5°C scenarios with no or limited overshoot. For example, delays in current permitting procedures mean that the European Union is on track to install only half of the new wind capacity needed to reach its targets for renewable power generation by 2030 (Global Wind Energy Council, 2022). Uncertainties such as the delays caused by permitting procedures can deter the necessary investments for wind energy's expansion. This, in turn, inhibits the ability to build power generation from wind energy at the scale needed to limit warming to 1.5°C (World Energy Forum, 2023).

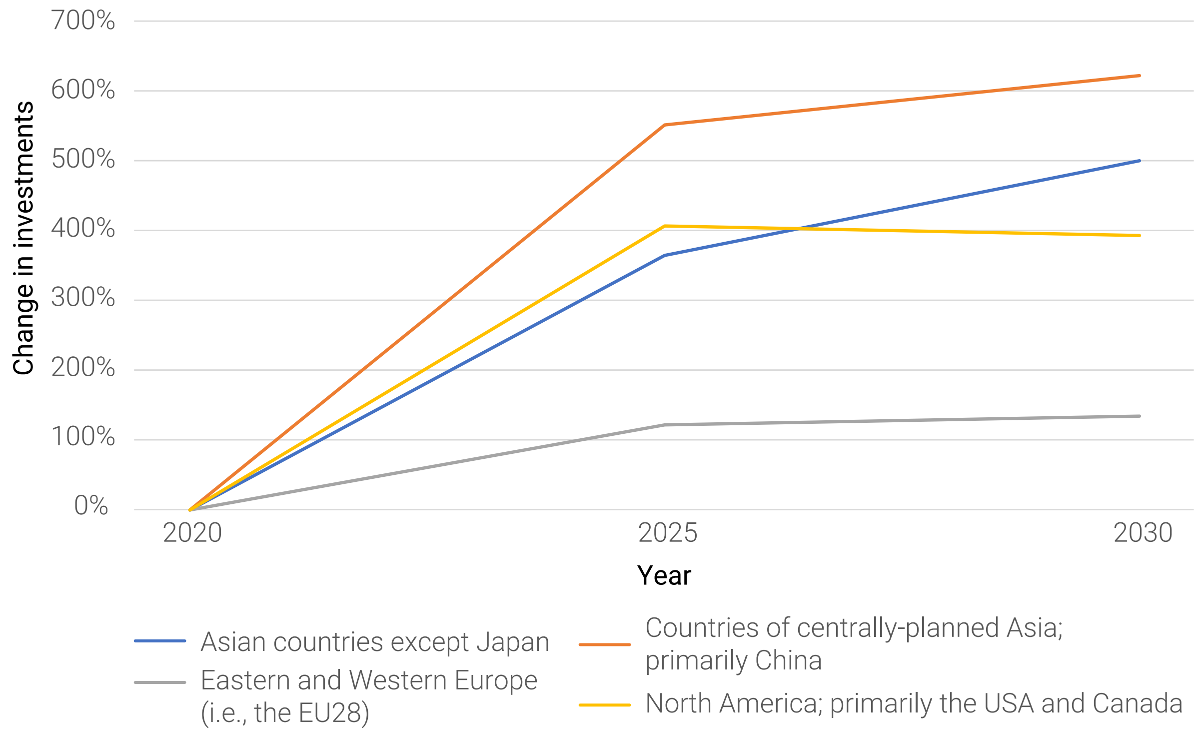


Figure 70: Percentage increase in investments in new power generation from wind for selected regions from 2020–2050 in the IPCC-assessed 1.5°C scenarios with no or limited overshoot

Box 34: Energy investments in the IPCC's Illustrative Mitigation Pathways (BloombergNEF, 2022)

BloombergNEF extrapolated from three of AR6's IMPs to determine the energy investments needed for each pathway to limit warming to 1.5°C with no or limited overshoot. The three IMPs focused on were:

- SP (Shifting Development)
- LD (Low Demand)
- REN (Renewables)

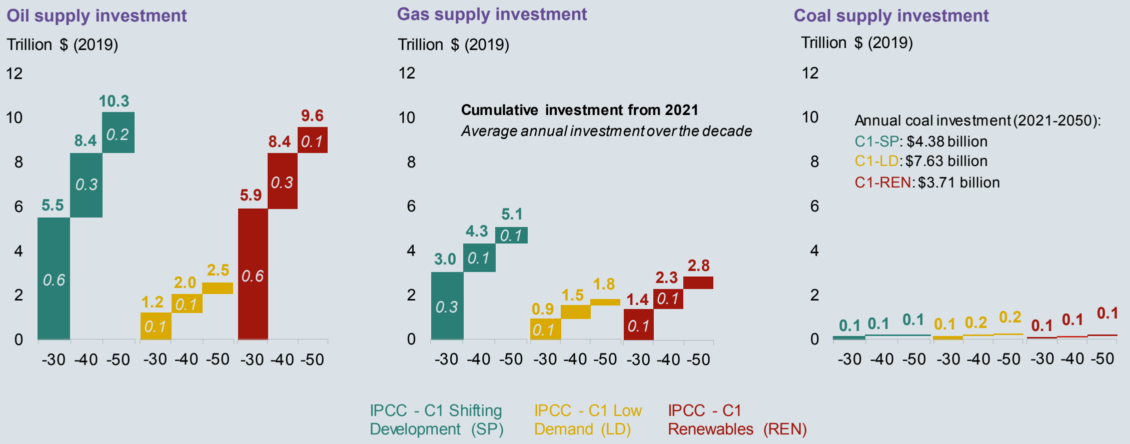


Figure 71: Total fossil fuels supply investment by fuel type

- Oil supply investment accounts for over half of the total fossil fuel investments across the scenarios.
- Due to higher reliance on oil and gas, IMP-SP shows the highest total investment in fossil fuel extraction (USD 15.5 trillion).
- By 2050, fossil fuel-based electricity investment is close to zero.
- In all three IMPs, coal investment is shown to decline but not reach zero; instead, coal investments range from USD 0.1 trillion to USD 0.2 trillion by 2050.
- For the 2020–2050 period, the decade to 2030 accounts for the largest share of investments across the three IMPs.

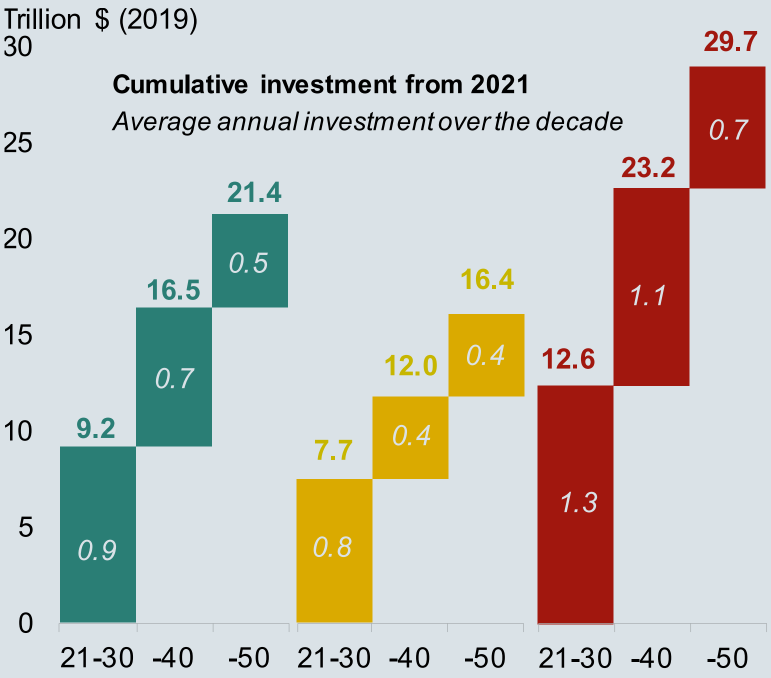


Figure 72: Investment in electricity supply generated from renewables

- Under IMPs SP and REN, renewables account for 95% of the total electricity supply investment.
- For IMP-LD, average annual investment in electricity generated from renewables remains quite constant from 2030 to 2050 due to end-use sectors shifting to electricity.

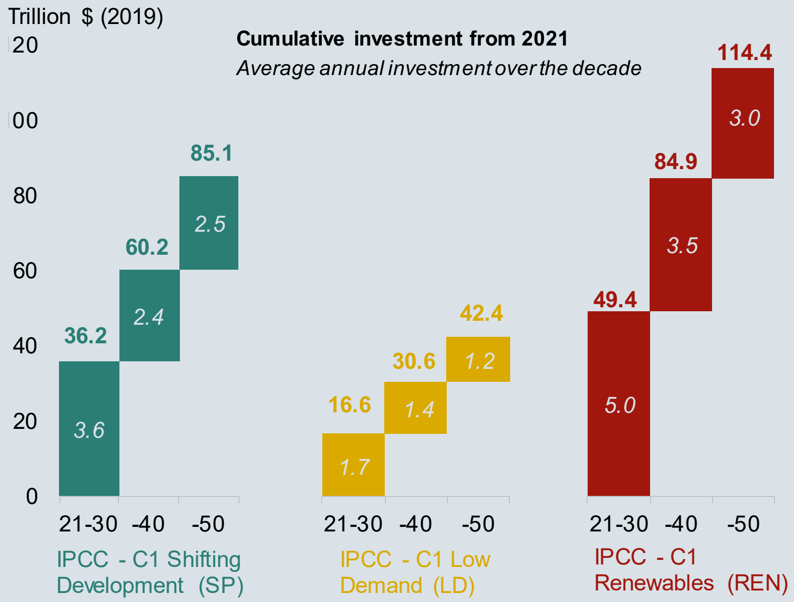


Figure 73: Total investment in energy infrastructure

- Across the three IMPs, total annual investment in global energy supply, transmission and distribution ranges from USD 1.7 trillion to USD 5.0 trillion annually between 2021 and 2030.
- For all three IMPs, investments are lower after 2030.
- IMP-REN scenario requires more investment than SP and LD due to higher projected energy demand and the pathways' focus on near-term growth of renewables before costs decline.
- For IMP-SP, annual investments increase slightly after 2040 as society makes a greater shift toward sustainability.
- IMP-LD has the lowest average annual investment and the lowest cumulative investment as demand and the needed generation capacity both decrease by 2050; this is also in line with IMP-LD having the lowest energy demand by 2050 out of the three IMPs.

7.4 Transport sector

To reach net zero by 2050, USD 5.4 trillion of investment will be needed for the transport sector over the next decade, according to the UNFCCC Race to Zero campaign (GFANZ, 2021). However, estimates from the OECD suggest that the transformation to sustainable transport could actually require up to USD 2 trillion of annual investment (UN, 2021). A large proportion of such investments will be driven by the increasing demand for EVs and the need for associated infrastructure. 1.5°C pathways with no or limited overshoot report simultaneous investment in **infrastructure and vehicle technologies to accelerate decarbonisation. Investment opportunities include EV batteries, fuel cells, improved materials, charging infrastructure, and integration within countries' power grids**.

Electrification and electric vehicles

In recent years, electrification has spread across various segments of the transport sector, with about 20 million passenger EVs and 1.3 million commercial EVs on the road (BloombergNEF, 2022) (see Chapter 6 on Energy Demand). Despite the rapid expansion of the EV market and sales of electric cars reaching record highs in 2021, continuous investments in rapidly decarbonising the transport sector are required for it to reach net zero CO_2 emissions by 2050 (IEA, 2022). For example, the IEA Net Zero 2050 pathway reports that 60% of global car sales will be electric by 2030 and that no new ICE cars will be sold by 2035 (IEA, 2022).

Investments in transport will comprise a strong driver for replacing combustion engine vehicles (ICEVs) with EVs, such as battery-powered vehicles. The use of EVs will need to be quickly implemented across transport systems to reach net zero by 2050. This will require increased investments in battery-powered light-duty cars, but also electric versions of other vehicles such as heavy-duty trucks, autorickshaws, scooters, bikes, and buses (IPCC, 2022).

For the electrification of the transport sector, **investments will need to be directed towards the supply of raw materials, an increase in the availability of electric models, technological advancements such as higher energy density batteries for heavy-duty vehicles, fuel cell models, and fuel efficiency** (IPCC, 2022; BloombergNEF, 2022c). To scale up direct electrification by batteries, financing will be needed to supply critical minerals; e.g., lithium, cobalt, and nickel, coupled with facilities for their refinement (BloombergNEF, 2022c). Investments in the sector can help expand the manufacturing of EVs and batteries. This will help decrease battery prices and thereby reduce the price parity between EVs and ICE vehicles, which, in turn, can further drive the adoption of EVs across the global economy. Financing will need to reach both developed and developing and emerging economies. If efforts are solely focused on developed countries, there is a risk of used ICE vehicles being exported from developed countries to other markets.

1.5°C scenarios with no or limited overshoot report an increase in investments in new passenger EV technologies from USD 1,268 billion (USD 1,058–USD 1,454 billion) in 2020 to USD 1,893 billion (USD 1,839–USD 2,000 billion) in 2050 (Figure 74). Investments are reported to slow down in the scenarios after rapid sales growth in EVs over the next decade. In comparison, investments in new ICEVs decrease from USD 1,089 billion (USD 947–USD 1,266 billion) in 2020 to USD 6 billion (USD 4–USD 12 billion) in 2050 (Figure 75). A shift in investments from ICEVs to EVs varies by region in the IPCC-assessed scenarios. In 1.5°C scenarios with no or limited overshoot, investments in ICEVs rapidly decrease from 2020 to 2025 in North America (72%) and Europe (100%), compared to India (64%) and China (12%). Similarly, the scenarios report investments in new electric heavy-duty freight trucks to increase from USD 647 billion (USD 595–USD 765 billion) in 2020 to USD 2,000 billion (USD 1,980–USD 2,000 billion) in 2050.[64] This reflects faster adoption of EVs in developed countries due to stronger policies implemented for the phasing out of ICEVs, making investments in these vehicles unfavourable in these coun-

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[64] These variables on investments in transportation only include scenarios modelled using WITCH, an integrated assessment model developed by RFF-CMCC European Institute on Economics and the Environment. Therefore, the investment levels mentioned in this paragraph are based on one model.

tries in the scenarios. In emerging markets such as India, strong economic growth and a growing population are crucial drivers for increasing demand for transport vehicles in the 1.5°C scenario pathways. This results in a more gradual phase-out of ICEVs and therefore a slower reduction in investments in this type of carbon-intensive vehicle.

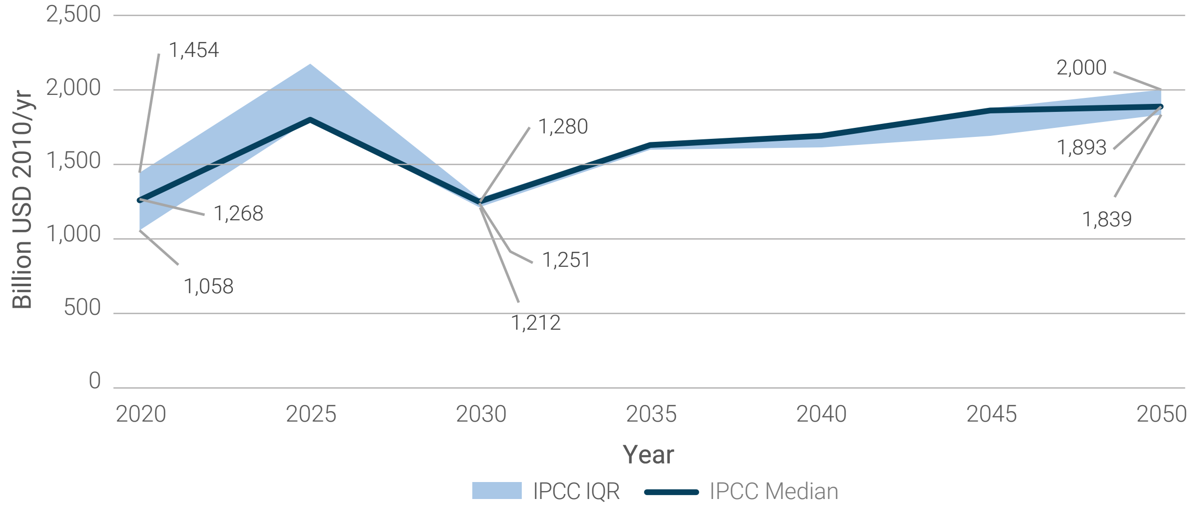

Figure 74: Investments into new passenger EV technologies[65] for the transport sector from 2020 to 2050 reported in the IPCC-assessed 1.5°C pathways with no or limited overshoot

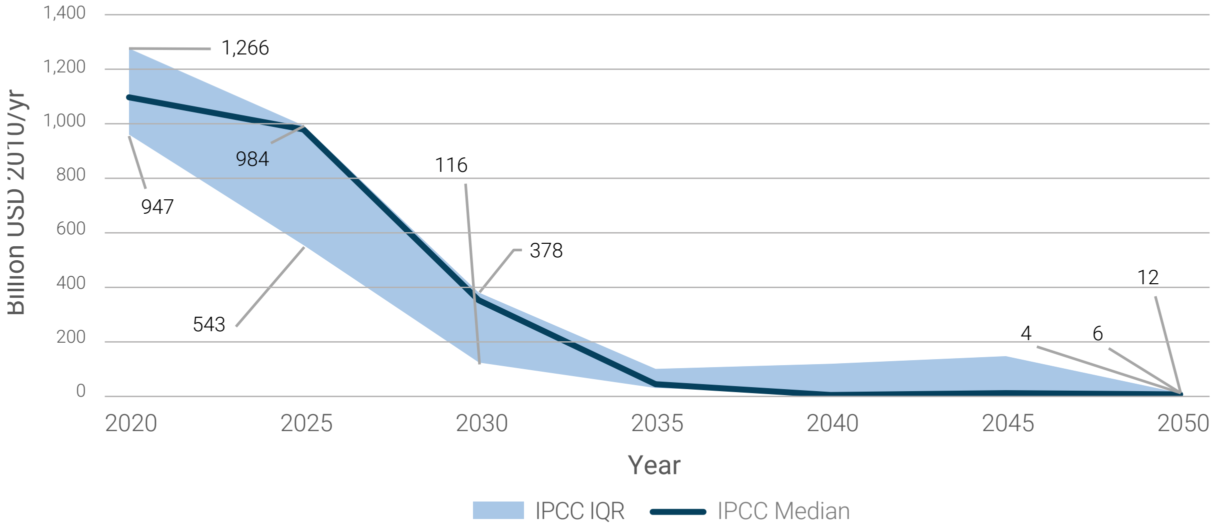

Figure 75: Investments into new passenger ICE vehicle technologies[66] for the transport sector from 2020 to 2050 reported in the IPCC-assessed 1.5°C pathways with no or limited overshoot

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[65] This variable only includes scenarios modelled using WITCH, an integrated assessment model developed by RFF-CMCC European Institute on Economics and the Environment. Therefore, the investment levels illustrated in Figure 74 are based on one model.

[66] This variable only includes scenarios modelled using WITCH, an integrated assessment model developed by RFF-CMCC European Institute on Economics and the Environment. Therefore, the investment levels illustrated in Figure 75 are based on one model.

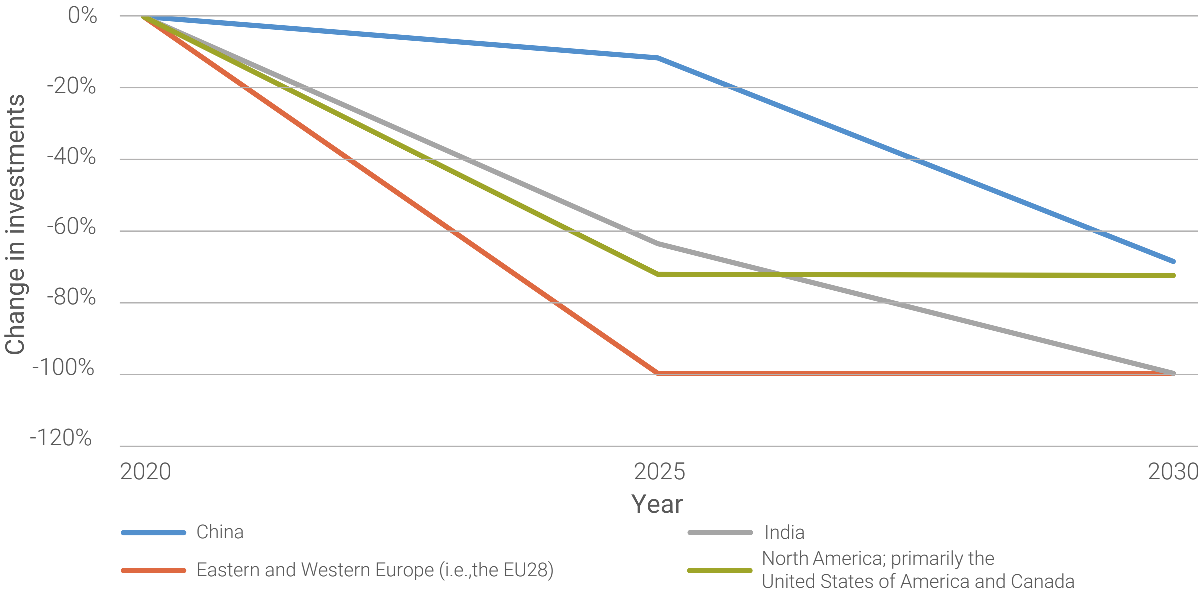

Figure 76: Regional investments reported in passenger ICE vehicles in the IPCC-assessed 1.5°C pathways with no or limited overshoot

7.4.1 Alternative fuels

Investments will be needed in alternative fuel types, such as hydrogen and biofuel, for sub-sectors that are hard to electrify. It is estimated that the capacity of sustainable fuels could increase to 46 Mt by 2025 with USD 40 billion to USD 50 billion of investments (McKinsey, 2022c). To scale up sustainable aviation fuel (SAF) by 2050, meanwhile, an estimated USD 1.45 trillion will be needed (Simple Flying, 2022).

Models offer a limited view of investments in alternative fuels for the transport sub-sectors, such as aviation and shipping. Current climate models do not serve an adequate job of modelling the financing need for alternative fuels.

7.4.2 Infrastructure

To ramp up the use of EVs and alternative fuel types, investments will also be required for the updating and expansion of EV-related infrastructure for the transport sector. New EV technologies are highly reliant on the deployment of grid infrastructure, which will need to be upgraded to include clean energy sources for transportation. To scale up the decarbonisation of the transport sector, consumers will require robust and reliable charging networks. Such networks give consumers the confidence that EVs can meet their driving range requirements and make long-distance driving possible (IPCC, 2022). A large expansion of charging infrastructure, such as new charging and re-fuelling stations, will need to be installed with ramped-up financing. This will support the uptake not only of more EVs, but also other battery-powered vehicles such as vans, buses and trucks. Additional investments will also be needed to help persuade consumers to cycle and walk more, as well as to use public transport more often. Actions like these will help reduce energy demand for the transport sector. 1.5°C scenarios with no or limited overshoot report an increase in investment in hydrogen infrastructure for the transport sector from USD 0.2 billion in 2020 to USD 0.8 billion annually in 2050 (Figure 77). Such infrastructure includes refuelling station and pipes.

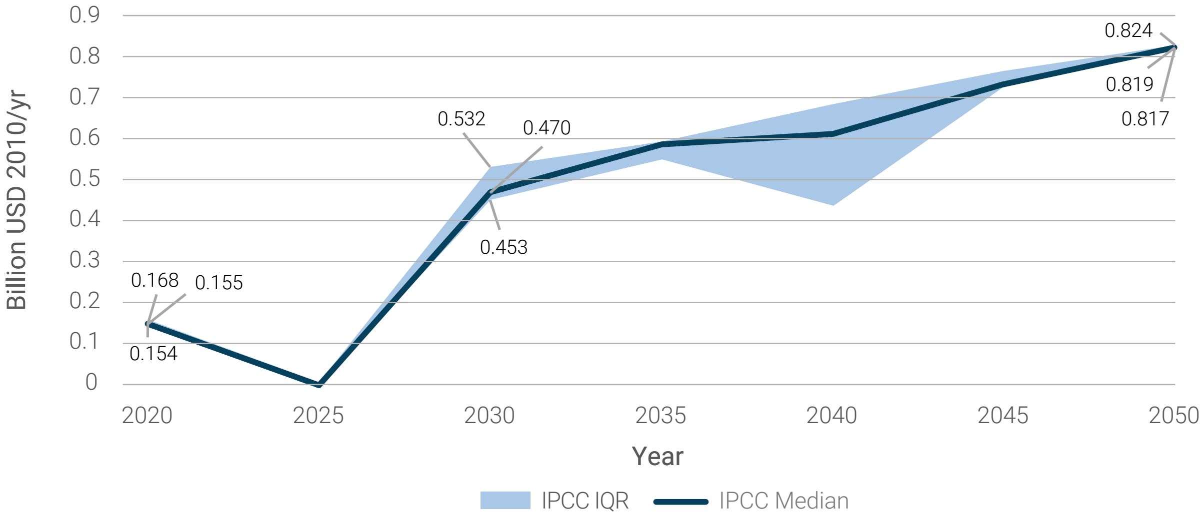

Figure 77: Investments in hydrogen infrastructure[67] for transportation reported in the IPCC-assessed 1.5°C pathways with no or limited overshoot from 2020 to 2050

Scenario models that report a slower phase-out of fossil fuels in the coming years are more optimistic about the use of fossil fuels as end use in the transport sector. Such models will differ in the financial variables reported with lower levels of investment in the electrification of vehicles and its needed infrastructure. They will instead show higher levels of continued investments in ICEVs.

7.5 AFOLU

Variable granularity for investments in the AFOLU sector is limited, with a large proportion of scenarios being generated from energy system models. Existing models also offer a limited view for investments in the AFOLU sector. Further, those models that do estimate investments for the sector have limited granularity. Current climate models therefore do not serve an adequate job for modelling the financing needs for the AFOLU sector for a net-zero transition. As a result, the sub-section below on investments for the AFOLU sector cannot make definitive statements.

Although investments required for the AFOLU sector are lower than for other sectors, (in absolute terms), investments will need to increase to ensure the crucial transition of the global food and land use systems to reach net zero by 2050 (CPI, n.d.). The UNFCCC Race to Zero campaign estimates that USD 1.5 trillion worth of investments will be needed for the sector over the next decade (GFANZ, 2021 [analysis conducted by Vivid Economics]). **Annual investments will be needed towards sustainable agricultural practices, the meeting of increased agricultural demand, changes in global diets, a reduction in food waste, the uptake of land-based solutions, and the growing use of biofuel for energy** (CPI, n.d).

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[67] This variable only includes scenarios modelled using WITCH (an integrated assessment model) which only covers investment in hydrogen infrastructure for the transport sector. Therefore, the investment levels illustrated in figure 77 are based on one model.

7.5.1 Sustainable farming practices

A shift towards sustainable farming practices will require investment into supplies and equipment which will help decarbonise the sector. New technologies, such as disease resistance for crops, provide investment opportunities for financial institutions (World Bank, 2022a; Commercial Agriculture for Smallholders and Agribusiness, 2021). Investments will be needed to overcome crucial barriers such as accessing limited technology and upscaling green farming (Brookings, 2022). Financing by financial institutions provides business opportunities for farmers in the transition to net zero.

Investments will need to be directed away from fossil fuels and towards renewable energy. Schemes on farms and estates can account for a large proportion of renewable energy capacity; e.g., through solar and wind energy. One of the most mature applications of renewable energy is solar irrigation, which also improves access to water and, as a consequence, increases the resiliency of crops. Renewable-based agro-processing systems, which can be stand-alone or based on mini-grids, are becoming a cost-effective alternative to fossil fuels. However, these still remain at an early stage of development. Renewable-based cold storage and refrigeration can provide various advantages, including affordable energy, easy transition from traditional infrastructure, and decentralised cold storage for small businesses and remote communities (FAO, 2021). Anaerobic digestion (AD) can convert animal manure, food waste, crops, and crop by-products into renewable energy. Investments in AD can help produce renewable energy and improve waste management. Investments can be directed towards using biomass by-products from agricultural activities can be used to produce energy for processing, storing and cooking (FAO, 2021).

As diets shift towards less-carbon-intensive consumption, investments will be needed to advance plant-based and artificially produced meat alternatives. Experts predict that alternative proteins could be provided as an option at the majority of fast-food and fine-dining restaurants by 2030 (McKinsey, 2022d).

7.5.2 Nature-based carbon capture

Pathways reliant on land use for carbon sequestration will need financing to increase the carbon sequestration potential of agricultural land. Increased carbon sequestration can reduce the net climate impact of agricultural production by removing and storing carbon in soil and biomass. To do so, investments will be required to protect organic soil by introducing trees into agricultural production (also known as agroforestry), changing tillage practices, and converting croplands to grasslands. Financing for the conversion of agricultural land to forests can help meet warming targets but it can have more significant implications for agricultural production and farm business models (Institute European Environmental Policy, 2019).

7.6 Industrials

Variable granularity for investments in the Industrials sector is limited, with a large proportion of scenarios being generated from energy system models. Existing models also offer a limited view for investments in the Industrials sector. Further, those models that do estimate investments for the sector have limited granularity. Current climate models therefore do not serve an adequate job for modelling the financing needs for the Industrials sector for a net-zero transition. As a result, the sub-section below on investments for the Industrials sector cannot make definitive statements.

Given that a portion of its emissions are likely to be hard to abate by 2050, the Industrials sector will require significant financing to advance less carbon-intensive technology and greater energy efficiency, as well as to reduce the carbon intensity of industrial processes and to deploy CCS on a large scale. The UNFCCC Race to Zero campaign estimates that investments of USD 2.2 trillion will be needed to reach net zero CO_2 emissions by 2050 (GFANZ, 2021). **Investments will be required to scale up capacity for less carbon-intensive power generation, to increase green hydrogen production, to advance specialised equipment, to construct new facilities, and to introduce CO_2 transportation and storage**. Most technologies needed to decarbonise the Industrials sector are not commercially competitive today. Investments will be crucial to reducing costs of such technologies to become competitive with traditional processes (World Economic Forum, 2022).

7.6.1 Steel

To decarbonise the steel sub-sector, investments will be needed in CO_2 carbon capture, clean technologies for steel production, green hydrogen made from renewable energy, and electrification. Investments in renewable electricity for secondary steel production can make the process almost carbon neutral (World Economic Forum, 2022).

Investments in electric arc furnace (EAF) technology can help substantially reduce the carbon intensity of steel production without a significant increase in the cost of production. Steelmaking through electrochemical processes holds potential to help the sub-sector reach net zero and will require substantial investments for it to be used commercially. Adoption of less emission-intensive power for steelmaking will also require investment in infrastructure for integration. As a hard-to-abate industry, the steel sub-sector will also be reliant on CCS to reach net zero by 2050. To be able to deploy CCS on a large scale, investments will be needed to advance the technology and decrease the costs. Along with investments in technologies and production assets, investments will also need to be directed towards infrastructure at facilities for clean-energy use for power, hydrogen production, and the transportation and storage of carbon (World Economic Forum, 2022). An estimated USD 170 billion–USD 200 billion will be needed annually to scale up the commercialisation and deployment of technology needed to achieve net-zero steel by 2050 (HSBC, 2022). The adoption of technologies such as green hydrogen and carbon capture at market scale could require USD 200 billion globally each year until 2050. An estimated USD 2 trillion will be needed to finance the necessary infrastructure (CPI, 2022a)

7.6.2 Cement

To decarbonise the cement sub-sector, investments will need to focus on abatement methods to reduce the carbon intensity of cement production. Investments will need to be directed towards advancing innovative technologies that can change the formulation of cement in order to decrease its carbon intensity. Viable steps include, lowering the proportion of limestone in cement, adding CO_2 to concrete to strengthen it, and reducing the quantity of cement needed for use (Lim, 2019; Imperial College London, 2021). Investments of up to USD 1 trillion by cement manufacturers will be required to reach net zero by 2050 (Carbon Pulse, 2022).

Across 1.5°C scenarios with limited to no overshoot, cement CCS plays a complementary role to emission reductions in reaching global climate goals. However, many technologies in this sector are still in the pilot phase and may only reach commercialisation in the 2030s. Accelerating the development and deployment of these technologies requires investment. Estimates suggest that at least USD 185 billion is needed to develop transport and storage for captured CO_2. Similarly, about USD 110–USD 240 billion must be invested in infrastructure for large-scale deployment of CCS. Investments in infrastructure will be crucial as only 1% of the needed infrastructure for CCS has been developed to date. Investments will also need to be directed towards green hydrogen and electric kilns, which can help further reduce emissions for cement plants with CCS. To decarbonise the sector, investments will also be required to make clinkers and cement production more efficient. Power generation for quarrying, crushing, grinding, and blending will also need to be decarbonised from fossil fuels to clean energy. Investments in infrastructure will also be required for decarbonisation process, including concrete recycling, alternative fuels, and low-carbon raw materials (World Economic Forum, 2022).

7.6.3 Aluminium

Electrification, green hydrogen, and inert anodes will be key to decarbonising the aluminium sub-sector. To scale these up across the industry will require substantial investments. It is estimated that about USD 510 billion could be needed in investments for clean energy, including hydrogen, infrastructure for clean technologies, clean hydrogen capacity, and CO_2 transport and storage (World Economic Forum, 2022).

Hydroelectricity already powers 25% of primary aluminium production but can be further scaled up with an estimated USD 439 billion. Investments will be needed to decarbonise the refining and smelting processes for aluminium, which can be achieved by using clean energy and electrifying refining and smelting and by deploying green hydrogen for high heat. Investing in electric boilers, mechanical vapour recompression, and inert anodes will help decrease emissions further. Investments in infrastructure for low-emission hydrogen production could require a minimum of USD 60 billion. Scrap-based secondary aluminium can be produced using electric furnaces. Such technologies are in the early stages of maturity for use in the aluminium sub-sector, increasing the importance of investments to scale up and reduce costs. Carbon capture could also play a crucial role in reaching net zero by 2050 but this would require investments to be further explored (World Economic Forum, 2022).

7.6.4 Ammonia

To decarbonise the ammonia sub-sector, investments will need to be directed towards CCUS and electrolysis. Both technologies are available at present but will require investments to scale up. Investments in green hydrogen will be necessary for low-carbon ammonia production to be used commercially. Methane pyrolysis and biomass gasification comprise other potential technological alternatives to support low emission hydrogen production. To develop methods such as electrolysis and CCS, investments will also need to focus on developing infrastructure (World Economic Forum, 2022). It is estimated that annually USD 60 billion–USD 105 billion is required in investment through to 2050 in order to commercialise and deploy technologies for near-zero emissions of ammonia. Of these investments, 80% will need to be directed towards green ammonia (HSBC, 2022).

7.7 Buildings

Variable granularity for investments in the Buildings sector is limited, with a large proportion of scenarios being generated from energy system models. Existing models also offer a limited view for investments in the Buildings sector. Further, those models that do estimate investments for the sector have limited granularity. Current climate models therefore do not serve an adequate job for modelling the financing needs for the Buildings sector for a net-zero transition. As a result, the sub-section below on investments for the Buildings sector cannot make definitive statements.

Buildings and their construction can be highly carbon-intensive. Therefore, the transition to net-zero buildings will create investment opportunities in retrofitting existing buildings and new low-emissions construction. The UNFCCC Race to Zero campaign estimates that USD 5.2 trillion of investment will be needed for buildings by 2050 to reach net zero CO_2 emissions (GFANZ, 2021). **Investment opportunities to decarbonise the sector include digitalisation, 'green' building materials, renewable energy, low-emissions building design and construction, material efficiency, and retrofits**. As the global population continues to grow, demand for housing and its related energy demand is expected to rise in the coming decades. Therefore, investments in the buildings sector stands to be crucial in accelerating the construction of new net zero buildings and updating existing buildings.

7.7.1 Existing buildings

An estimated annual investment of USD 700 billion will be needed for existing buildings to reach net zero by 2050. Of these investments, 80% will need to be directed towards retrofitting and heating, followed by appliances. The requirement for annual investments is projected to rise four times from 2020 (USD 186 billion) to 2040 (USD 714 billion). Of the investments for existing buildings by 2050, 70% will be concentrated in developed economies (GFANZ, 2021). To reduce carbon emissions produced by buildings, investments will be required in order to drive a reduction in thermal energy need and to shift to energy-efficient appliances, as well as to increase uptake of clean technologies and improve flexibility (IEA, 2022b).

Investments in energy efficiency will also be important to the decoupling of energy consumption from floor area growth (IEA, 2022b). For example, investments in heating and cooling will be needed in order to bring to market the innovative technologies required for decarbonisation. As temperatures rise, the need for energy-efficient air conditioning will become increasingly important. This provides investment opportunities for various well established and new technologies, such as ice refrigeration, thermal storage technologies and the use of renewable energy (such as solar power for air conditioning) to reduce energy consumption and power demand. Other technologies to improve energy efficiency include nanoparticles and solar thermoelectric cooling (IPCC, 2022). Financial institutions can support new companies developing technologies in the early stages through investments that help scale up such technologies and accelerate their adoption (IEA, 2022b). For energy efficiency, investments will also be needed for the digitalisation of buildings as this can help improve the tracking and management of energy consumption (IEA, 2019). UNEP's United for Efficiency financing manual provides an overview of innovative financing mechanisms encouraging energy-efficiency investments in the residential, commercial and public sectors, as well as case studies from around the world.

A large proportion of financing for building retrofits in some regions is estimated to come from individual households and private companies that either own the buildings in question or carry out retrofits on behalf of their building's owners. However, commercial financial institutions can contribute a significant proportion of the financing for building retrofits up to 2050 (GFANZ, 2023).

With more significant investments, alternative energy sources such as hydrogen can become an important energy carrier for decarbonising the building sector. Investments will be needed in sourcing hydrogen and converting gas grids to hydrogen.

7.7.2 New buildings

Approximately 40% of buildings and 75% of the infrastructure that is predicted to exist in 2050 has not yet been constructed (Schroders, 2022). This creates a massive opportunity for investment by the financial sector in constructing new, low-carbon emissions buildings. To limit warming to 1.5°C, these so-called "net-zero buildings" will have net-zero carbon across their lifecycle. The shift to these kinds of buildings will require investments for changes on a massive scale, such as the materials, heating and cooling design and systems, electricity generation, lighting, and thermal envelopes (CPI, 2022b).

The International Energy Agency (IEA) estimates up to USD 5.4 trillion of investment in the buildings sector by 2050 to limit warming to below 2°C. The majority of this investment is estimated to be concentrated towards Europe, the USA, India, and China. This is despite population growth, urbanisation, and rising incomes in low and middle-income countries in Africa and Asia leading to a rapid increase in the construction of new buildings in these regions. For new green buildings in emerging markets, IFC estimates there is a USD 24.7 trillion investment opportunity by 2030. For East Asia Pacific and South Asia alone, it puts the investment opportunity for green buildings (i.e. those 20% more energy efficient than baseline buildings) at USD 17.8 trillion. The investment opportunity for residential construction is estimated at USD 15.7 trillion. Financial instruments that support net zero carbon buildings include equipment leases, mortgages, bonds, on-bill repayment, energy services contracts, and property-assessed clean energy loans (CPI, 2022b).

Energy efficiency can produce cost-effective strategies that provide high returns on investment (Whole Building Design Guide, 2016). Investments will need to be ramped up for on-site and off-site renewables and for energy efficiency. Energy efficiency measures can include design strategies and features such as high-performance envelopes, air barrier systems, sun control and shading devices, windows and glazing, passive solar heating, natural ventilation, and water conservation (Whole Building Design Guide, 2016). Investments will also be needed to generate energy on site or off site in order to compensate for energy use in buildings. Financing will therefore be required for new facilities such as wind turbines and solar collectors that can generate renewable power at separate sites.

Investments will also be needed to reduce the embodied carbon footprint of materials used for constructing buildings. Investments can drive advances in construction technologies and materials that are cheap and sustainable as well as that help reduce waste and facilitate alternative structures. One such technology is 3D printing. This will not replace architectural construction but will instead help optimise new construction processes and tools. To decarbonise the sector, the digitalisation of construction processes will also be important. Investments can assist in advancing digital technologies, such as building information modelling (BIM), additive manufacturing, drones, sensors, and 3D scanning (IPCC, 2022).

Table 29: Recommended scenario variables to use for assessing financing needs in pathways (AR6 scenario explorer)

Variable	Unit	Definition	Additional information
Energy			
Investment | Energy Supply | Electricity | Coal	billion USD 2010/yr	Investments in new power generation by coal for the specified power plant category.	Further variables can be used to assess investments specifically for power plants equipped with CCS and without CCS. For plants equipped with CCS, the variable includes investment in the capturing equipment but not transport and storage.
Investment | Energy Supply | Electricity | gas	billion USD 2010/yr	Investments in new power generation by gas for the specified power plant category.	Further variables can be used to assess investments specifically for power plants equipped with CCS and without CCS. For plants equipped with CCS, the variable includes investment in the capturing equipment but not transport and storage.
Investment | Energy Supply | Electricity | Non-Biomass Renewables	billion USD 2010/yr	Investments in new power generation by non-biomass renewables for the specified power plant category.	Separate variables are available to assess investments in specific non-biomass renewables, such wind, solar, geothermal and hydro.
Investment | Energy Supply | Electricity | Oil	billion USD 2010/yr	Investments in new power generation by oil for the specified power plant category.	Further variables can be used to assess investments specifically for power plants equipped with CCS and without CCS. For plants equipped with CCS, the variable includes investment in the capturing equipment but not transport and storage.
Investment | Energy Supply | Electricity | Solar	billion USD 2010/yr	Investments in new power generation from solar energy for the specified power plant category.	No additional variables for a sectoral breakdown available.
Investment | Energy Supply | Electricity | Transmission and Distribution	billion USD 2010/yr	Investments in transmission and distribution of power generation.	No additional variables for a sectoral breakdown available.

Investment | Energy Supply | Electricity | Wind	billion USD 2010/yr	Investments in new power generation from wind energy for the specified power plant category.	No additional variables for a sectoral breakdown available.
Transportation			
Investment | Energy Demand | Transportation | Passenger | Aviation	billion USD 2010/yr	Investments into new Passenger vehicle technologies in the Aviation transport sector.	No additional variables for a sectoral breakdown available. Separate variables are available for other sub-sectors of transportation, such as roads and railways.
Investment | Energy Demand | Transportation | Passenger | Road | LDV | EV	billion USD 2010/yr	Investments into new vehicle technologies in the transport sector (light-duty cars and trucks: electric vehicle technologies, including all-electrics and plug-in hybrids).	No additional variables for a sectoral breakdown available.
Investment | Energy Demand | Transportation | Passenger | Road | LDV | ICE	billion USD 2010/yr	Investments into new vehicle technologies in the transport sector (light-duty cars and trucks: internal combustion engine technologies running on any type of liquid or gaseous fuel).	No additional variables for a sectoral breakdown available.
Investment | Infrstrastructure | Transportation	billion USD 2010/yr	Investment into transport infrastructure—both newly constructed and maintenance of existing (all types: roads, bridges, ports, railways, refueling stations, and charging infrastructure, etc.). *Please note this variable only includes data on investment in hydrogen infrastructure for transportation by the WITCH model.*	No additional variables for a sectoral breakdown available.

7.8 Adaptation finance

Adaptation finance remains significantly underfunded compared to mitigation. In 2021/2022, for example, USD 63 billion went towards financing adaptation. In contrast, USD 1.2 trillion was directed towards financing mitigation in the same period (with USD 51 billion earmarked for dual adaptation/mitigation projects). According to CPI, USD 614 billion from the private sector went towards mitigation between 2021 and 2022, but only USD 1.5 billion was financed towards adaptation (CPI, 2023).

In 2021/2022, adaptation finance increased by 29% as compared to 2019/2020, but it continues to lag (CPI, 2023). Even so, it remains below the level needed to respond to growing climate risks. Annual adaptation costs in developing countries are estimated to range between USD 140–USD 300 billion by 2030 and USD 280–USD 500 billion by 2050 (UNEP, 2021). Estimates suggest that annual investments of USD 11–USD 20 billion will be needed by 2050 to adapt urban infrastructure to climate risks (C40 Knowledge Hub, 2022). Furthermore, many vulnerable countries do not receive the financing available. It is notable, for instance, that middle-income countries receive almost 70% of the total climate finance mobilised by developed countries (OECD, 2023).

The public sector provides the majority of adaptation financing through multilateral and national development financial institutions (CPI, 2022c). At the same time, private financing for adaptation remains significantly low, with only USD 1.5 billion financed by corporations and institutional investors in 2021/2022 (CPI, 2023). Barriers to investments in adaptation by the private sector remain. This is due to concerns on the bankability of adaptation activities as well as the limited capacity for identifying and developing adaptation projects. Adaptation finance data from the private sector remain limited in quantity and quality. These data constraints, coupled with limited agreement regarding metrics, make it difficult to track adaptation finance from the private sector (CPI, 2021; CPI, 2022c).

7.9 Scenario limitations

Scenarios assessed in AR6 that limit warming to 1.5°C with no or limited overshoot are limited in their pathways reporting investments needed to meet the climate goal. Some of the key limitations of the scenarios are highlighted below.

1. Scenarios **use the least-cost pathway,** with a key element of the financing assumptions being how much technology costs decrease over time. The least-cost assumption makes the financing need a small percentage of a country's GDP but this will need to be further scaled up.
2. Scenario models **do not break down** the financing reporting in scenario pathways to the private and public sector. Models **do not provide coverage** of the financial sector and therefore are unable to report specific investment levels by financial institutions for 1.5°C scenario pathways with no or limited overshoot. As the models do not cover the financial sector, the complexities of how capital is allocated is greatly simplified. Simplifications can mean that significant frictional costs associated with capital spending are not considered. Similarly, climate scenarios

do not provide financial users with information on capital and provision for investments nor on the level of risk associated with specific investments.

3. **Limited standardisation** on the definitions that modellers use for key assumptions in investments, such as the financing of fossil fuels (GFANZ, 2022).
4. **Limited granularity** in investment variables of the models. Some of the crucial investment needs for various sectors are not included in the models. For example, AR6 states that investments in electrification derived from integrated assessment models (IAMs) "do not include systematically investments in end-use equipment and distribution" (IPCC, 2022). Only a limited number of variables on investments are available for the Industrials, Agriculture, Buildings, Aviation, and Shipping sectors. The same is true for sub-sectors. This results in only being able to gather a high-level view of the investments needed in respective sectors and sub-sectors for the pathway to limit warming to 1.5°C with no or limited overshoot. Similarly, scenarios can neglect behavioural changes and transport mode changes. Regional granularity, especially for less developed countries, is also limited as regions are modelled based on geographical proximity, with less developed countries grouped with other countries.
5. Scale-up of financing by financial institutions to meet climate goals will require financial tools and products. However, scenarios **do not provide information of the specific tools and products** that will be needed. Instead, scenarios can be used by investors to see the market size and financing opportunities.
6. Scenarios **do not provide information on the nature and duration** of financing. Instead, financial institutions need to differentiate the nature and duration of the financing, plus the specific destination of such financing.
7. **Estimates on investments can vary** between scenarios with limited information provided on the underlying technology cost assumptions. For example, estimates of the need for energy investment significantly differ between models, with little transparency of the underlying technology cost assumptions. IRENA reports selectively on financing needs for energy efficiency in Buildings and Industrials as separate categories, for instance. This leads to high assumptions for investment needs. In comparison, IEA's estimates of financing needs are lower for its net-zero scenario (IPCC, 2022).
8. **Cost of capital**[68] in different regions is not clearly considered in climate models. The cost of capital measures the expected financial return, or the minimum return, required for investment into a project. Risk and return of investors vary by country. Inadequate assumptions of the cost of capital can lead to mispricing, risk, and the potential for under investment or overinvestment across markets (IEA, 2021c). A study by Ameli *et al.*, (2021) found that decarbonisation pathways, like those of the IEA and IRENA, do not properly reflect the difference in financing conditions and instead use a uniform cost of capital. When a more accurate financing cost is applied, the transition to a net-zero economy in developing countries is shown to be more expensive than assumed in decarbonisation pathways. In comparison, the transition is cheaper for developed countries.

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[68] The cost of capital is calculated by the sum of a base rate and a premium. The base rate includes return on an investment with low perceived default in a benchmark global economy (IEA, 2021).

9. The impacts of **changing economic conditions** are not shown in climate scenarios. For example, central banks globally in recent times have hiked interest rates due to surging inflation. Higher interest rates mean that it is more costly to borrow money for mitigation or adaptation projects, which can increase the costs of the project itself. Such actions are not taken into considerations in decarbonisation pathways.
10. Climate models have simplifying assumptions on the functioning of the global economy. Therefore, climate scenarios **do not account for potential contraction** of credit during recessions and its impact on climate financing.

IAMs are the least-cost (or welfare-maximising) models. These models represent optimal allocation of financing based on low costs. However, this does not adequately reflect how real-world markets function. Low-cost assumptions will impact how finance is facilitated by different types of financial institutions, with lower-level decisions on financing needing to be made by financial users of the IAMs. For example, a model that is optimistic in its wealth assumptions will project higher energy consumption and higher reliance on fossil fuel if renewables cannot be expanded at a lower cost. Without taking into consideration factors such as real-world policies, political feasibility, economic barriers, and geo-political tensions, these models make pathways for financing a 1.5°C future look deceptively easy.

7.10 The climate finance gap

Despite growing momentum in climate finance over the past decade, only about 16% of climate financing needs are being met to reach net zero CO_2 emissions by 2050 (The Rockefeller Foundation, 2022). The CPI estimates that investments will need to increase fivefold to align with the Paris Agreement (CPI, 2023). A large financing gap exists between the investments reported in 1.5°C scenarios with no or limited overshoot, on the one hand, and investments observed in the previous years, on the other. This highlights the massive scale-up of financing that will be required to achieve the climate goal of limiting warming to 1.5°C.

7.10.1 Energy

Financing fossil fuels remains a substantial barrier to aligning financing for the energy sector to 1.5°C scenarios with no or limited overshoot. Between 2011–2020, fossil fuels subsidies for 51 major economies were 40 times more than climate financing, accounting for USD 6.8 trillion. Global fossil fuel subsidies as a proportion of worldwide GDP are projected to increase from 6.8% in 2020 to 7.4% in 2025 (CPI, 2022c). In comparison, 1.5°C scenarios with no or limited overshoot project a decrease in investments in fossil fuels to USD 53 billion annually from 2023–2032 for electricity supply.

Table 30 highlights the gap in 2021 investments in the energy sector and the investment levels reported in the IPCC assessed 1.5°C scenarios with no or limited overshoot. A massive increase in investments will be needed in renewable energy and the transmission and distribution of energy by 2030 and 2050. For renewable energy, investments will need to increase by 132% from 2022 levels to align with the 1.5°C scenario pathways with no or limited overshoot. Despite large proportions of investments in renewable energy currently being directed towards solar and winder energy, investments in these technologies will need to be ramped up to 39% and 124% by 2030, respectively. Similarly, investments in transmission and distribution will need to increase by 136% by 2030.

Table 30: Percentage increase from 2022 investment levels to meet IPCC assessed 1.5°C scenarios with no or limited overshoot assumptions

Segments for climate finance	2022 investment level (BloombergNEF, 2023b; IEA, 2023d)	IPCC assessed 1.5°C scenarios with no or limited overshoot		Percentage change from 2022 levels	
		2030 Median	2050 Median	2030	2050
Renewable energy	USD 495 billion	USD 1,147 billion	USD 906 billion	132	83
Solar energy	USD 308 billion	USD 427 billion	USD 344 billion	39	12
Wind energy	USD 175 billion	USD 392 billion	USD 479 billion	124	174
Transmission and distribution	c. USD 330 billion	USD 780 billion	USD 891 billion	136	170

7.10.2 Transport

In 2022, investments in the electrification of transportation increased by 54%, to USD 466 billion (including vehicles and their supporting infrastructure) (BloombergNEF, 2023c). However, despite a rapid increase in investments in the sector, a significant gap remains between financing levels at present and what is needed to decarbonise the sector to limit warming to 1.5°C. For example, average annual investments in the UK's transport sector need to increase tenfold over the next five years compared to the past five years (CPI, n.d.). The financing gap in transport infrastructure is estimated to be about USD 440 billion per year (Transformative Urban Mobility Initiative, 2022), with BloombergNEF estimating the need to increase investments in electrified transport to six times the 2022 levels by the year 2040. scale up 2022 levels of investments by six times by 2040 for USD 2.7 trillion in annual financing till 2030 to decarbonise the transport sector (BloombergNEF, 2023c).

7.10.3 Agriculture

Investments in the agriculture sector currently fall below what is needed to limit global warming to 1.5°C. According to the CPI, the sector will require an increase in annual funding of around 26 times that of current levels in order to align with the Paris Agreement. In 2019/2020, investments for the agriculture sector averaged USD 16.3 billion per year. These will need to increase to USD 432 billion per year by 2030. In particular, financing will need to be directed towards regenerative crop production, sustainable livestock and fishery practices, healthy diets and diversification in protein production, improved infrastructure, reductions in food waste, and steps to prevent land clearing (CPI, 2022d).

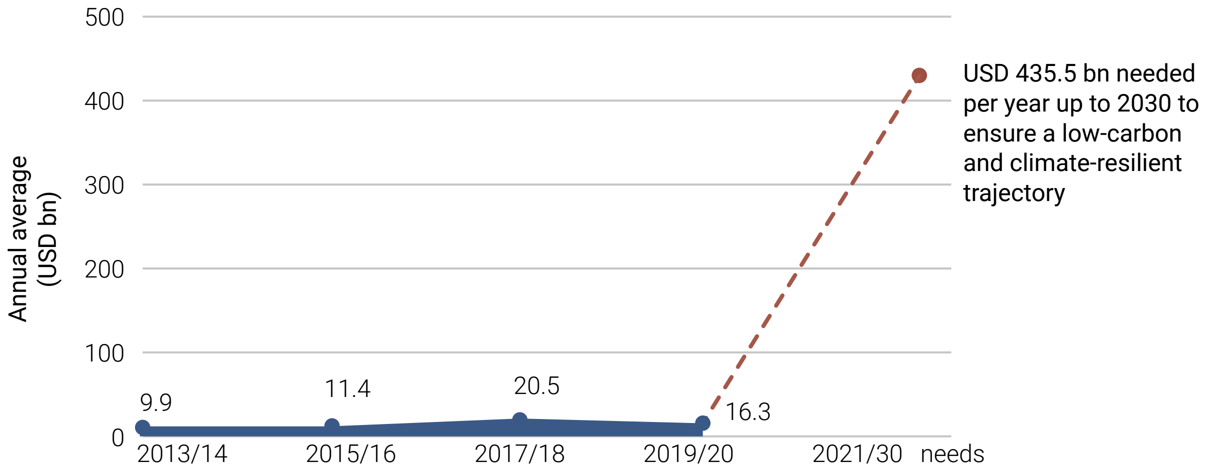

Figure 78: Increase in climate finance needed for the agriculture sector by 2030 (CPI, 2022d)

7.10.4 Industrial

Investments in the industrial sector will need to be significantly ramped up to overcome the current financing gap. An estimated USD 2.1 trillion will need to be invested into low-emission production assets to decarbonise the production of industrial products. About USD 4.2 trillion worth of investments could also be needed for developing low-emission power, green hydrogen production, and CO_2 transportation and storage—about twice the amount of global investments in energy in 2021. To transform the steel sub-sector's asset base, an additional USD 10 billion to business-as-usual investments is required annually until 2050. For the cement sub-sector, meanwhile, investments amounting to USD 500 billion will be needed to retrofit cement plants with carbon capture. As for the ammonia sub-sector, investments into less carbon-intensive power and CO_2 infrastructure for green/blue ammonia supply by 2050 will require more than USD 850 billion in investments. This is 12 times the current annual value of the ammonia market. It is difficult to determine the current financing gap for the aluminium sub-sector due to the unavailability of accurate data (World Economic Forum, 2022).

7.10.5 Buildings

Investments will need to rise to drive the decarbonisation of the buildings sector substantially—both in respect of the existing build stock and new buildings. In 2021, the retrofitting of existing buildings attracted USD 95 billion in financing (IEA, 2021d). In comparison, USD 700 billion per year will be needed for existing buildings in order to reach net zero by 2050. Retrofitting and heating will comprise 80% (i.e. USD 560 billion annually) of this total (GFANZ, 2021). This means that financing of building retrofits needs to be increased by up to 489% annually by 2050. In 2021, investments in new energy-efficient buildings were estimated to amount to USD 221 billion (IEA, 2022c). Though higher than the corresponding investments in retrofits, investments in new energy-efficient buildings also remain untapped.

7.10.6 Adaptation

Adaptation finance is substantially underfunded. It is estimated that developing countries need about USD 160–USD 340 billion annually by 2030 and about USD 315–USD 565 billion annually by 2050 for climate adaptation. However, at present, only 10% of climate finance (accounting for USD 50 billion) is being allocated towards adaptation. Figure 79 highlights the current adaptation finance compared to the annual estimated need. The majority of adaption has come from public capital, with corporations and institutional investors providing just 2% of total adaptation finance in 2019 and 2020.[69] Many adaptation projects are unable to attract private investments due to their long timescales and their inability to prove cash-flow potential. The large gap in private investment for adaptation finance can be attributed to numerous barriers. There is a perception that the investment will result in limited returns, for example, access to information on climate impacts, as well as future risks and adaptation outcomes, is also often restricted. In addition, adaptation projects are typically long term and have substantial upfront costs that can result in long payback times (WEF, 2023).

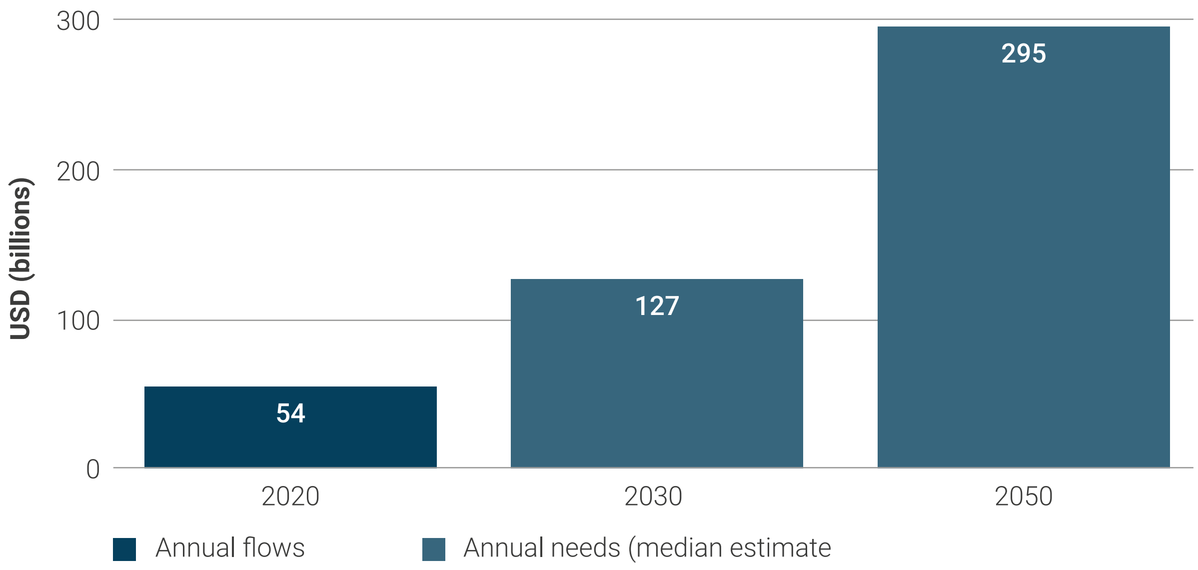

Figure 79: Current global adaptation finance compared to projected needs (WEF, 2023)

7.11 Overall climate financing gap

Based on available data, private institutions are not investing in climate at the levels needed to limit warming to 1.5°C. According to an analysis by the World Resource Institute (WRI), private climate finance will need to rise by more than 11 times by 2030 to reach at least USD 3.75 trillion worth of climate financing annually. This will require an average growth rate of USD 341 billion by 2030, 23 times greater than the historical growth rate (Figure 80) (WRI, 2021). According to the professional services firm, PwC, an annual decarbonisation rate of 15.2% needs to be achieved to limit global warming to 1.5°C and carbon intensity will need to be reduced by 77% by 2030 (PwC, 2022). Considering the pace of acceleration required to attain the estimated climate finance goal by 2030, it is imperative to thoroughly assess the feasibility and practicality of achieving such investment targets in the real world.

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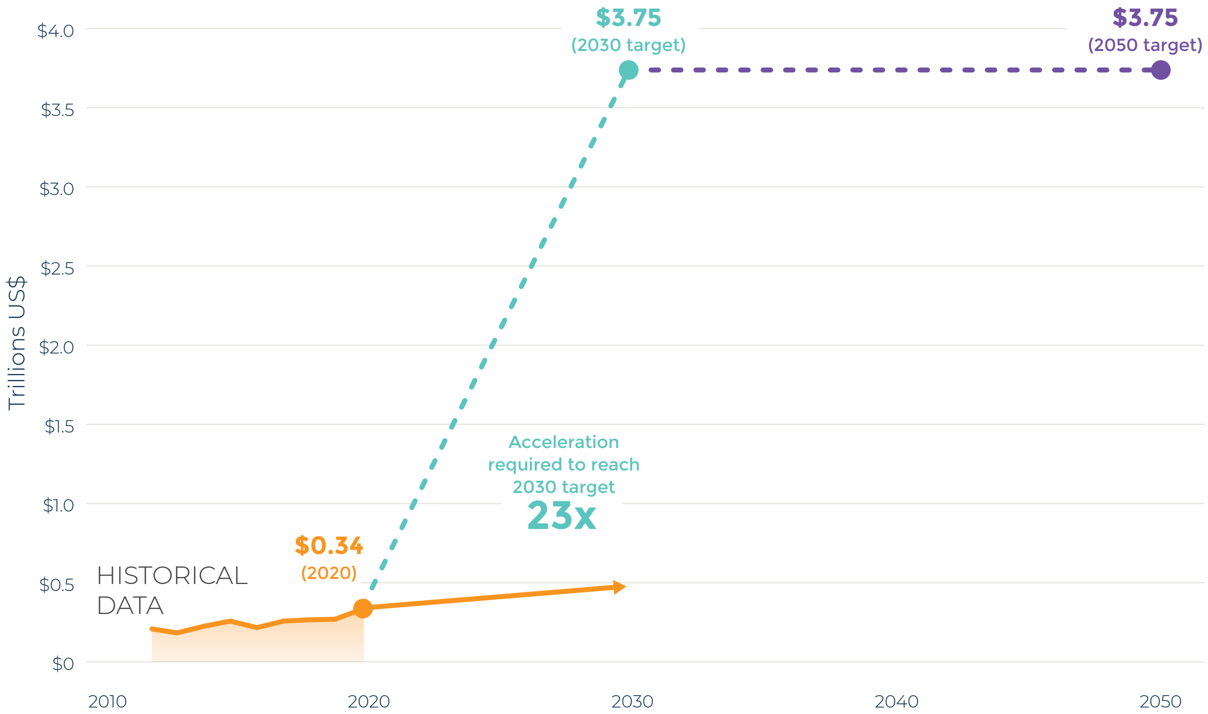
[69] These data only account for investment in adaptation projects with public benefits and do not include spending by companies to make their business models more resilient.



Sources: Historical data from Buchner et al. (2019); Macquarie et al. (2020); and CPI (2021); 2030 and 2050 targets based on analysis of IPCC (2018), IEA (2021c), OECD (2017), and UNEP (2016; 2021b).

Figure 80: Historical progress towards private climate financing for 2030 and 2050 (WRI, 2021)

7.11.1 Challenges for financing the transition to net zero

Multiple barriers can limit climate financing from financial institutions, such as high actual and perceived risks, upfront and transaction costs, long payback periods and low returns (CPI, 2022d). Described below are some of the key barriers to financing for limiting warming to 1.5°C.

Policy and economic considerations: Financing a net-zero transition by 2050 and limiting warming to 1.5°C with no or limited overshoot can be impacted by global political and economic conditions, such as the high inflation rates observed in 2022. Inflation levels can determine how much return investors can expect from their investments. For example, if returns on investment are less than the rate of inflation, investors will lose money (RMI, 2022). Further, high inflation can cause interest rates to go up, resulting in elevated borrowing costs (IPCC, 2022). This also poses a risk of debt vulnerabilities for countries with vulnerable exchange rates. Though inflation can impact the financing needed to meet climate goals in terms of return on investments received (especially by putting at risk spending programmes in countries susceptible to debt), inflation can also drive decarbonisation financing. Most notably, high levels of inflation can cause prices for energy, shipping, raw materials, and labour to spike globally. This can increase the competitiveness of renewable energy and thus incentivise the transition to clean energy, as seen during the recent energy crisis (CPI, 2022c). The impacts of inflation can vary by region as well as by the type of asset or investment. To limit exposure to such inflationary pressures, it is important for institutions to have a diverse portfolio of investments.

Costs: Costs of technology can be a potential barrier to financing. High upfront costs associated with mitigation and adaptation projects often act as a deterrent to private investment (CPI, 2022c). Compared to advanced economies, the cost of capital is also typically higher in emerging markets as climate vulnerabilities in these markets are judged to be higher. Falling costs of technology and other investment opportunities mean that more capacity can be added for each dollar invested. For example, costs for renewable energy have decreased significantly over the previous decade. Global investments in renewable energy fell by 7% in 2017, the most significant decrease observed since 2002. The reduction in investments can be partly attributed to a decrease in the costs of renewable energy in 2017 (IEA, 2018). However, the recent record high in prices of oil has pushed investments towards EVs as ICEVs have become more expensive to produce (BloombergNEF, 2022d). Meanwhile, high costs for construction and materials present an obstacle to investments in the Buildings sector (IEA, 2022b).

Limited understanding and awareness: Lack of information on decarbonisation solutions, coupled with knowledge gaps within financial firms, can be a barrier to financing efforts to reach net zero by 2050. Limited data, such as a lack of baseline data for building retrofits, can also hinder financing efforts.

Regulation: Governance and regulation can be a strong driver for investments. For example, limited progress of national adaptation plans can act as a barrier to adaptation finance. Similarly, a lack of building regulations and standards can limit investments in new low-emission buildings and retrofits. In addition, a lack of regulation and policies (such as carbon pricing) can deter shifts in investments away from fossil fuels and towards clean energy. Further, investments in infrastructure for decarbonising the transport sector is only realistic when countries have comprehensive national plans in place (CPI, 2022c). Lack of local currency instruments and fluctuating exchange rates in countries can also comprise a risk to investments denominated by foreign currency. Finally, underdeveloped domestic financial systems, plus the ability of governments to raise capital, will impact the financing directed towards limiting warming to 1.5°C (IPCC, 2022).

High risk and uncertainty: Some projects face challenges in securing financing due to increased risk and uncertainty, leading to higher risk premiums. For instance, projects in unfamiliar countries may carry risk premiums that render them financially unfeasible. As a result, financial institutions must implement de-risking measures to address these challenges (WRI, 2022).

Box 35: Technology and products assumptions of 1.5°C scenarios with no or limited overshoot

Factors to consider that influence climate-related investment opportunities:

Discount rate: A discount rate can be used to express a future monetary value in today's terms. A high discount rate reduces the value of a future stream of benefits or costs compared to a lower discount rate. A high discount rate implies that the further in the future the benefits are, the lower their value. Selecting the right discount rates for discounting costs and benefits of investment projects is important for identifying investment opportunities (World Bank, 2022b).

Rate of emissions: The rate at which emissions increase or decrease can influence the types of financing needed and can therefore impact the investment opportunities available. For example, if emissions do not fall at the rate required to reach net zero by 2050, greater investments will be needed for technologies removing and storing CO_2 due to a higher reliance on CDR and CCS technologies.

Technology availability: The pace at which the development of different technologies progress often varies. Some decarbonisation technologies are still in an early planning phase or at prototype stage, for example. In contrast, other technologies are more advanced and are already being deployed and or used commercially. Each require different financing strategies. For example, because of their relative maturity, renewable energy technologies require investment in order to reach greater commercial scale. In contrast, CCS technologies are still in the prototype phase, so will need investments for them to progress to the stage of deployment at a commercial level.

Technology costs: Technologies differ in their costs and projections for cost changes in the coming years. High upfront costs can be a barrier to investments, and changes in technology costs can impact the return on investments.

Macroeconomic growth: GDP, inflation rate, exchange rates, interest rates, and other macroeconomic growth variables are important to consider when determining the returns of climate-related investments. When coupled with a country's ability to pay its debt, such factors can help determine whether a country is able to grow and generate revenue, making it a good and reliable candidate for investments.

Coordinated and uncoordinated policies: Types of policies implemented by governments can strongly influence the investment opportunities available in mitigating and adapting to climate change.

Other growth factors: Other factors indicating growth for opportunities of investments in countries include population growth, behavioural changes, political climate, and geopolitical tensions. Uncertainty and instability can deter financial institutions from investing in certain countries.

Questions for readers

- Identify potential opportunities for investments in financing the transition to net zero by 2050 and consider how climate scenarios can help in the identification?
  - By sector?
  - By region?
- Do the 1.5°C pathways with no or limited overshoot meet your institution's assumptions on the financing required to support your clients' transition to a low-carbon economy?
- Do your institution's near-, mid-, and long-term plans meet the decrease in financing required in 1.5°C pathways with no or limited overshoot for fossil fuel-intensive activities?
- What information does your institution need to decide on financing a particular investment opportunity?

CHAPTER 8:

Socioeconomic considerations to limit warming to 1.5°C

Key messages

- Socioeconomic assumptions can have implications on emissions and, therefore, mitigation efforts.
- The majority of 1.5°C scenarios with no or limited overshoot are aligned with the assumptions of the “middle of the road” SSP2 and use data projections from the UN and the IMF.
- Changes in behaviour can be highly significant in reducing emissions, particularly in sectors where there are limited options for mitigation.

Suitability considerations of scenarios for exploring socioeconomic assumptions

Limited information and detail	Some information and detail	Good information and detail
▪ Information on equality, equity, and justice as a result of climate change is not provided ▪ Limited direct variables available on behavioural shifts ▪ Shock events are not incorporated ▪ Information on the impacts of climate change on social aspects, such as climate migration and geopolitical conflict are not available ▪ Most scenarios use the same socioeconomic narrative, in line with the assumptions of SSP2	▪ Scenarios are in line with one of the Shared Socioeconomic Pathways ▪ Consideration is given to socioeconomic factors related to poverty, employment, diets and the risk of hunger, and urbanisation ▪ Readily accessible information on key socio-economic assumptions, such as population and GDP	

Note: These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

8.1 Introduction

Socioeconomic factors, such as population, economic growth, education, urbanisation, and the rate of technological development, will impact the pathway to net zero. Initially, these socioeconomic pathways were developed to describe challenges for mitigation and adaptation of climate change. Since then, energy, land-use, and emission pathways have also been quantified for reference and mitigation scenarios (IPCC, 2022). In this chapter, we assess how socioeconomic assumptions among the scenarios differ. We then go on to describe the implications socioeconomic assumptions can have on the pathways reported to 1.5°C by the scenarios. Finally, we discuss the challenges different socioeconomic assumptions create for decarbonisation.

These socioeconomic narratives are known as the "Shared Socioeconomic Pathways" (SSPs). Initially published in 2017, the SSPs look at five different ways in which the world might evolve in the absence of climate policy and consider how different levels of climate change mitigation could be achieved. Each SSP has a baseline scenario that describes future developments in the absence of new climate policies beyond those already in place. SSPs can be combined with Representative Concentration Pathways (RCPs) to explore various emission trajectories or concentrations with defined socioeconomic characteristics.

SSPs consist of a narrative that outlines characteristics of the global future and country-level population, Gross Domestic Product (GDP), and urbanisation projections over the next century. The pathways chosen have implications for mitigation and adaptation. These pathways include:

- A world of sustainability-focused growth and equality (SSP1)
- A "middle of the road" world where trends broadly follow their historical patterns (SSP2)
- A fragmented world of "resurgent nationalism" (SSP3)
- A world of ever-increasing inequality (SSP4)
- A world of rapid and unconstrained growth in economic output and energy use (SSP5).

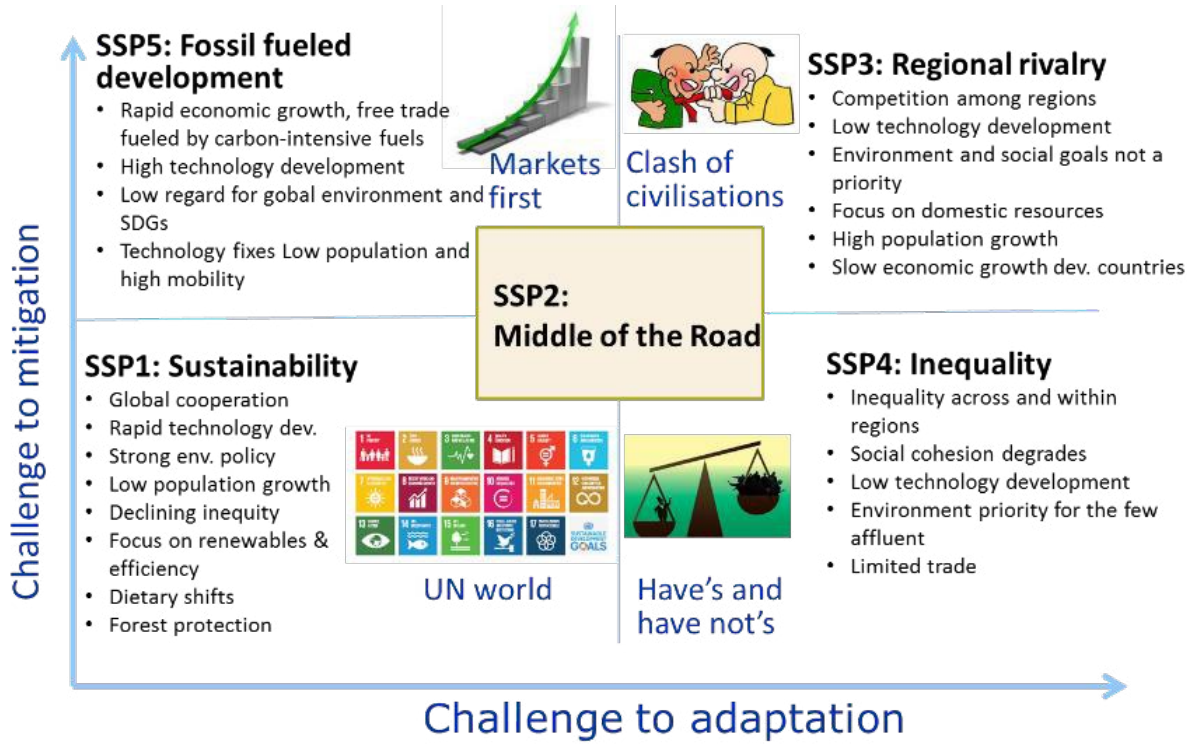


Figure 81: Summary of narratives on the SSPs (UN, 2019)

For more details, see Appendix 4.

SSP1 and **SSP5** are pathways that have a high level of human development, with "substantial investments in education and health, rapid economic growth, and well-functioning institutions". They differ in that **SSP5** assumes this will be driven by an energy-intensive, fossil fuel-based economy, whereas SSP1 envisions a concerted shift toward sustainable practices. **SSP3** and **SSP4** are more pessimistic, with little investment in education or health in poorer countries, coupled with a fast-growing population and increasing inequalities. In **SSP3**, policies are driven by a nationalistic approach to decision-making that prioritises regional and local issues over global issues. Meanwhile, the pathway for **SSP4** focuses on deepening inequality between high-income and low-income regions and within countries. **SSP2** represents a "middle of the road" scenario with historical development patterns continuing throughout the twenty-first century. The main differences between SSPs come from their assumptions on global population growth, access to education, urbanisation, economic growth, resources availability, technology developments and drivers of demand, such as lifestyle changes. Figure 83 shows key driving forces included in the SSPs

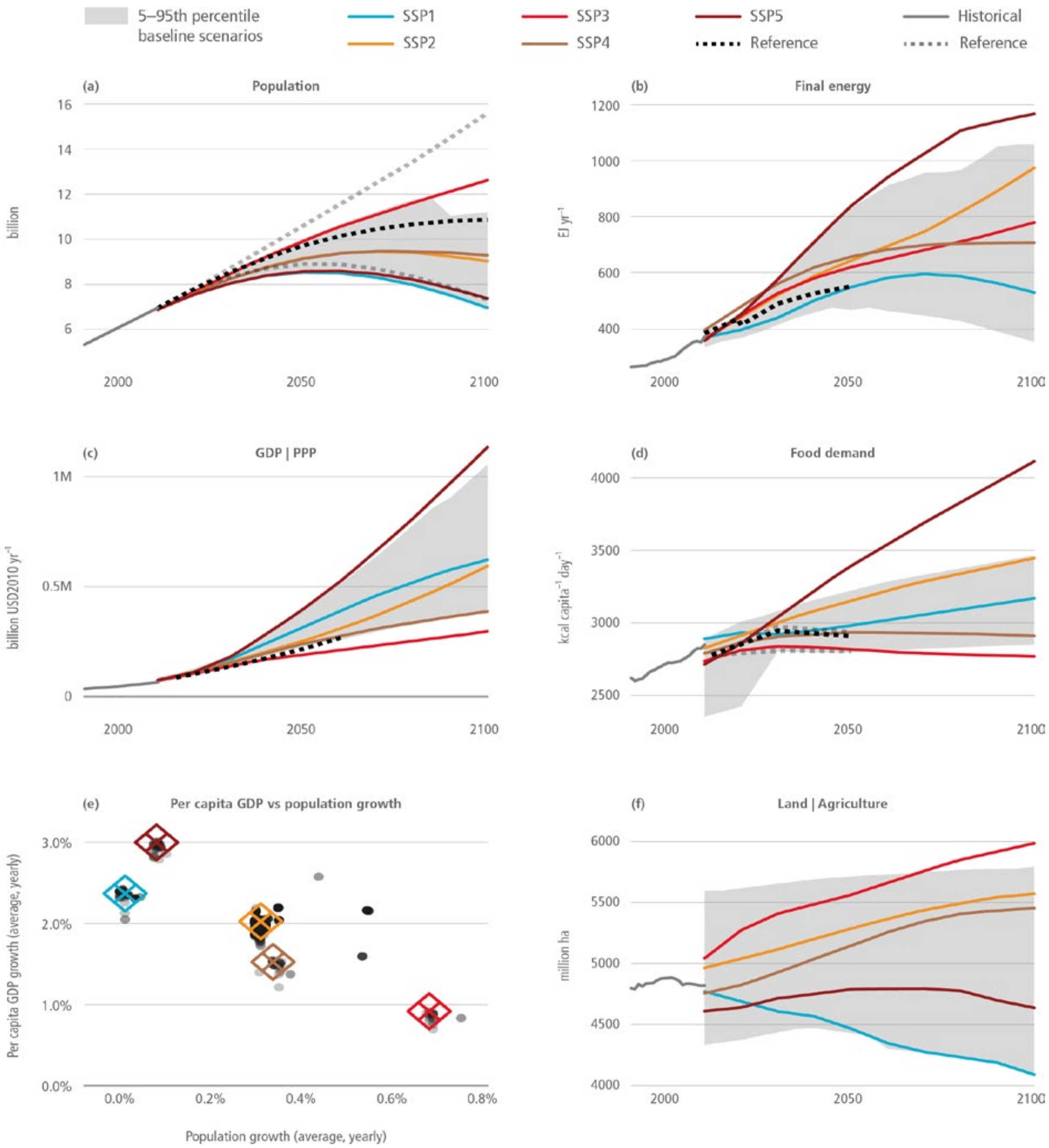


Figure 82: Trends in key scenario characteristics and driving forces as included in the SSPs (IPCC, 2022)

Most of the scenarios in the Assessment Report 6 (AR6) database are SSP-based. The majority of the 1.5°C scenarios with no or limited overshoot assessed in AR6 are consistent with the middle-of-the-road assumptions of **SSP2**. Out of 92 1.5°C scenarios with no or limited overshoot, 89% are consistent with **SSP2**, and 11% are consistent with **SSP1** (IPCC, 2022).[70]

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[70] Data sourced from AR6 scenario explorer.

8.2 Deep-dive into socioeconomic drivers

Population

> **All else being equal, a higher population means tougher mitigations actions will be needed to reduce emissions.**

One of the main drivers of GHG emissions is population growth. The range of global population estimates included under the different SSPs range from 8.5 billion (**SSP1**) to 9.7 billion (**SSP3**) in 2050 (IPCC, 2022). Figure 84 shows 1.5°C scenarios with no or limited overshoot assumptions on population. The scenarios collectively use similar assumptions for population growth to 2050, increasing from 7.7 billion (median) in 2020 to 9.2 billion (median) in 2050. After 2050, scenario projections for the population begin to diverge.

The 1.5°C scenarios with no or limited overshoot align with the assumptions of **SSP2** for population growth. The socioeconomic pathway assumes that the global population will grow to 9.4 billion by 2070 before slightly declining (UNECE, 2019). There are also other population projections that are frequently used or are free, such as the UN Population Prospects. The UN Population Prospects assumes higher values for medium projection than the SSPs. Projections reach a global population of about 11 billion by 2100. Projections by the UN Population Prospects rely more on current demographic trends than the SSPs, whereas the latter take into consideration a broader range of factors, such as the impact of education on fertility rates (IPCC, 2022). The NGFS Phase III scenarios use data on the population based on the IMF World Economic Outlook, which includes COVID-19. The World Economic Outlook is a survey by the IMF published twice annually and consists of an analysis of global economic developments in the near- and medium-term (IMF, n.d.). Assumptions about age distribution will also affect consumption, political actions, and other societal developments that affect decarbonisation.

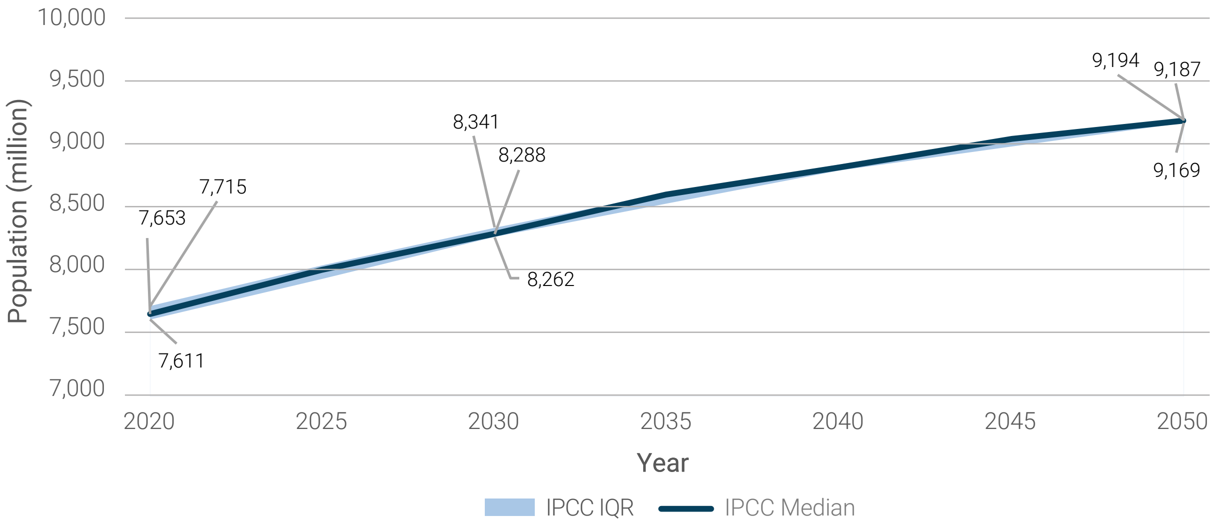


Figure 83: Global population growth assumptions in the IPCC-assessed 1.5°C scenarios with no or limited overshoot

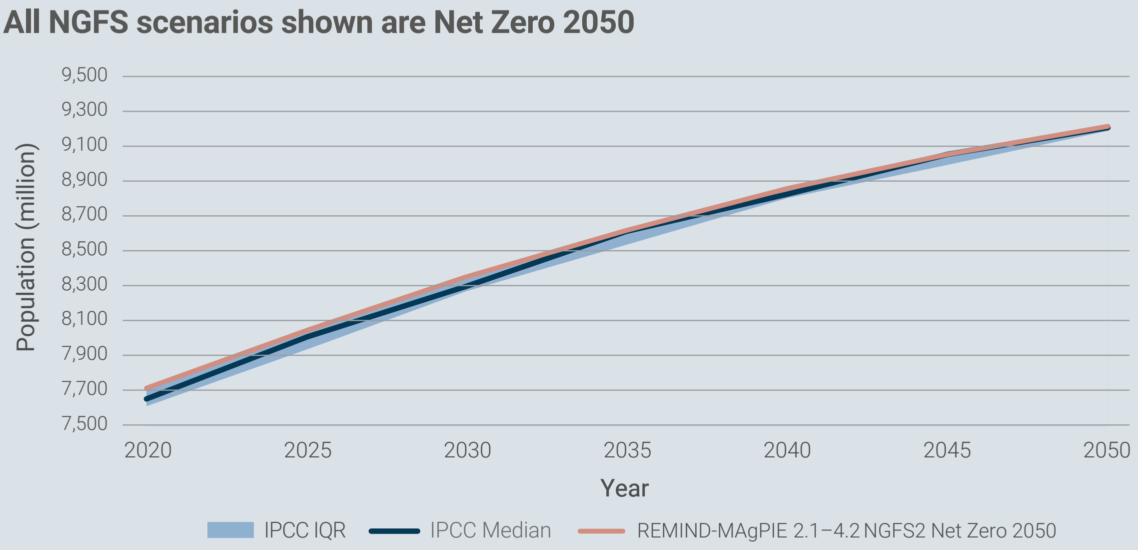
Drivers of population assumptions in scenarios

- Replacement level of fertility is the fertility level at which a population replaces itself from one generation to another. Replacement levels can vary among countries. In developed countries, it typically averages to 2.1 children per female. Average births in countries with high infant and mortality rates need to be higher (UN, n.d.).
    - Fertility below replacement levels will result in a decline in the global population later in the century, as shown in SSP1 and SSP5 (IPCC, 2022).
- Mortality:
    - Higher mortality rates that exceed birth/fertility rates lead to a shrinking global population.
- Migration:
    - Population sizes can decline in regions where the net inflow of migrants is not sufficient to make up for the excess of deaths over births and emigration (UN, 2017).
- Education:
    - Investment in education is correlated to decreased children per family (IPCC, 2022).
    - Evidence suggests that greater educational access for women results in smaller family sizes. Universally educated populations are also shown to have lower mortality (KC and Lutz, 2017).

Implication of population assumptions in scenarios for net zero

All else being equal, a higher population rate will result in higher energy and food demand and consumption. This makes achieving net-zero goals more challenging. Not only does it require additional energy infrastructure to be built, but it also leads to demand for existing energy sources (especially fossil fuels) becoming more persistent. More significant quantities of food and goods will also need to be produced in such pathways, meaning more mitigation will be required.

Box 36: Global population assumptions of the NGFS net-zero scenarios compared to the IPCC-assessed 1.5°C scenarios with no or limited overshoot


All NGFS scenarios shown are Net Zero 2050

Population assumptions among 1.5°C scenarios with no or limited overshoot, including the NGFS scenarios, exhibit consistency with negligible deviations observed.

Data source: AR6 scenario explorer

Gross Domestic Product (GDP) and Wealth

All else being equal, a higher GDP means mitigation to reduce emissions will be more challenging.

Rising global GDP has historically been positively correlated with increased energy demand, increased consumption of physical goods, and, by extension, increased emissions. The range of estimates for the rise in global GDP included under the different SSPs range from 2.7% (**SSP3**) to 4.1% (**SSP5**) annually between 2015 and 2050 (IPCC, 2022). Figure 85 shows 1.5°C scenarios with no or limited overshoot assumptions for GDP growth. The scenarios show an increase in GDP (PPP) from 112 trillion USD 2010/yr (106–115 trillion USD 2010/yr)[71] in 2020 to 247 trillion USD 2010/yr (238–252 trillion USD 2010/yr) in 2050. Compared to population growth assumptions, GDP growth assumptions show more significant variation among the 1.5°C scenarios with no or limited overshoot. However, a majority of the scenarios use SSP2 socioeconomic assumptions.

Common data sources for GDP in scenarios are the IMF World Economic Outlook and Economic Forecasts by Oxford Economics.

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[71] Median (interquartile range)

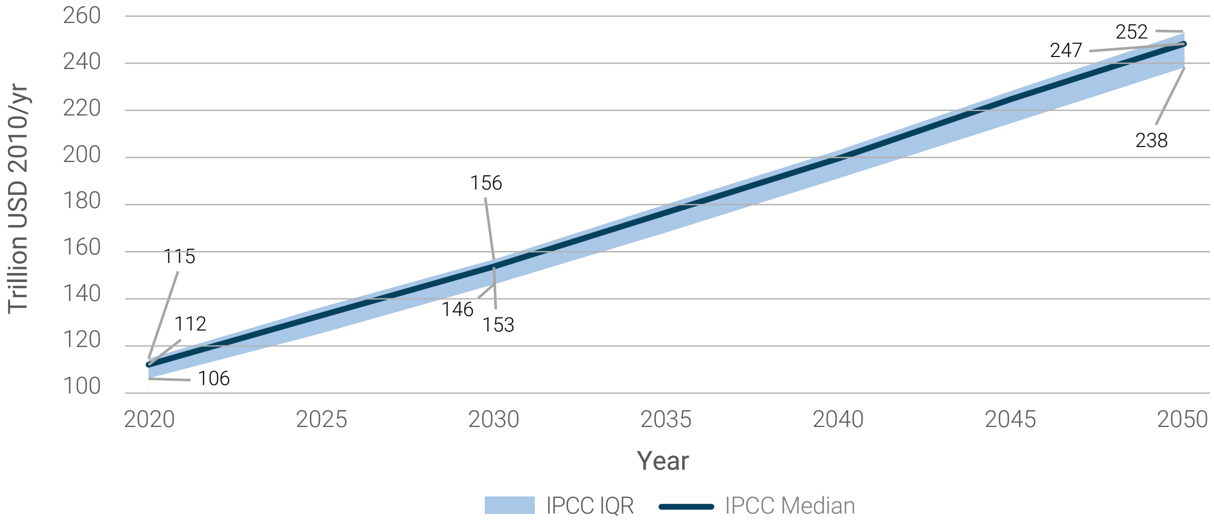

Figure 84: Global GDP growth assumptions in the IPCC-assessed 1.5°C scenarios with no or limited overshoot

Near-term differences in GDP growth are also incorporated into the pathways. The 1.5°C scenarios show that developing and emerging countries have a greater percentage growth in GDP than developed countries during the present decade (Figure 86a). The scenarios collectively show the greatest average growth in GDP for South Asia, primarily driven by economic growth in India. Central Asia (especially China) and Sub-Saharan Africa are set to follow next in terms of median percentage growth in GDP. Countries in Europe and North America are shown to have the lowest increase in median economic growth.

Country-specific GDP growth reported in 1.5°C scenarios with no or limited overshoot can differ from the real GDP growth observed in the countries. Figure 86b compares the compound annual GDP growth rate in the IPCC-assessed scenarios from 2020 to 2025 to real GDP as of 2023 for selected countries. GDP growth incorporated in the scenarios for India from 2020 to 2025 (6%) is similar to real GDP 2023 levels (5.7%). However, GDP growth rates between real GDP projections for 2023 (0.7%) and that shown in the scenarios (2%) differ for the United States of America. For China, the scenarios show a 6% annual GDP growth rate and real GDP growth for 2023 is estimated to be lower at 4.7%. For Eastern and Western Europe, the scenarios assume a higher GDP growth rate (2%) than the current GDP growth of 0.6%. Similarly, scenarios assume an annual GDP growth rate of 3% for Brazil by 2025, where real GDP estimates for 2023 stand at 0.8% (OECD, 2022). Differences can be attributed to the design of many Integrated Assessment Models (IAMs), which estimate GDP exogenously and include a simplified representation of the global economy that do not take into account potential shock events. For example, the scenarios considered in this report were developed a few years ago and therefore do not consider recent macro events, such as the Russian Federation's invasion of Ukraine and the high energy prices that followed. Nor, as a consequence, do they reflect the subsequent inflationary pressure placed on European countries, which has led GDP growth to decrease (OECD, 2022). The same is also true for national events. Existing scenarios, for example, do not consider the recent decision by Brazil's central bank to set high interest rates as a means to reduce inflationary pressures. Inevitably, they also miss the slowdown in the economy that occurred as a result (Reuters, 2023). In summary, scenarios can understate or overstate economic growth assumptions that can have implications for the mitigation options chosen in the scenario pathways compared to mitigation options that are viable in reality.

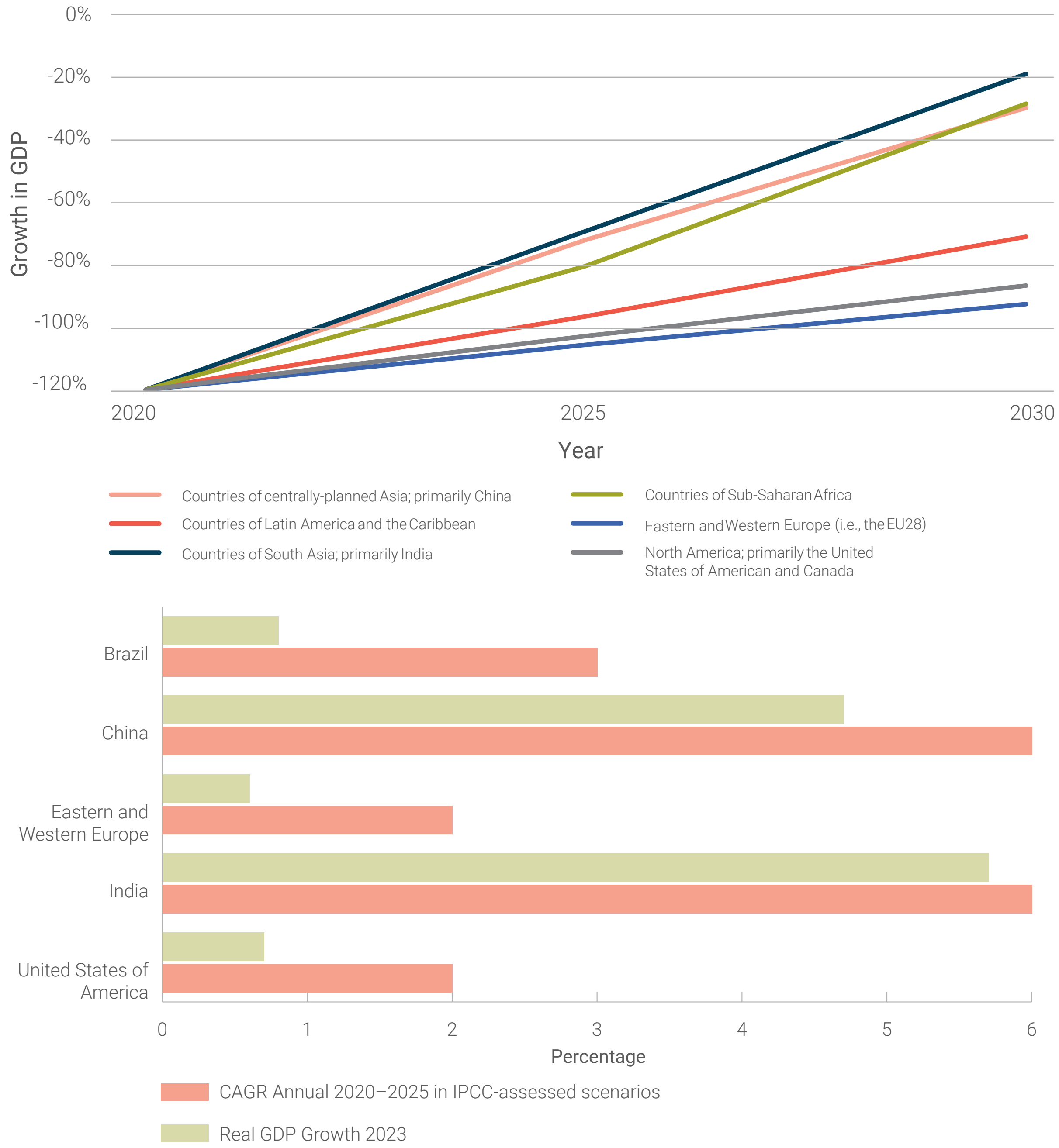

Figure 85: a) Percentage growth in GDP (b) Comparison between real GDP growth and percentage growth in GDP as shown in IPCC-assessed 1.5°C scenarios with no or limited overshoot across different regions

Drivers of GDP assumptions in scenarios:[72]

- Infrastructure: factories, transport links, machinery, and other infrastructure of this kind reduce costs, facilitate international trade, and improve labour productivity; developing infrastructure can therefore act as a powerful driver of economic output and efficiency.
- Resource availability: economic growth can be driven by energy resources that increase production capacity, such as oil; governments therefore need to ensure that such resources are available and accessible, as well as then being utilised effectively.
- Productivity: technology advancements and education can help drive economic growth; new technology can increase productivity at lower costs, while education can lead to a highly skilled labour force that can improve efficiency and quality output.
- Population growth: an increase in the number of individuals can improve access to labour and productivity, which, in turn, can increase economic output; bigger populations can also increase demand for growth, leading to a higher production of goods.

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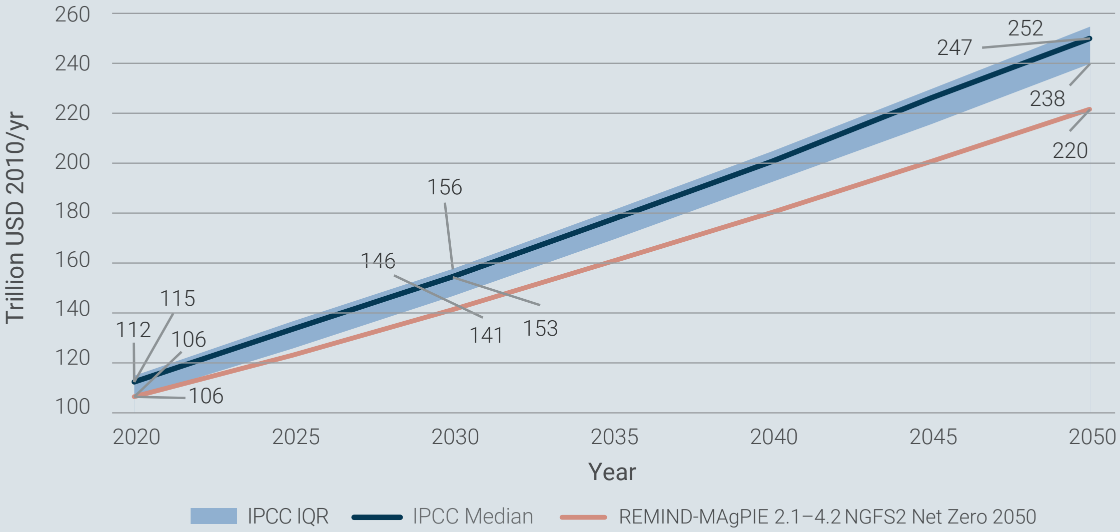
[72] University of Sunderland, 2022

Box 37: Global GDP assumptions of the NGFS net-zero scenarios compared to the IPCC-assessed 1.5°C scenarios with no or limited overshoot



REMIND is less optimistic in its economic growth assumptions than the IPCC-assessed dataset. Its assumptions of GDP are less than the lower quartile of the IPCC-assessed scenario values. For example, from 2020 to 2030, the lower quartile estimates of GDP growth of the IPCC-assessed scenarios is 38%. For the same duration, the REMIND Net Zero 2050 scenario shows GDP growth of around 30%. Between 2030 and 2050, the lower quartile estimates of GDP growth of the IPCC-assessed scenarios is 63%. The REMIND pathway shows GDP growth of 56% for the same duration. Lower economic growth assumptions in the REMIND model imply that the mitigation pathways for the model will be easier due to smaller economies. This is because smaller economies consume less across the decades on the road to net zero. However, smaller economies may find it challenging to finance mitigation efforts, which could offset the benefits of lower consumption rates.

Data source: AR6 scenario explorer

Economic growth is a key driver for reducing poverty and increasing wealth. 1.5°C scenarios with no or limited overshoot assessed by the IPCC show a significant poverty reduction (Figure 87). Scenarios report a reduction from 616 million people (613–626 million) living in extreme poverty in 2020 to 27 million people (22–81 million) by 2050.

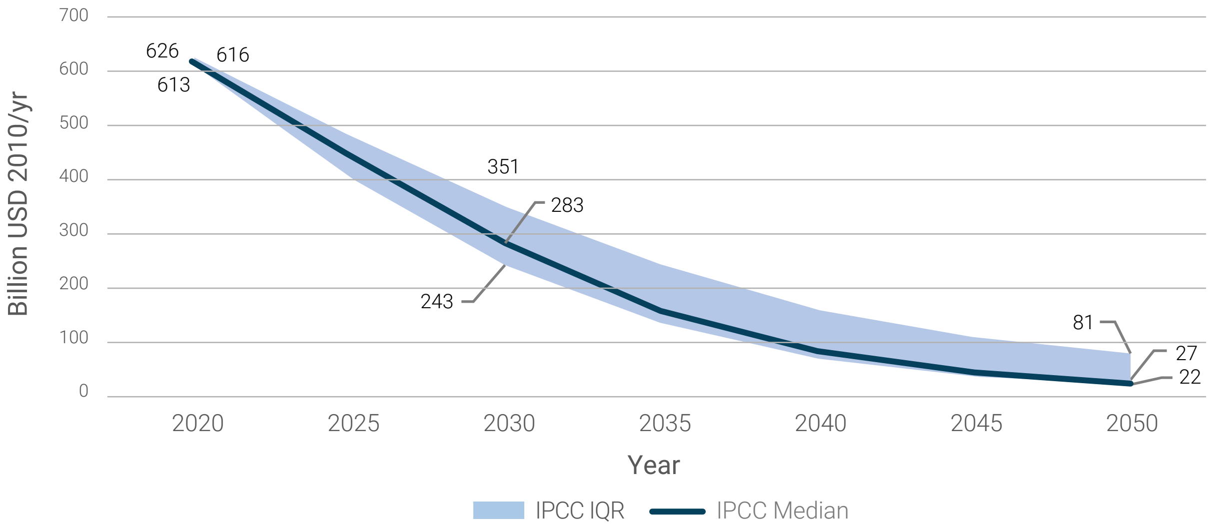


Figure 86: Global population living in extreme poverty assumptions in the IPCC-assessed 1.5°C scenarios with no or limited overshoot

Historically, an increase in wealth has led to an increase in GHG emissions due to a rise in energy consumption. A study by Leeds University found that the top 10% of all country and income classes consume 20 times more energy than the bottom 10%. As people become wealthier, they spend more money on energy-intensive goods such as cars and vacations. The study found that in terms of wealth, the top 10% of consumers consume 187 times more vehicle fuel energy than the bottom 10% (Leeds, 2020). Figure 88 illustrates per-capita emissions for the bottom 50%, middle 40% and top 10% of the population.

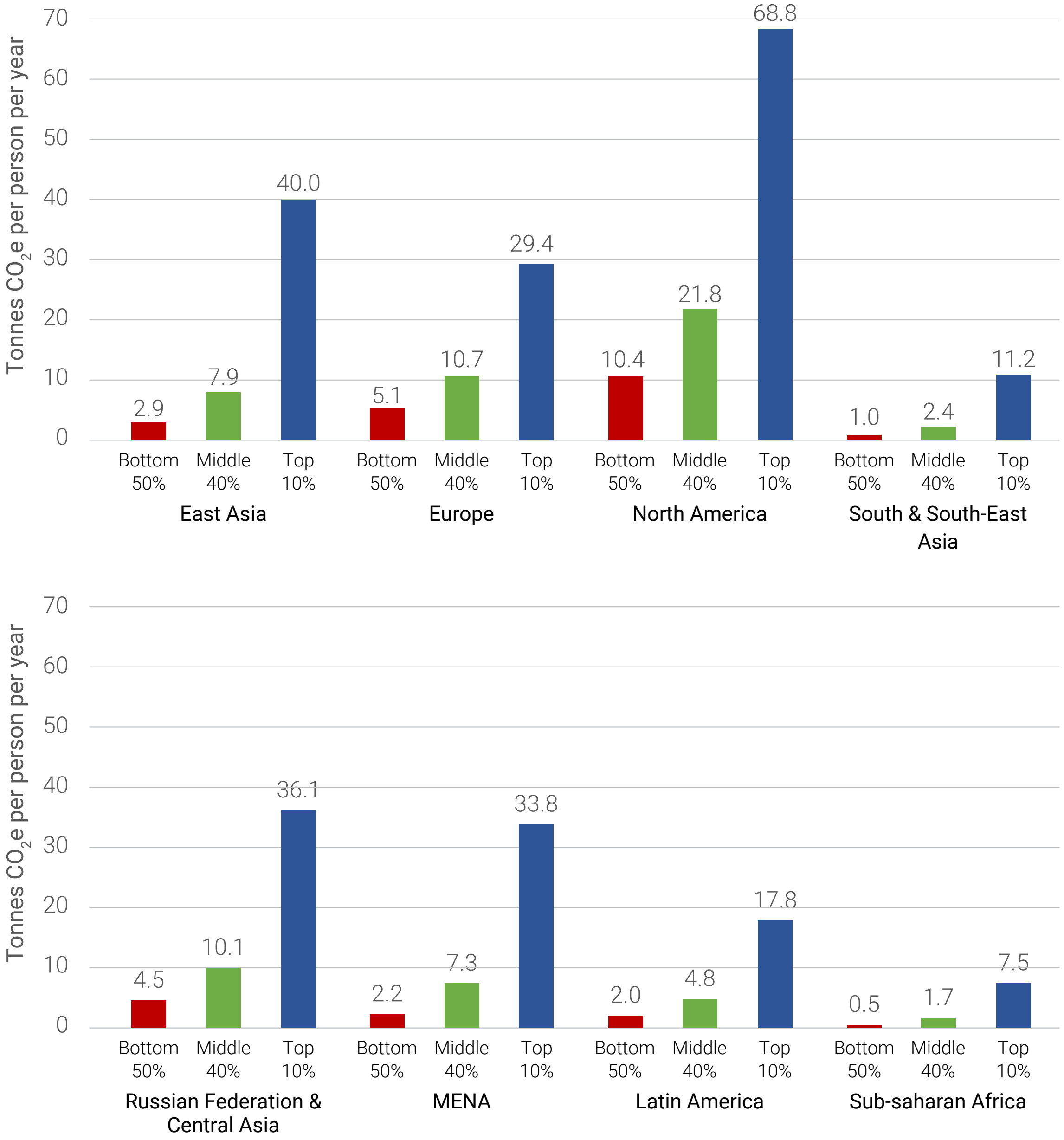


Figure 87: Per-capita emissions by wealth group in 2019 across regions (Chancel, 2022)

Implication of GDP and wealth assumptions in scenarios for net zero

All else being equal, higher economic growth will result in higher energy demand. Increased incomes will lead to a rise in energy consumption, and growing economies will require more significant amounts of energy for production across industries. Increasing energy demand will require more mitigation actions, such as electrification and energy efficiency in order to meet energy consumption while limiting warming to 1.5°C .

To achieve a 1.5°C future, decoupling emissions and energy demand with economic growth will be necessary. The IPCC defines decoupling as "economic growth which is no longer strongly associated with the consumption of fossil fuels". Decoupling from energy demand will require improved energy efficiency, and decoupling from emissions will require transitioning to low-carbon emission energy sources. There are two types of decoupling: relative and absolute. In relative decoupling, both economic growth and fossil fuel consumption continue to rise, but economic growth occurs at a faster rate. In absolute decoupling, economic growth continues to occur, but fossil fuel consumption decreases. Decoupling CO_2 emissions with economic growth can be achieved by decreasing energy and carbon intensity (CMCC, 2022).

8.3 Behavioural shifts

All else being equal, behavioural shifts reducing energy consumption means the need for weaker mitigations actions to reduce emissions.

Societal behaviour is continually shifting and susceptible to ongoing changes over time. These changes can include the adoption of low-carbon technologies by consumers and changes in everyday preferences. Examples of changing consumer choices include a drop in driving, an increase in cycling and walking, a reduction in flying, the uptake of public transport, the use of electric vehicles, the consumption of less meat, and a lowering of household thermostats. Such changes can help reduce emissions and energy demand and improve the well-being of societies. Behavioural changes can reduce emissions in sectors where mitigation options are limited and can help reduce dependence on new low-carbon energy sources by reducing energy demand (IEA, 2023). Therefore, assumptions in individual and group consumption choices can influence the pathway for decarbonisation. Climate scenarios can take behavioural changes into consideration through assumptions like changes in energy consumption by consumers in everyday life to reduce energy waste and to reduce the disproportion of energy use between high-income and low-income countries (IEA, 2023). However, behavioural shifts are still captured to a limited extent in scenarios.

Drivers of behavioural shifts (IPCC, 2022; IEA, 2023):

- **Income** influences an individual's behavioural patterns; high-income households spend more on carbon-intensive recreational activities such as travel and eating out, while low-income household spending is concentrated on fuel for heating and cooking.
- **Age** demographics and aging of a population can also influence consumption patterns leading to behavioural shifts.
- Differences in **urban and rural living** can impact behavioural choices related to energy consumption due to factors such as compactness, proximity, and access to services. For example, houses tend to be larger in suburban areas and therefore have more considerable heating and cooling requirements, and commuting distances are shorter in urban areas with access to public transportation.
- **Technological changes and access to information** can alter daily activities and how individuals prefer to use their time, such as reducing their working hours.
- **Changes in social norms** can impact how individuals consume energy and goods; an example of changing social norms is the increased sharing and borrowing of goods between consumers.
- Influence of **status** can drive the adoption of behaviours that society considers to be high-status.
- The **rise of the middle-income class** in many emerging economies will drive the adop-

tion of new lifestyle choices and consumption patterns.

- **Availability of infrastructure**, such as footpaths for walking, cycling lanes, public transport, and railways, can influence consumers' ability to shift energy-related behavioural choices.
- **Effective policies** by governments can bring about systemic changes in lifestyles; for example, in the IEA's Net Zero 2050 scenario, 75% of emissions reductions related to behavioural shifts can be incentivised or mandated by policies.

Implications of behavioural shifts in scenarios for net zero:

Assumptions in behavioural shifts that lead to a decrease in energy consumption will mean less need for more stringent mitigation actions (such as carbon dioxide removal) in pathways to reduce emissions to limit warming to 1.5°C . However, assumptions in behavioural shifts that lead to an increase in energy consumption will mean a greater need for more mitigation actions (such as electrification and energy efficiency) to meet energy consumption in the pathways while limiting warming to 1.5°C .

Diets

All else being equal, increasing food demand means tougher mitigation actions will be needed to reduce emissions.

Food demand in 1.5°C scenarios with no or limited overshoot is reported in terms of caloric intake per capita. Scenarios report an increase in food demand with variation (see Chapter 6 on Energy Demand).

Scenarios also report changes in agricultural demand (Figure 89). For example, the 1.5°C scenarios with no or limited overshoot show an increase in total agricultural demand for food livestock from 284 million tons of dry matter per year (DM/yr) (258–301 million t DM/yr) in 2020 to 375 million t DM/yr (245–467 million t DM/yr) in 2050. This reflects the amount of land used for agriculture in scenarios. In 2020, global agricultural land area accounted for 38% of the total global land surface (FAO, 2020).

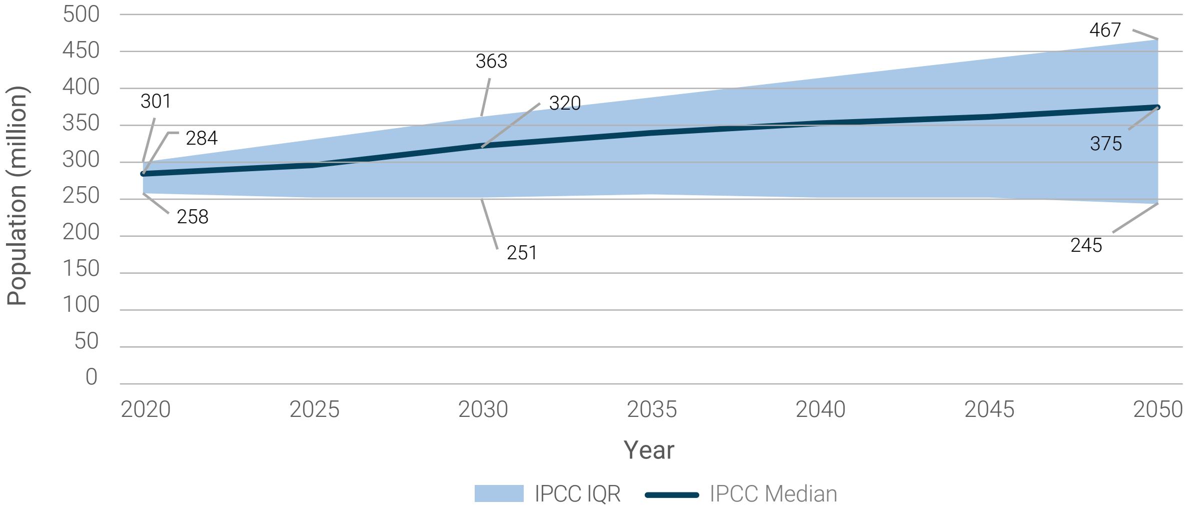


Figure 88: Global total demand for food livestock in the IPCC-assessed 1.5°C scenarios with no or limited overshoot

Consideration of diets in 1.5°C scenarios with no or limited overshoot is important due to the contribution of meat consumption to GHG emissions. As 1.5°C scenarios with no or limited overshoot show an increase in wealth, consumption of meat can be expected to rise—a correlation that has been observed over the past 50 years (Figure 89). For example, the NGFS scenarios assume that dietary changes are in line with historical patterns, including meat consumption rising with wealth (NGFS Scenario Portal, n.d.).

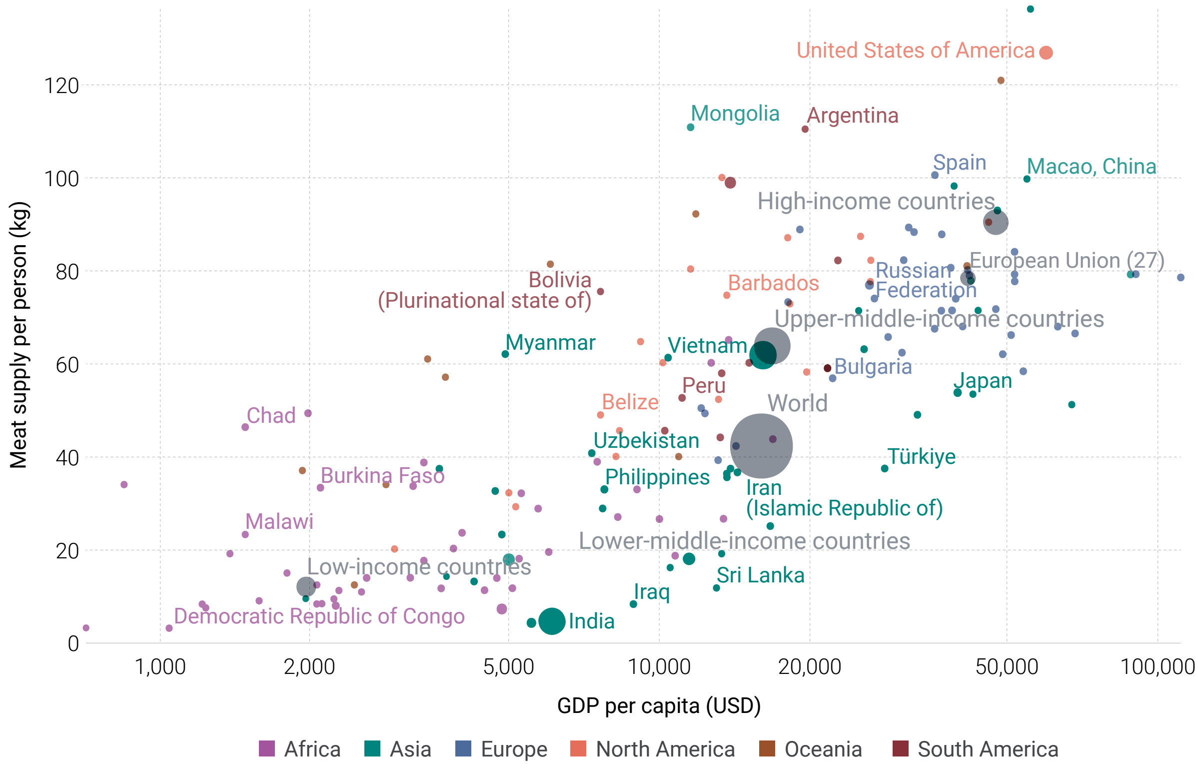
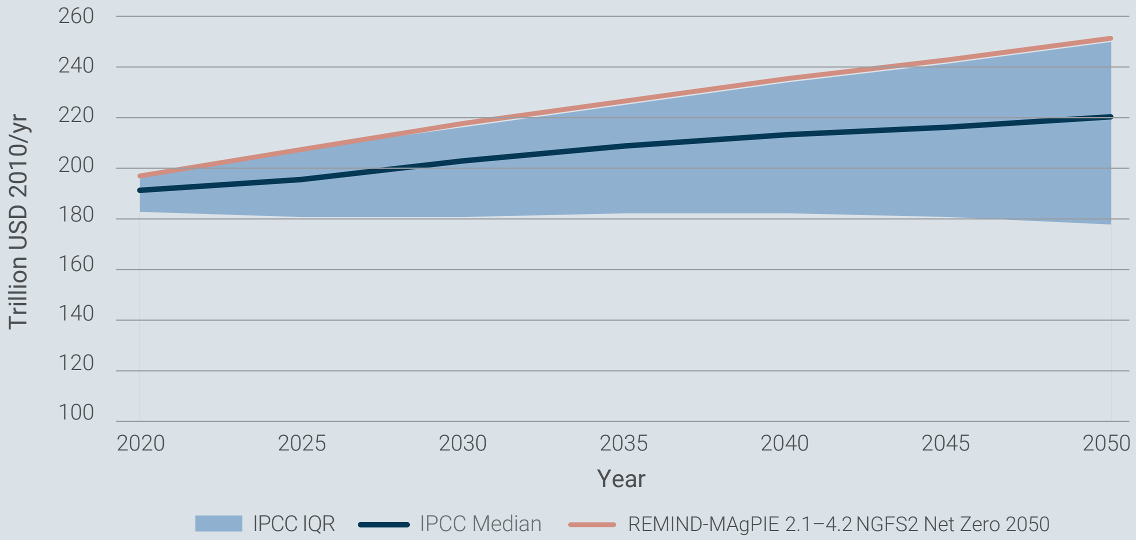


Figure 89: Meat consumption based on GDP per capita in 2020 (FAO, n.d.; Our World in Data, 2023)

With all else being equal, historical trends suggest an increase in wealth and a growing population will lead to a rise in food demand, especially demand for consuming emissions-intensive protein. This will make achieving net-zero goals more challenging as we need to produce greater quantities of food in such pathways, meaning more mitigation will be needed, including substantial lifestyle changes specific to dietary changes. Consumer behaviour will need to switch from emission-intensive diets towards less emission-intensive alternatives, such as plant-based alternatives or lab-based meat.

Box 38: Global total food livestock demand assumptions of the NGFS net-zero scenarios compared to the IPCC-assessed 1.5°C scenarios with no or limited overshoot



Demand levels of total food livestock in the net zero scenario using the REMIND model are in line with the upper quartile values of the IPCC-assessed scenario dataset. In 2050, the REMIND pathway reports demand to be 1.3 times higher than the median of the IPCC-assessed scenario dataset.

Data source: AR6 scenario explorer

Table 31: Recommended scenario variables to use for understanding socioeconomic assumptions (AR6 scenario explorer)

Variable	Unit	Definition	Additional information
Agricultural Demand	Million t DM/yr	Total demand for food, non-food and feed products (crops and livestock) and bioenergy crops (1st & 2nd generation)	Further variables can be used to assess agriculture demand for crops and livestock.
Employment	Million	Paid labour service (*Author's definition*)	Further variables available for employment across different sectors.
Food Demand	kcal/cap/day	All food demand in calories	Further variables can be used to assess food demand for crops and livestock.
GDP | PPP	billion USD 2010/yr	GDP based on purchasing power parity. (*Author's definition*)	N/A

Variable	Unit	Definition	Additional information
Population	Million	Number of people living in a given area. (*Author's definition*)	Further variables can be used to assess population characteristics like a share of population living in urban areas, the population living in rural areas, the population at risk of hunger, the population living in extreme poverty, and the population with access to electricity.
Unemployment	Million	Number of people above a specified age not taking part in paid or self-employment but are available for work. (*Author's definition*)	N/A
Unemployment | Rate	%	Fraction of unemployed inhabitants (based on ILO classification)	N/A

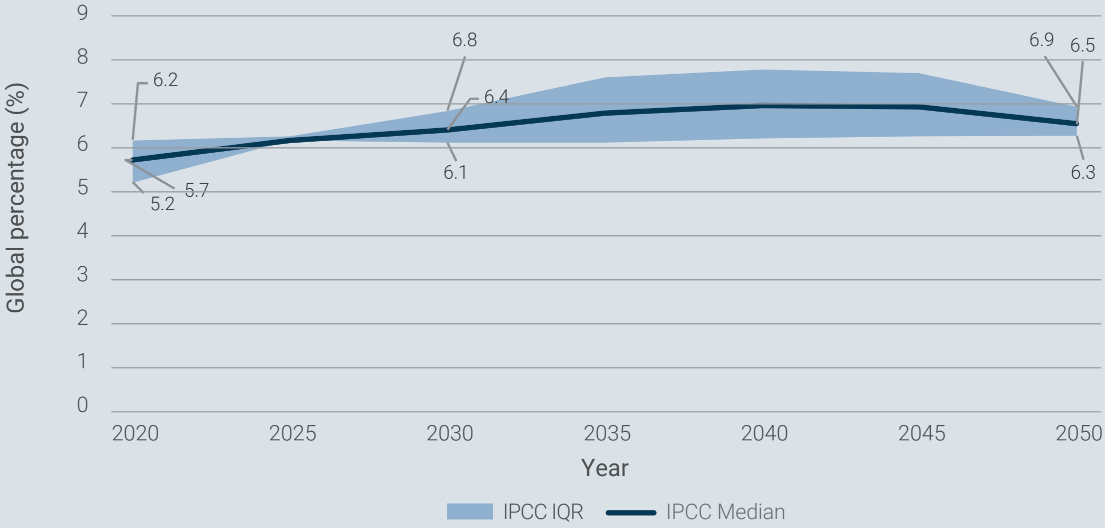
Box 39: Importance of employment as a variable

Employment as a variable is dependent on population and economic growth. For example, if fewer people are born, fewer jobs will be needed in the long term. Similarly, lower employment can lead to a decrease in GDP. All else being equal, rising employment will result in increased incomes resulting in energy and food demand, making the transition to a net-zero economy challenging. To meet the rising demand for existing energy sources and to produce larger quantities of food and goods in the pathways, greater mitigation action will be needed. Furthermore, decarbonisation to a low-carbon economy can also impact the labour market and the skills required for the global workforce (ILO, 2022).

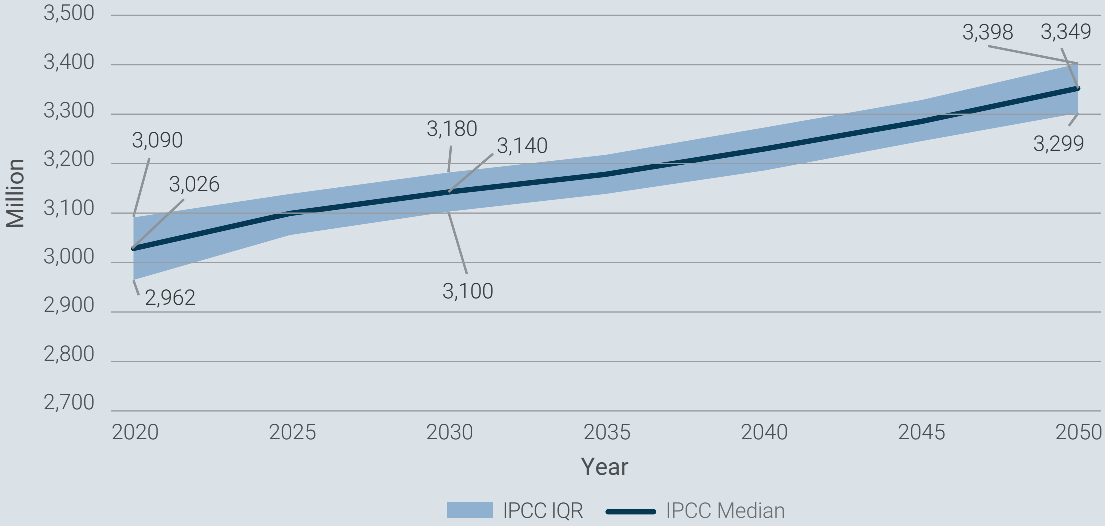
McKinsey's analysis of the NGFS Net Zero 2050 scenario found that the transition to a low-carbon economy could create 202 million job opportunities while decreasing demand for about 187 million jobs by 2050 in the global economy. Jobs losses and gains due to decarbonisation will be specific to certain sectors and regions. Job gains are mainly associated with the transition towards production that is less carbon-intensive (Mckinsey, 2022). Energy efficiency and renewable power will be one area where job growth will be observed this decade in countries like the USA. Other areas of job growth in the coming decades include transmission and distribution, EV manufacturing, the commercialisation of CCS technologies, and alternative fuels such as hydrogen (Decarb America Research Initiative, 2022). Job losses will be focused towards fossil-fuel-intensive industries. A net-zero transition will observe a massive reallocation of jobs across the economy. McKinsey estimates demand for direct operations and maintenance jobs in fossil fuel extraction and production will decrease by nine million and four million in fossil fuel power generation in the NGFS Net Zero 2050 scenario. The agriculture sector could also face the reallocation of jobs as consumer demand for animal protein switches. Meanwhile, an estimated 34 million jobs directly linked to livestock and feed-related industries could be lost by 2050, with a further 19 million jobs lost in ruminant meat farming. However, such losses in the agriculture sector will be offset by the creation of 12 million direct jobs from the increased demand for less emission-intensive activities like poultry farming (Mckinsey, 2022).

However, decarbonisation's impact on employment will not be isolated. As economies decarbonise to limit global warming to 1.5°C , other global trends such as demographic shifts, technological changes, and digitalisation will also impact employment (ILO, 2022). Employment will be particularly impacted by aging populations of developed countries and by migration (both rural-to-urban and global).

Unemployment rates in the 1.5°C scenarios with no or limited overshoot assessed by the IPCC remain consistent with only slight changes in the rate from 2020 to 2030 and 2050. The unemployment rate slightly rises from 5.7% (5.2%–6.2%) in 2020 to 6.4% (6.1%–6.8%) in 2030 and 6.5% (6.3%–6.9%) in 2050. The scenarios also show an increase in the number of people employed, from 3,026 million (2,962 million–3,090 million) in 2020 to 3,349 million (3,299 million–3,398 million) in 2050. Such an increase in number of individuals employed can be attributed to population growth resulting in an increase in the number of people entering the workforce.



(a) Global unemployment rate assumptions in 1.5°C scenarios with no or limited overshoot



(b) Global employment assumptions[73] in 1.5°C scenarios with no or limited overshoot

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[73] This variable only includes data from 2 scenarios, all modelled using the GEM-E3_V2021 model.

8.4 Scenario limitations

Although 1.5°C scenarios with no or limited overshoot cover key socioeconomic drivers, such as population, economic growth, and employment, the scenarios have limitations in the information they provide about the socioeconomic drivers of decarbonisation. Below some of these key limitations are described, including limited granularity of variables and exogenous assumptions.

- GDP estimates are often produced **exogenously or semi-exogenously,** resulting in the narrative pursued in the scenario having little effect on the values of the GDP in the pathway; therefore, scenarios rarely produce estimates of GDP that appropriately factor in climate risks, opportunities, and other economically relevant data.
- IAMs include a **simplified representation** of the global economy and therefore do not include volatility caused by shock events such as Covid-19 or the political stability of a country; for example, the NGFS scenario models are constrained optimisation models and therefore do not model effects such as the business cycle or adverse economic conditions.
- IAMs incorporate certain components of lifestyle changes; still, the **impacts of lifestyles on emissions need to be more comprehensively included** in pathways, such as the aggregated impacts of lifestyle changes needed to limit warming to 1.5°C (Koide *et al.*, 2021).
- Scenarios **do not consider the social aspects** of climate change, such as climate migration, geopolitical conflict, and social polarisation; climate migration is a key concern for financial institutions, for instance, but these are only in the early stages of being integrated into climate models (NGFS Scenario Portal, n.d.).
- The majority of assumptions are focused on SSP2—i.e. middle-of-the-road assumptions. As such, the scenarios **do not consider potential degrowth** in the economy from mitigation actions and their implications as part of the narrative (NGFS Scenario Portal, n.d.).
- Scenarios do not consider **the role of education** in mitigating climate change. For example, access to education for women and the youth globally will matter in reducing CO_2 emissions and taking action towards decarbonisation. Education of girls can reduce emissions at about USD 10/tCO_2 and the cost of avoiding emissions through investments in family planning is estimated to be around USD 4.50/tCO_2. Increased investments in family planning and girls' education could avoid an estimated 85 GtCO_2 emissions between 2020 and 2050, equivalent to shutting down 22,000 coal-fired power plants (Population Connection, n.d.). Scenarios also do not take into consideration the unequal effects of climate change on women and its impact on the transition.
- GDP is used as a metric for economic progress in scenarios. However, it is **important for scenarios to consider metrics other than GDP**. GDP measures economic success through the output of any economy. However, GDP does not take into account factors such as equality and equity, health and well-being, and environmental impacts. Metrics that are wider in scope are needed to measure economic success (Gallagher, 2020).

- The majority of scenarios do not account for **planetary boundaries or limitations on future growth and consumption patterns**. For example, according to the IPCC, environmental factors will require income levels in developed countries to stabilise or even decline. Such narratives are not considered in scenario pathways (IPCC, 2022). Instead, IAMs show a smooth increase in economic growth, as per their assumption of a sustained increase in overall output. Similarly, the scenarios assume that **climate policies will not affect population growth**.

Box 40: The role of gender in the transition to net zero

Climate change has been observed to disproportionately affect women, yet only a small proportion of long-term low-emissions development strategies by countries explicitly incorporate gender considerations (UK Aid, 2022; LSE, 2023). Without further action, gender disparity can act as a barrier to the transition to net zero.

Global supply and demand

Women are pivotal in global supply chains, constituting 43% of the global agriculture workforce, with many women in the positions of producers, distributors and entrepreneurs (UK Aid, 2022). Despite their substantial contributions, women often face barriers to accessing financial resources and information crucial for effective climate mitigation. Climate financing will need to take gender into consideration, such as supporting climate-smart agricultural practices and providing microfinance for female farmers. Equal access to financing, reskilling opportunities, insurance, and land, could potentially reduce annual CO_2 emissions by 1 Gt, equivalent to the emissions of the aviation sub-sector (BCG, 2021).

In addition to their role in the supply chain, women wield significant influence over global brand purchasing decisions, accounting for 70% of purchasing decisions (UK Aid, 2022). Consequently, efforts to decarbonise through demand change need to consider gender roles in purchasing decisions.

Technological innovations

The transition to net zero requires rapid innovation in low-carbon technologies and widespread deployment. Without closing the gender gap, a large proportion of the global population's skills will remain untapped which could be used to accelerate technological innovations. Closing the gap in fields like science, technology, engineering, and mathematics (STEM) is crucial. If women's participation in STEM fields matched that of men, women-led startups could contribute to an annual reduction of 0.5 $GtCO_2$ emissions (BCG, 2021).

Employment opportunities

The transition to net zero will create new job opportunities. However, gender disparities are likely to persist, with men having greater access to jobs in sectors like power generation, construction, and manufacturing (PwC, 2022). Current projections estimate that women will only represent 25% of green jobs by 2030 (LSE, 2023). Furthermore, women are often concentrated in informal and low-paid jobs which face higher vulnerability to climate change, particularly in sectors like agriculture. Without the consideration of increasing opportunities for women, the transition to a low-carbon economy can further widen the gender gap. Improved access to finance, technology, education, and consideration of land rights are essential for ensuring an inclusive and fair employment landscape (BCG, 2021).

Implications for transition pathways

As a result, considerations of gender equality play a crucial role in transition pathways. For example, the considerations of gender-sensitive investments, such as investments in education, access to healthcare and upskilling of women, can lower birthrates and increase contributions to the GDP. Such impacts can have implications for emission reductions in pathways.

Questions for readers:

- Which IPCC-assessed pathways do you agree the most with for the following factors: GDP and wealth, employment, population, and diets?
- Which of the Shared Socioeconomic Pathways (SSP), apart from SSP2, should 1.5°C scenarios with no or limited overshoot consider?
- Are there other socioeconomic factors considered at your institution for scenario analysis but not included in integrated assessment models? What other narratives would you like to see in SSPs?

CHAPTER 9:

Conclusion

The scientific community widely agrees that CO_2 emissions need to reach net zero to ensure that the cumulative amount of CO_2 emissions emitted is within the remaining carbon budget needed to successfully limit global warming to 1.5°C. The IPCC's AR6 provides a global assessment of the mitigation actions needed to reduce emissions and the progress of mitigation efforts globally. These mitigation actions include (WRI, 2020; WRI, 2019):

- A rapid transition to clean energy and cessation of fossil fuel emissions;
- Electrification across the global energy sector and, where possible, across sectors such as transportation and real estate;
- Increased circularity for inputs into heavy industry;
- Advancements in technologies, such as CCS, to decarbonise hard to abate sectors;
- Improved energy and fuel efficiency;
- Increased use of sustainable agricultural practices;
- Shifts in agriculture and other land use from a carbon source to a carbon sink;
- Greater uptake of nature-based solutions to reduce vegetation loss and restore degraded lands.

As part of the sixth assessment cycle, the IPCC assessed 97 scenario pathways for limiting warming to 1.5°C with no or limited overshoot. These scenarios have a range of applications for financial users with the growing need to perform climate-related risk analysis, disclosure, and stress testing.

In recent years, numerous climate scenarios have been developed and been made publicly accessible for use. However, questions remain about their suitability for use within the financial sector. This is not a straightforward matter. As an initial step, financial institutions need to grasp how these scenarios can be applied and what kind of information they can provide. This report offers a detailed view of the range of assumptions and pathways presented by the IPCC in its set of 1.5°C scenarios with no or limited overshoot. It provides essential takeaways from the scenario pathways that are crucial for financial institutions to understand in order to use them effectively in their own assessment. The report summarises key features of climate scenarios that financial institutions should consider when utilising them.

Nonetheless, further efforts and advancements are necessary to optimise scenarios for applications within the financial sector. This endeavour will entail a collective, industry-wide collaboration involving modellers, financial institutions, supervisory authorities, and industry initiatives working closely.

What type of information can climate scenarios provide for financial users?

- Levels of emission reductions needed to limit global warming to 1.5°C with no or limited overshoot;
- Prioritisation of GHGs in terms of reductions in the near and long term;
- The different types of CDR options available and the scale of deployment needed under given time frames;

- Changes in energy use needed across sectors to decarbonise the economy, including the change in energy mix, expansion of electrification across sectors, energy efficiency gains, and the availability of relevant technologies and alternative fuel types;
- Investment opportunities and potential new markets available for firms looking to accelerate the transition to a net-zero economy;
- Financing levels needed to limit warming to 1.5°C.

Key parameters for scenario use

Overall key scenario assumptions:

- Lowest cost mitigation options are selected to reach a given target level of global warming;
- Show a smooth deployment and adoption of new technologies across global sectors and regions;
- Show implementation of policy choices globally, often represented by a carbon price;
- Show a change in energy mix and energy reliance across global energy systems to decarbonise.

Overall key model assumptions:

- Simplified representation of the global economy;
- Structure focused on cost optimisation;
- Removal of uncertainty from future events;
- Estimates for macroeconomic factors are produced exogenously or semi-exogenously;
- Long-run equilibrium with data provided at five-year time steps;
- Aligned with the assumptions of SSP2, which follows historical patterns till 2100.

1.5°C scenarios with no or limited overshoot collectively agree on:

- Deep and rapid cuts in CO_2 with emissions reduced by 100% (median) in 2050,[74] other GHG emissions following shortly after;
- Decrease in the use of fossil fuels, especially the phase-out of coal, with primary energy from coal decreasing by 75% (median) from 2019 to 2030;
- Scale-up in primary energy generated from non-biomass renewables, especially solar (746% (median) increase from 2020 to 2030) and wind energy (323% (median) increase from 2020 to 2030);
- Uptake of electrification across sectors;
- Increase spending in climate finance and decrease financing towards carbon-intensive activities;
- Decrease in carbon intensity of industrial processes by 69% (median) in steel production and 34% (median) in cement production by 2030 (compared to a 2020 baseline);
- Sustained increase in global population (median compound annual growth rate of 1.5%) and GDP (median compound annual growth rate of 5.2%) from 2020 to 2050.

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[74] Compared to 2019 levels

Table 32: Benefits and drawbacks of climate scenarios

Benefits of climate scenarios	Drawbacks of climate scenarios
▪ Data provided on emissions trajectories for various GHGs and the Kyoto gases ▪ High granularity provided for the energy sector and energy systems across the global economy. ▪ Sector breakdown is available to obtain information on emissions and energy-use pathways for sectors such as AFOLU, industrials, transportation, and buildings. ▪ Regional breakdown is available to obtain information. ▪ Breakdown into different energy types—e.g. primary, secondary, and final energy. ▪ A broad view is given of potential allocations for limiting warming. ▪ Information on key socioeconomic assumptions, such as population and GDP, is easily available.	▪ Underlying limitations of data available are hard to detect ▪ Some of the climate scenarios developed multiple years ago contain outdated assumptions. ▪ Details on the emissions reduction potential of various mitigation options are not provided. ▪ Delays are evident in integrating trends, which can lead to the under or overestimation of various trends in some pathways. ▪ Consideration of socio-political feasibility in the scenarios is limited. ▪ The impacts of changing economic conditions on the transition are not taken into account. ▪ Shock events, such as Covid-19 and Russian Federation's invasion of Ukraine, not modelled. ▪ Failure to explicitly model the financial sector. ▪ Granularity of pathways is variable across scenarios and their underlying models. ▪ The number of metrics and variables to characterise changes in the energy system is limited (Gambhir *et al.*, 2019). ▪ No breakdown is provided of financing reported in the pathways down to the private and public sector levels, as well down to institutional types. ▪ No consideration is made of costs associated with capital spendin. ▪ Information on equality, equity, and justice as a result of climate change in not provided. ▪ Information is not available at present on the social impacts of climate change, such as climate migration and geopolitical conflict. ▪ Representation of socioeconomic assumptions is limited. ▪ A lack of gender segregated data available in the pathways, such as for population growth and employment.

Suggested next steps for scenario users

As suggested next steps, financial institutions looking to integrate existing climate scenarios into their climate risk assessment toolkits must first understand the assumptions behind these scenarios. Each scenario pathway gives different weight to a range of possible policy and technology options. This weighting can dramatically alter the nature of the final pathway.

It is also important to note that climate modellers are continually working on improving the scenarios available. As they do so, financial institutions must continue to:

- Understand the robustness and uncertainty of scenario assumptions;
- Build internal capacity to enhance and downscale climate scenarios;

- Set up in-house practices to validate the outputs of the climate scenarios used;
- Apply information obtained from long-term climate scenarios in real-economy decisions with shorter business cycles.

Series of recommendations for scenario use by financial institutions:

1. Identify sector-specific risk drivers to enhance sectoral granularity and sectoral coverage;
2. Identify region-specific risk drivers to enhance regional and national granularity;
3. When uncertain about the data, compare model data available on the AR6 scenario explorer to the source data for model outputs;
4. Enrich scenarios with macroeconomic and financial variables;
5. Determine areas of sectoral and financial market dynamics in scenarios that seem at odds with the user's own expectations or analysis.

Suggested next steps for supervisors and policymakers

Supervisory authorities and policymakers have a pivotal role in advancing the necessary improvements in climate scenarios to address the drawbacks confronting financial users. In recent years, supervisory authorities have implemented practices such as mandatory reporting and have carried out climate stress-testing exercises. These activities have been instrumental in driving the adoption of climate scenario analysis within financial institutions. Outlined below are six key recommendations tailored for supervisory authorities and policymakers to further improve climate scenario analysis across the finance sector.

1. Clearly provide justification for the climate scenarios chosen for use.
2. Build the capacity of supervised financial institutions to understand and use climate scenarios through training and scenario analysis exercises.
3. Provide standardised guidance to financial institutions for scenario enhancement and enrichment.
4. Engage with modellers to develop granular, national pathways of scenarios for use.
5. Ensure scenarios used in exercises are up to date and include the latest available data.
6. Select scenarios of varying time horizons (short- and long-term) and severity for climate scenario analysis exercises.

Suggested next steps for modellers

Climate modellers continue to improve their models and scenario pathways to enhance their applicability for a range of stakeholders and use cases. For example, the NGFS modelling consortium and the IEA tend to update their net-zero scenarios annually to include the latest data available. As modellers continue to enhance their scenarios, it is important for them to take note of the drawbacks faced by financial users of the scenarios and the enhancements needed to make them more useful for the financial sector. Below are eight suggested enhancements that climate modellers should consider as the next steps.

1. Incorporate endogenous estimates of macroeconomic and financial variables
    a. Integrate endogenous macroeconomic factors into scenarios
    b. Determine how macroeconomic shocks can affect different types of transitions
    c. Development of short-term scenarios with macroeconomic shocks
2. Consider smaller time steps and shorter time horizons
    a. Reduce five-year time steps of scenarios to shorter time steps, such as annual
    b. Incorporate shock events and disruptive transitions
    c. Re-evaluate the near-term transitions shown in scenarios until 2030
3. Improve the granularity of sector representation
    a. Incorporate the finance sector
    b. Develop sector-specific assumptions for scenarios for the AFOLU, industrials, transportation, and real estate sectors
4. Reach consensus on baseline estimates
    a. Agree on the same emission, energy use, and investment baselines to use
5. Expand regional variable coverage
    a. Provide granular data for specific countries rather than regional groupings
    b. Incorporate national policies, economic conditions and sociopolitical feasibility factors which can influence the transition of countries
6. Include investment decisions
    a. Provide granular investment data across sectors
    b. Incorporate data on adaptation finance
    c. Break down investment variables for public and private sectors
7. Update socioeconomic assumptions of scenarios
    a. Align the socioeconomic assumptions of scenarios with SSPs other than SSP2
    b. Develop updated socioeconomic pathways for scenarios
    c. Incorporate social impacts of climate change
8. Check underlying model data available for users
    a. Inspect whether model data available on the AR6 scenario explorer is in line with the source data for model outputs

Next steps at UNEP FI

At UNEP FI, the Climate Risk and TCFD programme will continue working on climate scenarios for risk assessment as one of its major workstreams. The programme's goal is to help make climate scenarios more 'fit for purpose' for use by the financial sector. To this end, it remains committed to fostering a platform for collaboration and discussion between scenario developers and UNEP FI members. This cooperative approach represents an effective way of generating new insights about scenario characteristics, such as granularity, sectoral dynamics and assumptions. These insights serve to make climate scenarios more relevant for use by financial institutions. Such discussions will prove crucial as the IPCC enters its seventh assessment report. UNEP FI will also continue working with its members to create practical tools and methodologies to support financial institutions when using climate scenarios for risk assessment.

Appendices

Appendix 1

Global warming potential of GHGs

Global warming potential (GWP) is a measure used to determine how much each GHG contributes to global warming. GWP measures the amount of energy that one tonne of gas emissions absorbs over time relative to the emissions of one tonne of carbon dioxide. GHGs vary in the time they remain in the atmosphere, ranging from a few years to thousands of years. Different gases also have different global warming impacts. Compared to other GHGs, F-gases are emitted in smaller quantities but are the most potent, with some gases being up to 16,300 times more potent than carbon dioxide (UN, 2022).

In comparison to carbon dioxide, nitrous oxide and methane are 280 times and 80 times more potent, respectively (UN, 2022). Water vapor is the most abundant GHG in the atmosphere and a primary driver of the greenhouse effect. It is not a driver for global warming. Molecules of water vapor remain in the atmosphere for about nine days and are then recycled as rain or snow. As a result, despite the large quantity of water vapor in the atmosphere, it does not accumulate. However, water vapor can amplify the warming caused by other greenhouse gases (NASA, 2022).

Over 100 years, methane has a GWP of 27–30 (Environmental Protection Agency, 2022). Carbon dioxide can remain in the atmosphere for up to 300 to 1,000 years (NASA, 2019). About 20% of carbon dioxide can remain in the atmosphere for thousands of years (NASA, 2011). However, it is difficult to accurately determine how long CO_2 emissions last in the atmosphere as carbon moves among parts of the ocean–atmosphere–land system (EPA, 2022). Methane, in comparison, lasts in the atmosphere for around a decade but absorbs much more energy than CO_2. Nitrous oxide has a GWP of about 273 and can stay in the atmosphere for up to 100 years (Environmental Protection Agency, 2022). The GWP of F-gases can range from 124 to 22,800 depending on the particular gas in question (UK Gov, 2014). F-gases can last in the atmosphere for a few weeks and up to thousands of years (EPA, 2022).

A 20-year GWP is sometimes used as an alternative to a GWP of 100 years. A 100-year GWP looks at the energy absorbed by a gas over 100 years. Similarly, a 20-year GWP looks at the energy absorbed by a gas over 20 years. It only considers the impacts of emissions for 20 years. As with a 100-year GWP, a 20-year GWP is also calculated relative to CO_2. A shorter timeframe of GWP will result in larger GWPSs for gases with a lifetime shorter than CO_2. For methane, the 100-year GWP is 27–30, but the 20-GWP is 81–83. CF4 has a lifetime of 50,000 years; the 100-year GWP is 7,380, and the 20-year GWP is 5,300 (EPA, 2022). As a result, using 20-year GWPs to set GHG reduction goals can increase the weighting of short-lived GHGs that remain in the atmosphere for a few years in a given target. This would lead to a significant reduction in CH_4 in comparison to CO_2 (Climate Analytics, 2017).

An advantage of using a 20-year GWP is that it could lead to a rapid reduction in short-term global warming and could therefore buy time to reduce CO_2 emissions. However, the removal of GHGs in the short-term will arguably be outweighed by the additional warming caused by higher concentrations of CO_2 and other long-lived GHGs in the subsequent decades. It is feared that the incorporation of 20-year GWPs in reporting GHGs could provide countries with incentives to delay vital mitigation measures for reducing CO_2 emissions, increasing the concentration of CO_2 in the atmosphere (Climate Analytics, 2017).

Appendix 2

Summary of status, costs, potentials, risk and impacts, co-benefits, trade-offs and spillover effects and the role in mitigation for CDR methods (IPCC, 2022)

CDR method	**Status (TRL)**	**Cost (USD tCO_2^{-1})**	**Mitigation potential1 ($GtCO_2\ yr^{-1}$)**	**Risk and impacts**	**Co-benefits**	**Trade-offs and spillover effects**	**Role in mitigation pathways**
Afforestation/ reforestation	8–9	0–240	0.5–10	Reversal of carbon removal through wildfire, disease, pests may occur. Reduced catchment water yield and lower groundwater level if species and biome are inappropriate.	Enhanced employment and local livelihoods, improved biodiversity, improved renewable wood products provision, soil carbon and nutrient cycling. Possibly less pressure on primary forest.	Inappropriate deployment at large scale can lead to competition for land with biodiversity conservation and food production.	Substantial contribution in IAMs and also in bottom-up sectoral studies.
Soil carbon sequestration in croplands and grasslands	8–9	−45–100	0.6–9.3	Risk of increased nitrous oxide emissions due to higher levels of organic nitrogen in the soil; risk of reversal of carbon sequestration.	Improved soil quality, resilience and agricultural productivity.	Attempts to increase carbon sequestration potential at the expense of production. Net addition per hectare is very small; hard to monitor.	In development—not yet in global mitigation pathways simulated by IAMs in bottom-up studies: with medium contribution.

CDR method	Status (TRL)	Cost (USD tCO_2^{-1})	Mitigation potential1 ($GtCO_2$ yr^{-1})	Risk and impacts	Co-benefits	Trade-offs and spillover effects	Role in mitigation pathways
Peatland and coastal wetland restoration	8–9	Insufficient data	0.5–2.1	Reversal of carbon removal in drought or future disturbance. Risk of increased CH_4 emissions.	Enhanced employment and local livelihoods, increased productivity of fisheries, improved biodiversity, soil carbon and nutrient cycling.	Competition for land for food production on some peatlands used for food production.	Not in IAMs but some bottom-up studies with medium contribution.
Agroforestry	8–9	Insufficient data	0.3–9.4	Risk that some land area lost from food production; requires very high skills.	Enhanced employment and local livelihoods, variety of products improved soil quality, more resilient systems.	Some trade-off with agricultural crop production, but enhanced biodiversity, and resilience of system.	No data from IAMs, but in bottom-up sectoral studies with medium contribution.
Improved forest management	8–9	Insufficient data	0.1+2.1	If improved management is understood as merely intensification involving increased fertiliser use and introduced species, then it could reduce biodiversity and increase eutrophication.	In case of sustainable forest management, it leads to enhanced employment and local livelihoods, enhanced biodiversity, improved productivity	If it involves increased fertiliser use and introduced species it could reduce biodiversity and increase eutrophication and upstream GHG emissions.	No data from IAMs, but in bottom-up sectoral studies with medium contribution.
Biochar	6–7	10–345	0.3–6.6	Particulate and GHG emissions from production; biodiversity and carbon stock loss from unsustainable biomass harvest.	Increased crop yields and reduced non-CO_2 emissions from soil; and resilience to drought.	Environmental impacts associated particulate matter; competition for biomass resource.	In development—not yet in global mitigation pathways simulated by IAMs.
Direct air carbon capture and storage (DACCS)	6	100–300 (84+386)	5–40	Increased energy and water use	Water produced (solid sorbent DAC designs only).	Potentially increased emissions from water supply and energy generation.	In a few IAMs; DACCS complements other CDR methods.

CDR method	Status (TRL)	Cost (USD tCO_2^{-1})	Mitigation potential1 ($GtCO_2$ yr^{-1})	Risk and impacts	Co-benefits	Trade-offs and spillover effects	Role in mitigation pathways
Bioenergy with carbon capture and storage (BECCS)	5–6	15–400	0.5–11	Inappropriate deployment at very large scale leads to additional land and water use to grow biomass feedstock. Biodiversity and carbon stock loss if from unsustainable biomass harvest	Reduction of air pollutants, fuel security, optimal use of residues, additional income, health benefits, and if implemented well, it can enhance biodiversity.	Competition for land with biodiversity conservation and food production.	Substantial contribution in IAMs and bottom-up sectoral studies. Note—mitigation through avoided GHG emissions resulting from bioenergy use is of the same magnitude as the mitigation from CDR (TS.5.6).
Enhanced weathering (EW)	3–4	50–200 (24–578)	2–4 (<1–95)	Mining impacts; air quality impacts of rock dust when spreading on soil.	Enhanced plant growth, reduced erosion, enhanced soil carbon, reduced soil acidity, enhanced soil water retention.	Potentially increased emissions from water supply and energy generation.	In a few IAMs; EW complements other CDR methods.

CDR method	**Status (TRL)**	**Cost (USD tCO_2^{-1})**	**Mitigation potential1 ($GtCO_2$ yr^{-1})**	**Risk and impacts**	**Co-benefits**	**Trade-offs and spillover effects**	**Role in mitigation pathways**
'Blue carbon management' in coastal wetlands	2–3	Insufficient data	<1	If degraded or lost, coastal blue carbon ecosystems are expected to release most of their carbon back to the atmosphere; potential for sediment contaminants, toxicity, bioaccumulation and biomagnification in organisms; issues related to altering degradability of coastal plants; use of sub-tidal areas for tidal wetland carbon removal; effect of shoreline modifications on sediment redeposition and natural marsh accretion; abusive use of coastal blue carbon as means to reclaim land for purposes that degrade capacity for carbon removal.	Provide many non-climatic benefits and can contribute to ecosystembased adaptation, coastal protection, increased biodiversity, reduced upper ocean acidification; could potentially benefit human nutrition or produce fertiliser for terrestrial agriculture, anti-methanogenic feed additive, or as an industrial or materials feedstock	If degraded or lost, coastal blue carbon ecosystems are likely to release most of their carbon back to the atmosphere. The full delivery of the benefits at their maximum global capacity will require years to decades to be achieved.	Not incorporated in IAMs, but in some bottom-up studies: small contribution.

CDR method	Status (TRL)	Cost (USD tCO_2^{-1})	Mitigation potential1 ($GtCO_2$ yr^{-1})	Risk and impacts	Co-benefits	Trade-offs and spillover effects	Role in mitigation pathways
Ocean fertilisation	1–2	50–500	1–3	Nutrient redistribution, restructuring of the ecosystem, enhanced oxygen consumption and acidification in deeper waters, potential for decadalto-millennial-scale return to the atmosphere of nearly all the extra carbon removed, risks of unintended side effects.	Increased productivity and fisheries, reduced upper-ocean acidification.	Sub-surface ocean acidification, deoxygenation; altered meridional supply of macro-nutrients as they are utilised in the iron-fertilised region and become unavailable for transport to, and utilisation in other regions, fundamental alteration of food webs, biodiversity.	No data.
Ocean alkalinity enhancement (OAE)	1–2	40–260	1–100	Increased seawater pH and saturation states and may impact marine biota. Possible release of nutritive or toxic elements and compounds. Mining impacts.	Limiting ocean acidification.	Potentially increased emissions of CO_2 and dust from mining, transport and deployment operations	No data.

Appendix 3

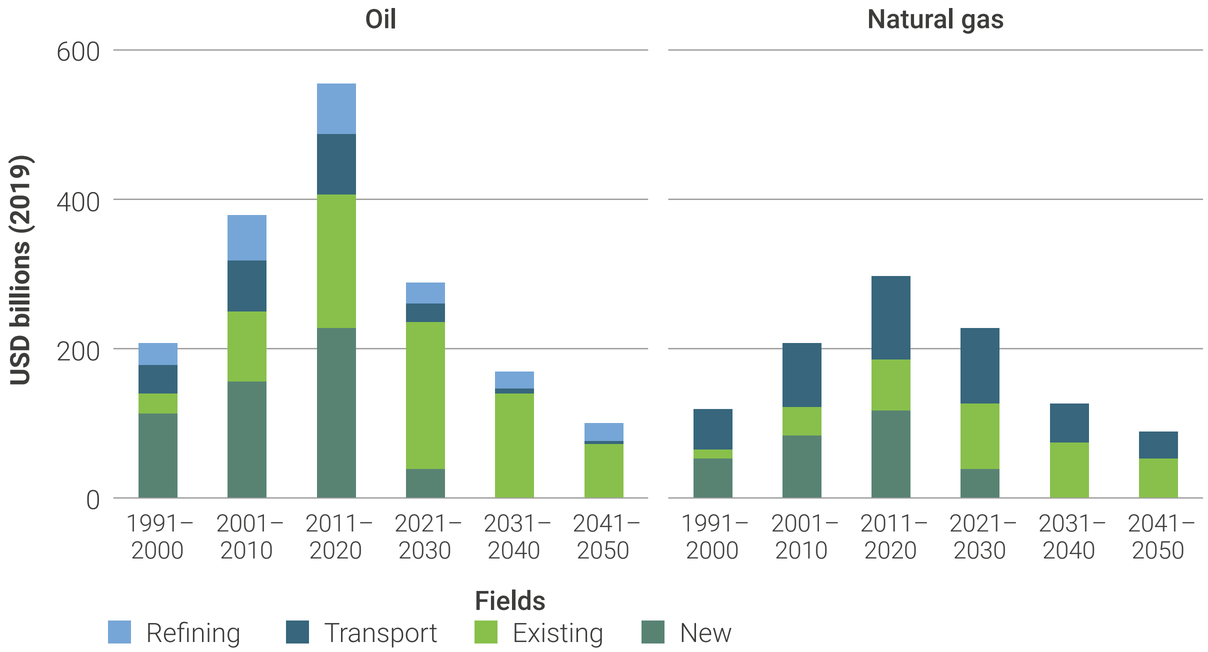

Figure 90: Investment in oil and natural gas supply in IEA's NZE scenario (IEA, 2021)

Appendix 4

SSPs in AR6 Working Group I

AR6 Working Group 1 used output from the latest generation of global climate models produced as part of the sixth Coupled Model Intercomparison Project (CMIP6). The model simulations used “a new set of scenarios, derived from the Shared Socio-economic Pathways (SSPs)”. The SSP narratives and drivers are used to develop scenarios of energy use, air pollution control, land use, and greenhouse gas (GHG) emissions developments using integrated assessment models (IAMs). The five illustrative SSP scenarios show a wide range of plausible societal and climatic futures from potentially below 1.5°C best-estimate warming to over 4°C warming by 2100.

- SSP1–1.9: Holds warming to approximately 1.5°C above pre-industrial temperatures by 2100 “after slight overshoot” and implied net zero CO_2 emissions around the middle of the century.
- SSP1–2.6: Stays below 2C warming with implied net zero emissions in the second half of the century.
- SSP2–4.5: Keeps approximately in line with the upper end of combined pledges under the Paris Agreement. The scenario “deviates mildly from a ‘no-additional climate-policy reference scenario, resulting in a best-estimate warming around 2.7°C by the end of the 21st century”.
- SSP3–7.0: Anticipates a medium-to-high reference scenario resulting from no additional climate policy, with “particularly high non-CO_2 emissions, including high aerosols emissions”.
- SSP5–8.5: Projects a high reference scenario with no additional climate policy. Emissions as high as SSP5–8.5 are only achieved within the fossil-fuelled SSP5 socioeconomic development pathway.

The figure below compares the different Illustrative Mitigation Pathways, climate categories, and SSP scenarios.

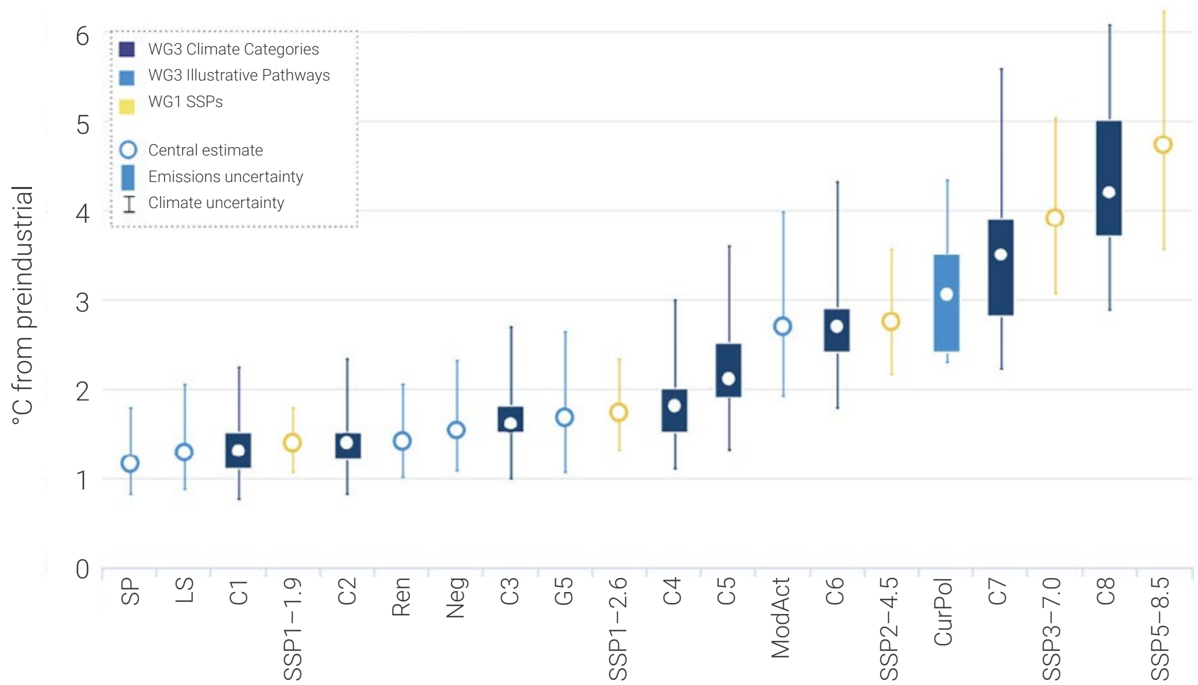

Figure 91: Warming in 2100 for illustrative mitigation pathways (WGIII), climate categories (WGIII), and SSP scenarios (WGI) (Carbon Brief, 2022)

Further details on the SSPs

- SSP1 Sustainability: A coordinated and gradual global shift towards a more sustainable path
  - Economic emphasis on human well-being with lower resource and energy intensity
- SSP2 Middle of the Road: Social, economic, and technological trends do not shift significantly from historical patterns
  - Uneven income growth
  - Environmental systems experience degradation despite some improvements and an overall reduction in the intensity of resource and energy
  - Slow progress towards international sustainable development goals
  - Population growth is moderate
- SSP3 Regional Rivalry: Increased nationalism, competition, and regional conflicts
  - Countries focus on goals within their region with low priority for the environment
  - Investments in education and technology decline
  - Population growth is low
  - Slow economic development
- SSP4 Inequality: Unequal investments with increasing inequalities across and within countries
  - Increase in conflict and unrest
  - A rise in the gap between internationally connected society and fragmented lower-income societies
  - An internationally connected society diversifies its energy mix

  - Technology development is high in the high-tech sectors, and energy sector diversifies
  - Environmental policies focus on issues around middle and high-income areas

- SSP5 Fossil-fuelled Development: Rapid technological progress and global integration for economic growth and development.
  - Exploitation of fossil fuels and the adoption of resource and energy-intensive lifestyles
  - Fossil fuels drive economic growth
  - Global population peaks and falls by 2100
  - Local environmental problems are managed
  - Technological advancements, such as geo-engineering, are expected to manage climate change

Appendix 5

Scenario considerations of scenarios by sector

These are general considerations based on the set of scenarios assessed by the IPCC. These scenarios have differences in characteristics, with models and scenarios varying in granularity.

1. Energy sector

Overall rating: good

Potential areas of greatest suitability: Risk analysis and stress testing, sensitivity analysis, client engagement, opportunity assessment, benchmark for target setting, internal strategy setting

Suitability considerations of scenarios for exploring emissions

Limited information and detail	Some information and detail	Good information and detail
▪ Breakdown of the contribution of specific energy types, such as fossil fuels, renewables and nuclear, on emissions in the pathways not available ▪ How should specific investment and lending activities contribute to emission pathways ▪ Some of the scenarios included in the IPCC's assessment were developed multiple years ago and contain outdated assumptions ▪ Details on the emission reduction potential of various mitigation options are absent ▪ Difference in the historical baseline used in the scenarios as baseline emissions	▪ Regional breakdowns of emission pathways	▪ Levels of emission reductions needed for limiting warming to 1.5°C with no or limited overshoot ▪ Data provided on emission trajectories for various GHGs & Kyoto gases ▪ Which GHGs need to be prioritised in terms of reductions in the near and long term ▪ Information available on emissions from various types of energy use, such as electricity, heat, and gases

Suitability considerations of scenarios for exploring energy demand

Limited information and detail	Some information and detail	Good information and detail
▪ Integration delays in models may lead to under/overestimation of trends in certain pathways, with a risk of missing existing trends or underestimating future trends due to the reliance on historical data or infrequent updates (e.g. deployment rates of renewables) ▪ Limited consideration of socio-politics of energy-mix changes and income distribution ▪ No reflection on how national priorities can differ from projected changes in energy use ▪ Information on security and affordability of national energy sources not provided ▪ Feasibility of grid integration and disruption of current energy systems not addressed	▪ Granularity of energy systems at the geographic and temporal scale across scenarios and their underlying models ▪ Simplified information on technological innovations and their respective adoption	▪ Granularity for the energy sector and energy systems across the global economy ▪ Details on change in energy mix, the expansion of electrification, energy efficiency gains, and alternative fuel types available to limit warming to 1.5°C ▪ Breakdown into different energy types – primary, secondary and final energy

Suitability considerations of scenarios for exploring financing

Limited information and detail	Some information and detail	Good information and detail
▪ No explicit modelling of the financial sector ▪ Breakdown of financing is not reported at the sectoral level (i.e. private or public) nor by institution type ▪ Information on the risks associated with specific investments and the capital and provision need for investments is not provided ▪ Limited consideration of costs associated with capital spending ▪ The impacts of changing economic conditions on investments and availability of finance are not taken into account ▪ Lack of clear considerations of cost of capital in different regions, rendering the expected financial return from projects unclear.		▪ Show levels of financing needed and offer a broad view of potential allocations for limiting warming ▪ Able to identify investment opportunities and potential new markets for firms looking to accelerate the transition to a net-zero economy

2. Transportation sector

Overall rating: average to good

Potential areas of greatest suitability: Risk analysis and stress testing, sensitivity analysis, client engagement, opportunity assessment, benchmark for target setting, internal strategy setting

Suitability considerations of scenarios for exploring emissions

Limited information and detail	Some information and detail	Good information and detail
▪ Contributions of specific sectoral activities & investment and lending activities on emissions in the pathways are not available (e.g. the contribution of ICE vehicles, private jets, commercial airlines, etc.) ▪ Some of the scenarios included in the IPCC's assessment were developed multiple years ago and contain outdated assumptions ▪ Details on the emission reduction potential of various mitigation options are absent ▪ Difference in the historical baseline used in the scenarios as baseline emissions	▪ Regional breakdowns of emission pathways ▪ Breakdown of data for some emission types available at the sub-sector level, such as aviation, maritime, rail and road	▪ Levels of emission reductions needed for limiting warming to 1.5°C with no or limited overshoot ▪ Data provided on emission trajectories for various GHGs & Kyoto gases ▪ Which GHGs need to be prioritised in terms of reductions in the near and long term

Suitability considerations of scenarios for exploring energy demand

Limited information and detail	Some information and detail	Good information and detail
▪ Limited variables covering direct energy demand changes ▪ Limited consideration of socio-politics of energy-mix changes and income distribution ▪ No reflection on how national priorities can differ from projected changes in energy use ▪ Models do not address the feasibility of raw materials availability and infrastructure needs to electrify the sector ▪ Models inherently rely on historical data which puts them at risk of being unable to capture current trends. For example, models are not updated frequently enough to incorporate new trends in the deployment rates and sales of EVs, potentially leading to underestimates in their future use.	▪ Granularity at the geographic and temporal scale across scenarios and their underlying models ▪ Simplified information on technological innovations and their respective adoption ▪ Energy use breakdowns for sub-sectors covered by some pathways (e.g. final energy use of ICE freight vehicles, final energy use for aviation, etc.)	▪ Details available on change in energy mix, the expansion of electrification, and alternative fuel types available to limit warming to 1.5°C

Suitability considerations of scenarios for exploring financing

Limited information and detail	Some information and detail	Good information and detail
▪ Limited view of investments needed for some of the transport sub-sectors, such as aviation and shipping. ▪ Lack of modelling covering the financing needs for alternative fuels ▪ No explicit modelling of the financial sector ▪ Breakdown of financing is not reported at the sectoral level (i.e. private or public) nor by institution type ▪ Information on the risks associated with specific investments and the capital and provision needed for investments is not provided ▪ Limited consideration of costs associated with capital spending ▪ The impacts of changing economic conditions on investments and availability of finance are not taken into account ▪ Lack of clear considerations of cost of capital in different regions, rendering the expected financial return from projects unclear.	▪ Information available on investment opportunities for the transportation sector ▪ Some variables available are only covered by certain integrated assessment models (e.g., investments in infrastructure and EVs)	▪ Offer a broad view of potential allocations of financing for the sector

3. Agriculture

Overall rating: limited

Potential areas of greatest suitability: High-level risk analysis and opportunity assessment

Suitability considerations of scenarios for exploring emissions

Limited information and detail	Some information and detail	Good information and detail
▪ Contribution of specific sectoral activities and investment and lending activities on emissions in the pathways is not available (e.g. fertiliser use) ▪ Some of the scenarios included in the IPCC's assessment were developed multiple years ago and contain outdated assumptions ▪ Details on the emission reduction potential of various mitigation options are absent ▪ Difference in the historical baseline used in the scenarios as baseline emissions	▪ Regional breakdowns of emission pathways ▪ Breakdown of data for some emission types available for different types of land uses, such as manure management and soil management.	▪ Levels of emission reductions needed for limiting warming to 1.5°C with no or limited overshoot ▪ Data provided on emission trajectories for various GHGs & Kyoto gases ▪ Which GHGs need to be prioritised in terms of reductions in the near and long term

Suitability considerations of scenarios for exploring energy demand

Limited information and detail	Some information and detail	Good information and detail
▪ Lack of variables covering direct energy demand changes, including final energy, electrification and change in energy type ▪ Limited consideration of socio-politics of energy-mix changes and income distribution ▪ No reflection on how national priorities can differ from projected changes in energy use ▪ Lack of information on technological innovations and their respective adoption ▪ Models inherently rely on historical data which puts them at risk of being unable to capture current trends. For example, models are not updated frequently enough to incorporate new trends in the deployment rates of renewable technologies, potentially leading to underestimates in their future use.	▪ Granularity at the geographic and temporal scale across scenarios and their underlying models	▪ Details available on changes in agriculture production and demand

Suitability considerations of scenarios for exploring financing

Limited information and detail	Some information and detail	Good information and detail
▪ No variables available that directly cover investment for the sector ▪ Sector granularity is highly limited and therefore pathways do not address the financing needs for the sector and cannot be used to be made definitive statements on investment opportunities for financial institutions	▪ Information available on changes in land use, agriculture production and demand which can be used to infer investment needs for the sector to decarbonise	

4. Industrials

Overall rating: average to limited

Potential areas of greatest suitability: Risk analysis and stress testing, sensitivity analysis, client engagement, opportunity assessment, benchmark for target setting, internal strategy setting

Suitability considerations of scenarios for exploring emissions

Limited information and detail	Some information and detail	Good information and detail
▪ Some of the scenarios included in the IPCC's assessment were developed multiple years ago and contain outdated assumptions ▪ Details on the emission reduction potential of various mitigation options are absent ▪ Difference in the historical baseline used in the scenarios as baseline emissions ▪ Contributions of specific sectoral activities and investment and lending activities on emissions in the pathways are not available	▪ Regional breakdowns of emission pathways ▪ Breakdown of data for some emission types available for some sub-sectors and industrial processes, such as cement, steel and chemicals.	▪ Levels of emission reductions needed for limiting warming to 1.5°C with no or limited overshoot ▪ Data provided on emission trajectories for various GHGs & Kyoto gases ▪ Which GHGs need to be prioritised in terms of reductions in the near and long term

Suitability considerations of scenarios for exploring energy demand

Limited information and detail	Some information and detail	Good information and detail
▪ Limited variables covering direct energy demand changes ▪ Limited consideration of socio-politics of energy-mix changes and income distribution ▪ Lack of data provided on improving energy efficiency ▪ No reflection on how national priorities can differ from projected changes in energy use ▪ Models are inherently prone to lagging behind current time, which can lead to the underestimation and overestimation of various trends in pathways. For example, models are not updated frequently enough to incorporate new trends in the deployment rates of renewable technologies, potentially leading to underestimates in their future use.	▪ Granularity at the geographic and temporal scale across scenarios and their underlying models ▪ Simplified information on technological innovations and their respective adoption ▪ Carbon intensity of production for sub-sectors covered by some pathways	▪ Details available on the expansion of electrification and alternative fuel types for sub-sectors available to limit warming to 1.5°C

Suitability considerations of scenarios for exploring financing

Limited information and detail	Some information and detail	Good information and detail
▪ No variables available that directly cover investment for the sector ▪ Sector granularity is highly limited and therefore pathways do not address the financing needs for the sector and cannot be used to be made definitive statements on investment opportunities for financial institutions	▪ Information available on changes in energy use for the sector, including carbon intensity and final energy amount of various industrial processes and the use of carbon sequestration. These variables can be used to infer investment needs for the sector to decarbonise	

5. Real Estate

Overall rating: average to limited

Potential areas of greatest suitability: Risk analysis and stress testing, sensitivity analysis, client engagement, opportunity assessment, benchmark for target setting, internal strategy setting

Suitability considerations of scenarios for exploring emissions

Limited information and detail	Some information and detail	Good information and detail
▪ Information on emissions generated from various energy sources in the sector for a given pathway is not available, and there is no breakdown of different energy uses in buildings, including contributions from appliances, cooling, etc. ▪ Contribution of specific building types & construction activities is not available ▪ How should specific investment and lending activities contribute to emission pathways ▪ Some of the scenarios included in the IPCC's assessment were developed multiple years ago and contain outdated assumptions ▪ Details on the emission reduction potential of various mitigation options are absent ▪ Difference in the historical baseline used in the scenarios as baseline emissions	▪ Regional breakdowns of emission pathways ▪ Breakdown of data for some emission types available at the commercial and residential level	▪ Levels of emission reductions needed for limiting warming to 1.5°C with no or limited overshoot ▪ Data provided on emission trajectories for various GHGs & Kyoto gases ▪ Which GHGs need to be prioritised in terms of reductions in the near and long term

Suitability considerations of scenarios for exploring energy demand

Limited information and detail	Some information and detail	Good information and detail
▪ Limited variables covering direct energy demand changes and by building type ▪ Models inherently rely on historical data, which puts them at risk of being unable to capture current trends. For example, models are not updated frequently enough to incorporate new trends in the deployment rates of renewable technologies, potentially leading to underestimates in their future use. ▪ Information not available on renovation and construction rates ▪ Lack of data provided on improving energy and operational efficiency of buildings ▪ Limited consideration of socio-politics of energy-mix changes and income distribution	▪ Granularity at the geographic and temporal scale across scenarios and their underlying models ▪ Simplified information on technological innovations and their respective adoption ▪ Changes in energy use, such as for cooking, lighting and appliances, covered by some pathways	▪ Details available on the changes in energy mix and the expansion of electrification needed to limit warming to 1.5°C ▪ Energy use breakdown available for residential and commercial buildings covered

Suitability considerations of scenarios for exploring financing

Limited information and detail	Some information and detail	Good information and detail
▪ No variables available that directly cover investment for the sector ▪ Sector granularity is highly limited and therefore pathways do not address the financing needs for the sector and cannot be used to be made definitive statements on investment opportunities for financial institutions	▪ nformation available on changes in energy use for the sector, including electricity, heating and gas use of buildings. For example, energy use of appliances, cooking and cooling. These variables can be used to infer investment needs for the sector to decarbonise	

Appendix 6

Summary of key attributes of 1.5°C scenarios with no or limited overshoot assessed by the IPCC

Variable (unit)	2020 (median)	2030 (median)	2050 (median)
Net-CO_2 Emissions ($MtCO_2/yr$)	39,878.6	21,459.4	4,492.5
CH_4 Emissions ($MtCH_4/yr$)	362.2	245.0	181.2
N_2O Emissions (KtN_2O/yr)	11,068.8	9,379.7	7,827.6
F-Gases Emissions ($MtCO_2eq/yr$)	1,470.5	345.8	170.6
Total carbon sequestration using CCS ($MtCO_2/yr$)	0.04	1,095.2	7,286.9
Carbon Sequestration using BECCS ($MtCO_2/yr$)	0	325.8	3,833.9
Carbon Sequestration using Direct Air Capture ($MtCO_2/yr$)	0	3.0	103.4
Carbon Sequestration through Land Use ($MtCO_2/yr$)	116.8	731.6	3436.7
Primary energy coal (EJ/yr)	150.0	40.1	7.4
Primary energy oil (EJ/yr)	187.5	170.2	72.0
Primary energy gas (EJ/yr)	132.3	117.8	76.8
Primary energy non-biomass renewables (EJ/yr)	28.9	82.9	227.6
Primary energy solar (EJ/yr)	2.9	24.2	77.0
Primary energy wind (EJ/yr)	5.2	22.0	58.4
Energy efficiency (Billion USD 2010/yr)	10.7	13.3	15.9
Global final energy generated from electricity for the transportation sector (EJ/yr)	1.8	5.9	22.8
Global final energy generated from electricity for the transportation sector from hydrogen (EJ/yr)	0.01	0.1	3.6
Global per capita calories demanded (kcal/cap/day)	2,946.2	2,997.4	3,025.4
Global additional capacity of electricity from biomass (GW/yr)	3.5	3.5	1.5
Global carbon intensity of steel ($MtCO_2eq/Mt$)	2.1	0.7	0.3
Global carbon intensity of cement ($MtCO_2eq/Mt$)	1.1	0.7	0.2
Global final energy consumption by the industrial ammonia gas sub-sector (EJ/yr)	1.2	1.3	0.4
Global final energy consumption of electricity in residential buildings (EJ/yr)	23.6	25.2	43.1

Variable (unit)	2020 (median)	2030 (median)	2050 (median)
Global final energy consumption of gas in residential buildings (EJ/yr)	18.9	16.4	7.5
Investment in new power generation from coal (Billion USD 2010/yr)	58.2	12.7	1.2
Investment in new power generation from oil (Billion USD 2010/yr)	0.05	0.01	0.01
Investment in new power generation from gas (Billion USD 2010/yr)	59.9	30.8	23.0
Investment in new power generation from solar (Billion USD 2010/yr)	132.7	427.5	344.4
Investment in new power generation from wind (Billion USD 2010/yr)	102.6	391.6	478.9
Investments in the transmission and distribution of energy (Billion USD 2010/yr)	355.4	780.5	891.3
Investments in energy efficiency (Billion USD 2010/yr)	99.8	175.2	362.2
Investments into new passenger electric vehicle technologies (Billion USD 2010/yr)	1.3	1.3	2.0
Investments into new passenger ICE vehicle technologies (Billion USD 2010/yr)	1.1	0.4	0.01
Investments in transportation infrastructure (Billion USD 2010/yr)	0.2	0.5	0.8
Global population growth assumptions (million)	7,653.4	8,287.6	9,186.6
Global GDP growth assumptions (trillion USD 2010/yr)	112.1	153.4	247.4
Global total demand for food livestock (million t DM/yr)	284.5	320.3	374.8

Glossary

1.5°C pathway: A pathway of emissions of greenhouse gases and other climate forcers that provides an approximately one-in-two to two-in-three chance, given current knowledge of the climate response, of global warming either remaining below 1.5°C or returning to 1.5°C by around 2100 following an overshoot (*as defined in* IPCC, 2022).

Absolute Zero: Absolute Zero refers to a situation when no greenhouse gas emissions are attributable to an actor's activities across all scopes (*as defined in* Race to Zero, 2021).

Agriculture, forestry, and other land use (AFOLU): In the Agriculture, Forestry and Other Land Use (AFOLU) sector, data on area of different land uses, management systems, animal numbers, lime and fertiliser use are examples of activity data (*as defined in* IPCC, 2022).

Anaerobic digestion: Anaerobic digestion is a process through which bacteria break down organic matter—such as animal manure, wastewater biosolids, and food wastes—in the absence of oxygen (*adapted from* US EPA, n.d.).

Anthropogenic emissions: Emissions of greenhouse gases (GHGs), precursors of GHGs and aerosols caused by human activities. These activities include the burning of fossil fuels, deforestation, land use and land- use changes (LULUC), livestock production, fertilisation, waste management, and industrial processes (*as defined in* IPCC, 2022).

Asia Investor Group on Climate Change (AIGCC): The Asia Investor Group on Climate Change (AIGCC) aims to raise awareness and promote engagement within Asia's asset owners and financial institutions regarding the potential risks and benefits linked to climate change and the pursuit of net-zero investments (AIGCC).

Bioenergy: Energy derived from any form of biomass or its metabolic by-products (*as defined in* IPCC, 2022).

Bioenergy with carbon dioxide capture and storage (BECCS): Carbon dioxide capture and storage (CCS) technology applied to a bioenergy facility. Note that depending on the total emissions of the BECCS supply chain, carbon dioxide can be removed from the atmosphere (*as defined in* IPCC, 2022).

Black carbon (BC): Operationally defined aerosol species based on measurement of light absorption and chemical reactivity and/or thermal stability. It is sometimes referred to as soot. BC is mostly formed by the incomplete combustion of fossil fuels, biofuels, and biomass but it also occurs naturally. It stays in the atmosphere only for days or weeks. It is the most strongly light-absorbing component of particulate matter (PM) and has a warming effect by absorbing heat into the atmosphere and reducing the albedo when deposited on snow or ice (*as defined in* IPCC, 2022).

Blue Hydrogen: Hydrogen is labelled blue whenever the carbon generated from steam reforming is captured and stored underground through industrial carbon capture and storage (CSS). Blue hydrogen is, therefore, sometimes referred to as carbon neutral as the emissions are not dispersed in the atmosphere. However, some argue that "low carbon" would be a more accurate description, as 10–20% of the generated carbon cannot be captured (*adapted from* World Economic Forum, n.d.).

Carbon Border Adjustment Mechanism (CBAM): The EU's Carbon Border Adjustment Mechanism (CBAM) sets a fair carbon price on high-emission goods entering the EU, promoting cleaner production abroad. It aligns with ending free allowances in the EU Emissions Trading System, aiding EU industry decarbonisation. CBAM ensures equal carbon pricing for imports, upholding EU climate goals, and is WTO-compatible (*as defined in* EU, n.d.).

Carbon budget: This term refers to three concepts in the literature: (1) an assessment of carbon cycle sources and sinks on a global level, through the synthesis of evidence for fossil fuel and cement emissions, land-use change emissions, ocean and land CO_2 sinks, and the resulting atmospheric CO_2 growth rate. This is referred to as the global carbon budget; (2) the estimated cumulative amount of global carbon dioxide emissions that that is estimated to limit global surface temperature to a given level above a reference period, taking into account global surface temperature contributions of other GHGs and climate forcers; (3) the distribution of the carbon budget defined under (2) to the regional, national, or sub-national level based on considerations of equity, costs or efficiency. See also Remaining carbon budget (*as defined in* IPCC, 2022).

Carbon dioxide capture and storage (CCS): A process in which a relatively pure stream of carbon dioxide (CO_2) from industrial and energy-related sources is separated (captured), conditioned, compressed and transported to a storage location for long-term isolation from the atmosphere. Sometimes referred to as Carbon capture and storage (*as defined in* IPCC, 2022).

Carbon dioxide capture and utilisation (CCU): A process in which CO_2 is captured and then used to produce a new product. If the CO_2 is stored in a product for a climate-relevant time horizon, this is referred to as carbon dioxide capture, utilisation and storage (CCUS). Only then, and only combined with CO_2 recently removed from the atmosphere, can CCUS lead to carbon dioxide removal. CCU is sometimes referred to as carbon dioxide capture and use (*as defined in* IPCC, 2022).

Carbon dioxide removal (CDR): Anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage but excludes natural CO_2 uptake not directly caused by human activities (*as defined in* IPCC, 2022).

Carbon Neutral (ity): Race to Zero considers individual actors to be carbon neutral when: CO_2 emissions attributable to an actor are fully compensated by CO_2 reductions or removals exclusively claimed by the actor, such that the actor's net contribution to global CO_2 emissions is zero, irrespective of the time period or the relative magnitude of emissions and removals involved. It is not the same as net zero because it does not require “like for like” balancing. It is also not synonymous with GHG neutral(ity) or climate neutral(ity) because it only refers to carbon (*as defined in* Race to Zero, 2021).

Concentrating solar power (CSP): Concentrating solar power (CSP) plants use mirrors to concentrate the sun’s energy to drive traditional steam turbines or engines that create electricity. The thermal energy concentrated in a CSP plant can be stored and used to produce electricity when it is needed, day or night (*adapted from* SEIA, n.d.).

Conference of the Parties: The COP is the supreme decision-making body of the United Nations Framework on Climate Change. All States that are Parties to the Convention are represented at the COP, at which they review the implementation of the Convention and any other legal instruments that the COP adopts and take decisions necessary to promote the effective implementation of the Convention, including institutional and administrative arrangements. A key task for the COP is to review the national communications and emission inventories submitted by Parties. Based on this information, the COP assesses the effects of the measures taken by Parties and the progress made in achieving the ultimate objective of the Convention. (*as defined in* UNFCCC) See also *United Nations Framework Convention on Climate Change (UNFCCC)*.

Crude oil: Crude oil means a mixture of hydrocarbons that exists in liquid phase in natural underground reservoirs and remains liquid at atmospheric pressure after passing through surface separating facilities (*adapted from* EPA, n.d.).

Decarbonisation: The process by which countries, individuals or other entities aim to achieve zero fossil carbon existence. Typically refers to a reduction of the carbon emissions associated with electricity, industry and transport (*as defined in* IPCC, 2022).

Direct air capture (DAC): Direct air capture (DAC) technologies extract CO_2 directly from the atmosphere at any location, unlike carbon capture which is generally carried out at the point of emissions, such as a steel plant. The CO_2 can be permanently stored in deep geological formations or used for a variety of applications (*adapted from* IEA, 2023).

Distillate fuel: Distillate fuel oil is the second most-consumed petroleum product in the United States of America. Distillate fuel oil includes diesel fuel and heating oil. Diesel fuel is used in the diesel engines of heavy construction equipment, trucks, buses, tractors, boats, trains, some automobiles, and electricity generators. Heating oil, also called fuel oil, is used in boilers and furnaces for heating homes and buildings, for industrial heating, and for producing electricity in power plants (*adapted from* EIA, n.d.).

Emission pathways: Modelled trajectories of global anthropogenic emissions over the 21st century (*as defined in* IPCC, 2022).

Emissions trading: A market-based instrument aiming at meeting a mitigation objective in an efficient way. A cap on GHG emissions is divided in tradeable emission permits that are allocated by a combination of auctioning and handing out free allowances to entities within the jurisdiction of the trading scheme. Entities need to surrender emission permits equal to the amount of their emissions (e.g., tonnes of CO_2). An entity may sell excess permits to entities that can avoid the same amount of emissions in a cheaper way. Trading schemes may occur at the intra-company, domestic, or international level (e.g., the flexibility mechanisms under the Kyoto Protocol and the EU-EUTS) and may apply to carbon dioxide (CO_2), other greenhouse gases (GHGs), or other substances (*as defined in* IPCC, 2022).

Emissions trading scheme (ETS): Set up in 2005, the EU ETS is the world's first international emissions trading system. In an ETS, emission permits or allowances are given out or sold (allocated) to the entities that are included in the ETS. Entities with low abatement costs thus have an incentive to reduce their emissions, while those facing higher costs can choose to comply by purchasing allowances from the market (*adapted from* EU, n.d., ICAP, n.d.).

Final energy: Energy that is received by the consumer. It is secondary energy transported to the consumer.

Global warming potential (GWP): GWP was developed to allow comparisons of the global warming impacts of different gases. Specifically, it is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide. It is an index that attempts to integrate the overall climate impacts of a specific action (e.g., emissions of CH_4, NOx or aerosols). It relates the impact of emissions of a gas to that of emission of an equivalent mass of CO_2. The duration of the perturbation is included by integrating radiative forcing over a time horizon (e.g., standard horizons for IPCC have been 20, 100, and 500 years). The time horizon thus includes the cumulative climate change and the decay of the perturbation (*adapted from* US EPA and IPCC, n.d.).

Green hydrogen: Green hydrogen—also referred to as "clean hydrogen"—is produced by using clean energy from surplus renewable energy sources, such as solar or wind power, to split water into two hydrogen atoms and one oxygen atom through a process called electrolysis. Renewables cannot always generate energy at all hours of the day and green hydrogen production could help use the excess generated during peak cycles. It currently makes up about 0.1% of overall hydrogen production, but this is expected to rise as the cost of renewable energy continues to fall. Many sectors also now see green hydrogen as the best way of harmonising the intermittency of renewables—storing excess energy at times of low demand to be fed back into the grid when demand rises—while decarbonising the chemical, industrial and transportation sectors (*adapted from* World Economic Forum, n.d.).

Grey hydrogen: Grey hydrogen is the most common form and is generated from natural gas, or methane, through a process called "steam reforming". This process generates just a smaller amount of emissions than black or brown hydrogen, which uses black (bituminous) or brown (lignite) coal in the hydrogen-making process. Black or brown hydrogen is the most environmentally damaging as both the CO_2 and carbon monoxide generated during the process are not recaptured (*adapted from* World Economic Forum, n.d.).

Heating, Ventilation and Air-Conditioning Systems (HVAC) system: The main purposes of a Heating, Ventilation and Air-Conditioning (HVAC) system are to help maintain good indoor air quality (IAQ) through adequate ventilation with filtration and provide thermal comfort. HVAC systems are among the largest energy consumers in schools. The choice and design of the HVAC system can also affect many other high performance goals, including water consumption (water cooled air conditioning equipment) and acoustics (*adapted from* US EPA, n.d.).

Hydrocarbon gas liquids: Natural gas and crude oil are mixtures of different hydrocarbons. Hydrocarbons are molecules of carbon and hydrogen in various combinations. Hydrocarbon gas liquids (HGLs) are hydrocarbons that occur as gases at atmospheric pressure and as liquids under higher pressures (*adapted from* EIA, n.d.).

Institutional Investors Group on Climate Change (IIGCC): The Institutional Investors Group on Climate Change (IIGCC) stands as the foremost European collective of members, empowering the investment community in Europe to actively steer substantial and tangible advancements by 2030, aimed at achieving both a net-zero status and enhanced resilience for the future. With over 375 members, collectively overseeing €51 trillion in assets under management (AUM), IIGCC possesses the potential to trigger concrete transformations in the real world through their choices in distributing capital, their responsible oversight and interactions with corporations and the broader market, as well as their influential efforts in advocating for impactful policies (*adapted from* IIGCC).

Integrated assessment model (IAM): Integrated assessment models (IAMs) integrate knowledge from two or more domains into a single framework. They are one of the main tools for undertaking integrated assessments. One class of IAM used in respect of climate change mitigation may include representations of: multiple sectors of the economy, such as energy, land use and land use change; interactions between sectors; the economy as a whole; associated GHG emissions and sinks; and reduced representations of the climate system. This class of model is used to assess linkages between economic, social and technological development and the evolution of the climate system. Another class of IAM additionally includes representations of the costs associated with climate change impacts but includes less detailed representations of economic systems. These can be used to assess impacts and mitigation in a cost-benefit framework and have been used to estimate the social cost of carbon (*as defined in* IPCC, 2022).

Intergovernmental Panel on Climate Change: The Intergovernmental Panel on Climate Change (IPCC) is the international body for assessing the science related to climate change. The IPCC was set up in 1988 by the World Meteorological Organization (WMO) and United Nations Environment Programme (UNEP) to provide policymakers with regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation. IPCC assessments provide a scientific basis for governments at all levels to develop climate related policies, and they underlie negotiations at the UN Climate Conference—the United Nations Framework Convention on Climate Change (UNFCCC). The assessments are policy-relevant but not policy prescriptive: they may present projections of future climate change based on different scenarios and the risks that climate change poses and discuss the implications of response options, but they do not tell policymakers what actions to take (*as defined in* IPCC, n.d).

Investor Group on Climate Change (IGCC): The Investor Group on Climate Change (IGCC) is a collaboration of Australian and New Zealand institutional investors focused on the impact of climate change on investments. IGCC represents investors with tens of trillions of dollars in funds under management around the world. IGCC members are fiduciaries for more than 7.5 million people in Australia and New Zealand. As a not-forprofit organisation, its work is funded by members' fees, philanthropy, partnerships, and sponsorship from supporters who understand the power of capital to support climate action (*adapted from* IGCC).

IPCC-assessed scenarios: The third part of the IPCC's 6th assessment report, known as Working Group III (WG3), provides a detailed view of possible futures and draws on a database of more than 3,000 different future emissions pathways generated by integrated assessment models (IAMs). After a vetting process, 1,202 scenarios are qualified with sufficient information to calculate a broad range of future greenhouse gas emissions and global climate outcomes. These scenarios are broadly divided into eight different "climate categories" based on 21st century warming outcomes—labeled C1 through to C8 (*adapted from* IPCC, 2022; Carbon Brief, 2022, Climate Analytics, 2022).

Metallurgic coal: Metallurgical coal is a black sedimentary rock found within the earth's crust. It is higher in carbon, typically low in moisture and is an essential part of the steel-making process (*adapted from* BHP, n.d.).

Minimum tillage practices: Minimum tillage, which minimises stubble burial, and stubble retention at sowing or adding stubble mulches that help cover the ground, are standard cultural virus control measures that help to diminish the landing rates of aphid vectors and so decrease virus spread. Like early plant canopy cover, they act by minimising exposure of bare ground between plants and so repel incoming aphids (*as defined in* IPCC, 2022).

Mitigation pathways: A temporal evolution of a set of mitigation scenario features, such as greenhouse gas (GHG) emissions and socio-economic development (*as defined in* IPCC, 2022).

Nationally Determined Contributions (NDCs): A term used under the United Nations Framework Convention on Climate Change (UNFCCC) whereby a country that has joined the Paris Agreement outlines its plans for reducing its emissions. Some countries NDCs also address how they will adapt to climate change impacts, and what support they need from, or will provide to, other countries to adopt low-carbon pathways and to build climate resilience. According to Article 4 paragraph 2 of the Paris Agreement, each Party shall prepare, communicate and maintain successive NDCs that it intends to achieve. In the lead up to 21st Conference of the Parties in Paris in 2015, countries submitted Intended Nationally Determined Contributions (INDCs). As countries join the Paris Agreement, unless they decide otherwise, this INDC becomes their first Nationally Determined Contribution (NDC) (*as defined in* IPCC, 2022).

Net zero: Referring to the world as a whole, the IPCC defines net zero as: When anthropogenic emissions of greenhouse gases to the atmosphere are balanced by anthropogenic removals over a specified period (IPCC, n.d.). The Race to Zero campaign considers individual actors to have reached a state of net zero when: An actor reduces its emissions following science-based pathways, with any remaining GHG emissions attributable to that actor being fully neutralised by like-for-like removals (e.g. permanent removals for fossil carbon emissions) exclusively claimed by that actor, either within the value chain or through purchase of valid offset credits (*as defined in* Race to Zero, 2021).

Net zero CO_2 emissions: Net zero CO_2 emissions refer to the condition in which anthropogenic carbon dioxide (CO_2) emissions are balanced by anthropogenic CO_2 removals over a specified period (*as defined in* IPCC, 2022).

Net zero GHG emissions: Net zero GHG emissions refer to the condition in which metric-weighted anthropogenic greenhouse gas (GHG) emissions are balanced by metric-weighted anthropogenic GHG removals over a specified period (*as defined in* IPCC, 2022).

Non-overshoot pathways: Pathways that stay below a specified concentration, forcing, or global warming level during a specified period of time (e.g., until 2100) (*as defined in* IPCC, 2022).

Onshore and offshore wind energy: harnesses the kinetic energy of moving air. The primary application of relevance to climate change mitigation is to produce electricity from large wind turbines located on land (onshore) or in sea- or freshwater (offshore). Onshore wind energy technologies are already being manufactured and deployed on a large scale. Offshore wind energy technologies have greater potential for continued technical advancement. Wind electricity is both variable and, to some degree, unpredictable, but experience and detailed studies from many regions have shown that the integration of wind energy generally poses no insurmountable technical barriers (*as defined in* IPCC, 2018).

Overshoot pathways: Pathways that first exceed a specified concentration, forcing, or global warming level, and then return to or below that level again before the end of a specified period of time (e.g., before 2100). Sometimes the magnitude and likelihood of the overshoot is also characterised. The overshoot duration can vary from one pathway to the next, but in most overshoot pathways in the literature and referred to as overshoot pathways in the AR6, the overshoot occurs over a period of at least one decade and up to several decades (*as defined in* IPCC, 2022).

Paris Agreement: Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) was adopted on December 2015 in Paris, France, at the 21st session of the Conference of the Parties (COP) to the UNFCCC. The agreement, adopted by 196 Parties to the UNFCCC, entered into force on 4 November 2016 and as of May 2018 had 195 Signatories and was ratified by 177 Parties. One of the goals of the Paris Agreement is "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels", recognising that this would significantly reduce the risks and impacts of climate change. Additionally, the Agreement aims to strengthen the ability of countries to deal with the impacts of climate change. The Paris Agreement is intended to become fully effective in 2020 (*as defined in* IPCC, 2022).

Pathways: The temporal evolution of natural and/or human systems towards a future state. Pathway concepts range from sets of quantitative and qualitative scenarios or narratives of potential futures to solution-oriented decision-making processes to achieve desirable societal goals. Pathway approaches typically focus on biophysical, techno-economic, and/or socio-behavioural trajectories and involve various dynamics, goals, and actors across different scales (*as defined in* IPCC, 2022).

Permafrost: Ground (soil or rock, and included ice and organic material) that remains at or below 0°C for at least two consecutive years (Harris *et al.*, 1988). Note that permafrost is defined via temperature rather than ice content and, in some instances, may be ice-free (*as defined in* IPCC, 2022).

Photovoltaics (PV): A photovoltaic (PV) cell, commonly called a solar cell, is a nonmechanical device that converts sunlight directly into electricity. When the semiconductor material absorbs enough sunlight (solar energy), electrons are dislodged from the material's atoms (*adapted from* EIA, n.d.).

Primary energy: Energy available in its resource form before it has been transformed. Example: Coal before it is burned, oil barrels

Race to Zero Campaign: Race To Zero is a global campaign to rally leadership and support from businesses, cities, regions, investors for a healthy, resilient, zero carbon recovery. It mobilises a coalition of leading net-zero initiatives, representing 11,309 non-State actors including 8,307 companies, 595 financial institutions, 1,136 cities, 52 states and regions, 1,125 educational institutions and 65 healthcare institutions (as of September 2022) (*as defined in* Race to Zero Campaign).

Reference scenario: Scenario used as starting or reference point for a comparison between two or more scenarios.

> **Note 1:** In many types of climate change research, reference scenarios reflect specific assumptions about patterns of socioeconomic development and may represent futures that assume no climate policies or specified climate policies, for example those in place or planned at the time a study is carried out. Reference scenarios may also represent futures with limited or no climate impacts or adaptation, to serve as a point of comparison for futures with impacts and adaptation. These are also referred to as **baseline scenarios** in the literature;
>
> **Note 2:** Reference scenarios can also be climate policy or impact scenarios, which in that case are taken as a point of comparison to explore the implications of other features, for example, of delay, technological options, policy design and strategy or to explore the effects of additional impacts and adaptation beyond those represented in the reference scenario;
>
> **Note 3:** The term business as usual scenario has been used to describe a scenario that assumes no additional policies beyond those currently in place and that patterns of socio-economic development are consistent with recent trends. The term is now used less frequently than in the past;
>
> **Note 4:** In climate change attribution or impact attribution research, reference scenarios may refer to counterfactual historical scenarios assuming no anthropogenic greenhouse gas (GHG) emissions (climate change attribution) or no climate change (impact attribution).] (*as defined in* IPCC, 2022)

Remaining carbon budget: Estimated cumulative net global anthropogenic CO_2 emissions from the start of 2018 to the time that anthropogenic CO_2 emissions reach net zero that would result, at some probability, in limiting global warming to a given level, accounting for the impact of other anthropogenic emissions (*as defined in* IPCC, 2022).

Representative Concentration Pathways (RCPs): Scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases (GHGs) and aerosols and chemically active gases, as well as land use/land cover (Moss *et al.*, 2010). The word representative signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics. The term pathway emphasises that not only the long-term concentration levels are of interest, but also the trajectory taken over time to reach that outcome (Moss *et al.*, 2010). RCPs usually refer to the portion of the concentration pathway extending up to 2100, for which integrated assessment models produced corresponding emission scenarios (*as defined in* IPCC, 2022).

Scenario: A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change (TC), prices) and relationships. Note that scenarios are neither predictions nor forecasts, but are used to provide a view of the implications of developments and actions (*as defined in* IPCC, 2022).

Scope 1, 2, and 3 emissions: The GHG Protocol Corporate Standard classifies a company's GHG emissions into three 'scopes'. Scope 1 emissions are direct emissions from owned or controlled sources. Scope 2 emissions are indirect emissions from the generation of purchased energy. Scope 3 emissions are all indirect emissions (not included in scope 2) that occur in the value chain of the reporting company, including both upstream and downstream emissions (*adapted from* Greenhouse Gas Protocol).

Secondary energy: Energy converted from primary energy into a transportable form such as electricity. Example: Electricity generated from coal, oil refined into gasoline and diesel.

Shared Socio-economic Pathways (SSPs): Shared Socio-economic Pathways (SSPs) have been developed to complement the Representative Concentration Pathways (RCPs). By design, the RCP emission and concentration pathways were stripped of their association with a certain socio-economic development. Different levels of emissions and climate change along the dimension of the RCPs can hence be explored against the backdrop of different socio-economic development pathways (SSPs) on the other dimension in a matrix. This integrative SSP-RCP framework is now widely used in the climate impact and policy analysis literature, where climate projections obtained under the RCP scenarios are analysed against the backdrop of various SSPs. As several emissions updates were due, a new set of emissions scenarios was developed in conjunction with the SSPs. Hence, the abbreviation SSP is now used for two things: On the one hand SSP1, SSP2, …, SSP5 are used to denote the five socio-economic scenario families. On the other hand, the abbreviations SSP1–1.9, SSP1–2.6, …, SSP5–8.5 are used to denote the newly developed emissions scenarios that are the result of an SSP implementation within an integrated assessment model. Those SSP scenarios are bare of climate policy assumption, but in combination with so called shared policy assumptions (SPAs), various approximate radiative forcing levels of 1.9, 2.6, …, or 8.5 W m–2 are reached by the end of the century, respectively (*as defined in* IPCC, 2022).

Special Report on Global Warming of 1.5°C (SR15): In 2018, the IPCC released its Special Report on Global Warming of 1.5°C (SR15). Ninety-one scientists and policy experts authored the report The report concluded that meeting a 1.5˚C climate target was possible but would require significant actions for emissions reductions. In SR15, the IPCC assessed quantitative, model-based climate change mitigation pathways for 1.5°C. This included 90 distinct scenarios that have at least a 50% chance of keeping warming to 1.5°C by 2100 (*adapted from* Carbon Brief, 2018).

Sustainable Development Goals: A UN resolution in September 2015 adopting a plan of action for people, planet and prosperity in a new global development framework anchored in 17 Sustainable Development Goals (*as defined in* IPCC, 2022).

The Sixth Assessment Report (AR6): The IPCC is now in its sixth assessment cycle, in which the IPCC is producing the Sixth Assessment Report (AR6) with contributions by its three Working Groups and a Synthesis Report, three Special Reports, and a refinement to its latest Methodology Report. Three Working Groups (WGI, II, and III) covered the following topics: The Physical Science Basis (WGI); Impacts, Adaptation and Vulnerability (WGII); Mitigation of Climate Change (WGIII). The Working Group I contribution was released on 9 August 2021. The Working Group II and III contributions were released on 28 February and 4 April 2022 respectively. The Synthesis Report was released on 20 March 2023. AR6 is the IPCC's first major report on limiting global warming to 1.5˚C since its Special Report on Global Warming of 1.5°C (SR15) in 2018 (*as defined in* IPCC, 2022).

Tipping points: A level of change in system properties beyond which a system reorganises, often abruptly, and does not return to the initial state even if the drivers of the change are abated. For the climate system, it refers to a critical threshold when global or regional climate changes from one stable state to another stable state (*adapted from* Lenton *et al.*, 2019 and IPCC, 2022).

United Nations Framework Convention on Climate Change (UNFCCC): The UNFCCC, adopted in 1992 with near-universal membership, seeks to prevent harmful human interference with the climate system whose provisions are carried out through the Kyoto Protocol and the Paris Agreement (*adapted from* IPCC, 2022, UNFCCC).

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Chapter 7

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Chapter 8

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