TRANSITIONING AWAY FROM FOSSIL FUELS IN PARIS-ALIGNED MITIGATION PATHWAYS

A Policy Brief
from the Science Panel
for the Global Energy Transition

The Science Panel for the Global Energy Transition (SP-GET) is an independent body that provides policy relevant, state-of-the-art scientific assessments on the transition away from fossil fuels (TAFF), globally and regionally. It consists of four expert groups on Energy Transition Pathways, Policy Design and Evaluation, Technological Systems Analysis, and Financial Instruments and Institutions, an interface for stakeholder consultation, and a Technical Support Unit, and draws on the expertise of a diverse and international group of scientists and experts.

More info: spget.org

Editorial office:
Technical Support Unit of the Science Panel for the Global Energy Transition
Potsdam Institute for Climate Impact Research
P.O. Box 60 12 03
D-14412 Potsdam
Germany

Email: info@spget.org
Use this email for inquiries and comments on this policy brief.

The policy brief has been prepared by the Expert Group on Energy Transition Pathways of SP-GET. The views, findings, and conclusions expressed in this report are solely those of the authors. They do not necessarily reflect the views or endorsement of any affiliated institutions or funding bodies.

The production of this report was supported by the Global Challenges Foundation. The funding institution had no role in the analysis, assessment or drafting of this report.



Disclaimer:
SP-GET is an independent scientific body without legal personality. While the authors have made every effort to ensure the accuracy and reliability of the information presented, it is provided on an 'as-is' basis. The information, conclusions and recommendations provided are for informational purposes only and do not constitute professional, legal, or financial advice. In no event shall the authors be held liable for any loss or damage arising from reliance on this material. Readers are encouraged to verify findings independently and are invited to communicate any feedback or factual corrections to the authors.

AUTHORS

Convening Lead Authors:
Gunnar Luderer[1,2] (Lead Author)
Keywan Riahi[3] (Co-Lead Expert Group Energy Transition Pathways)
Ritu Mathur[4] (Co-Lead Expert Group Energy Transition Pathways)
Ambiyah Abdullah[5]
Claire Fyson[1]
Shonali Pachauri[3]
Youba Sokona[6]
Elmar Kriegler[1,7] (Co-Chair SP-GET)

Coordinating Authors:
Adrian Heilemann[1]
Fabrice Lécuyer[1]
Nibwene Mwakibinga[1]
Robert Pietzcker[1]
Philipp Verpoort[1]
Lila Warszawski[1]

1 Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Germany
2 Technical University of Berlin, Institute of Energy Engineering, Germany
3 International Institute for Applied Systems Analysis (IIASA), Austria
4 The Energy and Resources Institute (TERI), India
5 ASEAN Center for Energy (ACE), Indonesia
6 African Institute for Sustainable Energy and System Analysis (AISESA)
7 University of Potsdam, Faculty of Economics and Social Sciences, Germany

Authors of the SP-GET Expert Group on Energy Transition Pathways:
Keywan Riahi[1] (Co-Lead)
Ritu Mathur[2] (Co-Lead)
Ambiyah Abdullah[3]
Jesse Burton[4]
Vaibhav Chaturvedi[5]
Cheolhung Cho[6]
Ryna Cui[7]
Hancheng Dai[8]
Shinichiro Fujimori[9]
Gunnar Luderer[10,11]
Shonali Pachauri[1]
Alexandre Szklo[12,13]
Youba Sokona[14]
Masahiro Sugiyama[15]
Stephanie Roe[16]
Detlef van Vuuren[17,18]
Biying Yu[19]

1 International Institute for Applied Systems Analysis (IIASA), Austria
2 The Energy and Resources Institute (TERI), India
3 ASEAN Centre for Energy, Indonesia
4 University of Cape Town, South Africa
5 Council on Energy, Environment and Water, India
6 Korea Advanced Institute of Science and Technology, Republic of Korea
7 Center for Global Sustainability, University of Maryland, USA
8 Peking University, China
9 Graduate School of Engineering, Kyoto University, Japan
10 Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Germany
11 Technical University of Berlin, Institute of Energy Engineering, Germany
12 Centre for Energy and Environmental Economics (Cenergia), Energy Planning Program (PPE), Coppe, Universidade Federal do Rio de Janeiro, Brazil
13 Federal University of Rio de Janeiro, Brazil
14 African Institute for Sustainable Energy and System Analysis (AISESA)
15 Institute for Future Initiatives, University of Tokyo, Japan
16 World Wide Fund for Nature, USA
17 PBL Netherlands Environmental Assessment Agency, The Netherlands
18 Utrecht University, The Netherlands
19 Beijing Institute of Technology, China

Contributing Authors:
Frank Jotzo[1] (Co-Lead Stakeholder Interface)
Yacob Mulugetta[2,3] (Co-Lead Expert Group Technological Systems Analysis)
Gregory Nemet[4] (Co-Lead Expert Group Technological Systems Analysis)
Elena Verdolini[5, 6] (Co-Lead Expert Group Policy Design and Evaluation)
Da Zhang[7] (Co-Lead Expert Group Policy Design and Evaluation)
Falk Benke[8]
Setu Pelz[9]
Manish Shrivastava[10]

1 Australian National University, Australia
2 African Institute for Sustainable Energy and System Analysis (AISESA)
3 University College London, UK
4 University of Wisconsin, USA
5 University of Brescia, Italy
6 Centro Euro-Mediterraneo sui Cambiamenti Climatici, Italy
7 Tsinghua University, China
8 Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Germany
9 International Institute for Applied Systems Analysis (IIASA), Austria
10 The Energy and Resources Institute (TERI), India

SP-GET Co-Chairs:
Gilberto M. Jannuzzi[1]
Elmar Kriegler[2,3]
Vera Songwe[4]

1 State University of Campinas, Brazil
2 Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Germany
3 University of Potsdam, Faculty of Economics and Social Sciences, Germany
4 Brookings Institution, USA

Authors of the on the African continent:
Youba Sokona[1] (Lead Author)
Yacob Mulugetta[1,2]
Meron Tesfamichael[1]
Philipp Trotter[1,3]
Benard Wabukala[1,4]
Mark Akrofi[1]
Nibwene Mwakibinga[5]
Jesse Burton[6]
Vera Songwe[7]

1 African Institute for Sustainable Energy and System Analysis (AISESA)
2 University College London, UK
3 Wuppertal Institute for Climate, Environment and Energy, Germany
4 Makerere University, Uganda
5 Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Germany
6 University of Cape Town, South Africa
7 Brookings Institution, USA

Authors of the box on the Association of Southeast Asian Nations (ASEAN):
Ambiyah Abdullah[1] (Lead Author)
Claire Fyson[2]
Frank Jotzo[3]
Joni Jupesta[4]
Ho Wai Shin[5]
Haslenda Hashim[5]
Nuwong Chollacoop[6]
Silva Kampanart[6]

1 ASEAN Centre for Energy, Indonesia
2 Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Germany
3 Australian National University, Australia
4 IPB University, Indonesia
5 University of Technology, Malaysia
6 National Energy Technology Center, Thailand

Authors of the box on Brazil:
Gilberto Jannuzzi[1] (Lead Author)
Mayara Melo[1]
Alexandre Szklo[2,3]
Luiz Bernardo Baptista[2]
Andre Lucena[2]

1 State University of Campinas, Brazil
2 Centre for Energy and Environmental Economics (Cenergia), Energy Planning Program (PPE), Coppe, Universidade Federal do Rio de Janeiro, Brazil
3 Federal University of Rio de Janeiro, Brazil

Authors of the box on China:
Hancheng Dai[1] (Lead Author)
Biying Yu[2]
Da Zhang[3]
Eduardo Andres Pardo-Piñashca[1]

1 Peking University, China
2 Beijing Institute of Technology, China
3 Tsinghua University, China

Authors of the box on the European Union:
Felix Schreyer[1] (Lead Author)
Robert Pietzcker[1]
Claire Fyson[1]
Keywan Riahi[2] (Co-Lead Expert Group Energy Transition Pathways)
Elena Verdolini[3,4] (Co-Lead Expert Group Policy Design and Evaluation)
Gunnar Luderer[1,5]

1 Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Germany
2 International Institute for Applied Systems Analysis (IIASA), Austria
3 University of Brescia, Italy
4 Centro Euro-Mediterraneo sui Cambiamenti Climatici, Italy
5 Technical University of Berlin, Institute of Energy Engineering, Germany

Suggested citation:
Luderer, G., Riahi K., Mathur, R., Abdullah, A., Fyson, C., Pachauri, S., Sokona, Y., Dai, H., Heilemann, A., Lécuyer, F., Mwakibinga, N., Pietzcker, R., Schreyer, F., Verpoort, P., Warszawski, L., Burton, J., Chaturvedi, V., Cho, C., Cui, R., Fujimori, S., Szklo, A., Sugiyama, M., Roe, S., van Vuuren, D., Yu, B., Akrofi, M., Baptista, L.B., Benke, F., Chollacoop, N., Hashim, H., Jotzo, F., Jupesta, J., Kampanart, S., Lucena, A., Melo, M., Mulugetta, Y., Nemet, G., Pardo-Piñashca, E.A., Pelz, S., Shin, H.W., Shrivastava, M., Tesfamichael, M., Trotter, P., Verdolini, E., Wabukala, B., Zhang, D., Jannuzzi, G.M., Kriegler, E., Songwe, V. Transitioning Away from Fossil Fuels in Paris-aligned Mitigation Pathways, November 2026, Science Panel for the Global Energy Transition, pp. 48, 10.5281/zenodo.23950115.

Date of Publication: 10 November, 2026
Version 1.0
DOI: 10.5281/zenodo.23950115

Copyright: ©2026 Science Panel for the Global Energy Transition. All rights reserved.

This report is licensed under a Creative Commons Attribution 4.0 International License (CC BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

TABLE OF CONTENT

EXECUTIVE SUMMARY 5

Key Messages 5

1. INTRODUCTION 8

BOX 1: THE CURRENT STATE OF THE TRANSITION AWAY FROM FOSSIL FUELS 9

2. PLACING GLOBAL ENERGY SYSTEM PATHWAYS IN CONTEXT 11

BOX 2: DIFFERENT NATIONAL CONTEXTS FOR THE TRANSITION AWAY FROM FOSSIL FUELS 12

3. INSIGHTS FROM GLOBAL PATHWAYS TOWARDS LIMITING WARMING IN LINE WITH PARIS CLIMATE TARGETS 14

3.1 Comparison of recent high-ambition scenarios with lowest-warming scenarios from the IPCC's latest assessment (AR6) 15

3.2 Phase-down of fossil fuel energy 17

3.3 Transforming the energy system 18

BOX 3: HOW IS CHINA SCALING UP CLEAN ENERGY TECHNOLOGIES ACROSS SECTORS? 22

BOX 4: THE EU'S PATH TO NET ZERO BY 2050 25

3.4 Equity in global energy transition scenarios 28

4. TAFF IMPLEMENTATION: ENABLERS AND BARRIERS 33

4.1 Technological enablers and barriers 33

BOX 5: ACCELERATING ASEAN'S ENERGY TRANSITION: FINANCE, TECHNOLOGY, AND REGIONAL COOPERATION 35

4.2 Economic enablers and barriers 37

BOX 6: AFRICA'S ENERGY CROSSROADS: TAFF, DEVELOPMENT AND THE DOUBLE TRANSITION 38

4.3 Institutional enablers and barriers 41

BOX 7: BRAZIL: A RENEWABLE-RICH ENERGY SYSTEM FACING THE CHALLENGE OF TRANSITIONING AWAY FROM FOSSIL FUELS 42

4.4 Distributional enablers and barriers 44

TECHNICAL ANNEX: SCENARIO PATHWAYS EVALUATION AND SELECTION 45

REFERENCES 46

EXECUTIVE SUMMARY

This report sets out new findings from recent high-ambition 1.5°C overshoot pathways (with estimated median warming < 1.7°C at peak, returning to below 1.5°C by 2100), and provides examples from different national contexts of key opportunities, barriers and enablers of the transition. Up-to-date information on how the current global energy system could transition is needed to guide policy makers as they develop national roadmaps. The IPCC's latest Sixth Assessment Report (AR6) drew evidence from modelled global pathways produced in or before 2021. Since then, green technologies developed rapidly, while fossil fuel use and emissions rebounded after COVID and remained high until 2025. As a result, the opportunity to limit warming to 1.5°C with no or limited overshoot has been lost.

Key Messages

Every year of delay in curbing global fossil fuel use raises the risk of irreversible climate change impacts. Fossil fuels are the main driver of climate change, accounting for around 85% of global CO_2 emissions. With warming beyond 1.5°C now unavoidable, transitioning away from fossil fuels has become an urgent priority. (Section 1)

Recent high-ambition pathways leave far less space for fossil fuels than earlier AR6 pathways with comparable ambition. By 2050, fossil primary energy use is 58–130 EJ/yr in recent high-ambition pathways, compared with 118–334 EJ/yr in high-ambition AR6 pathways and 520 EJ/yr in 2025. Three factors explain this difference: (1) continued and increasing fossil fuel use over the past five years has consumed a greater share of the remaining CO_2 budget; (2) recent pathways reflect the slower-than-anticipated scale-up of carbon capture and storage (CCS) and carbon dioxide removal (CDR); and (3) accelerated technological progress in renewables and electrification technologies has enabled deeper reductions. Cutting fossil fuel use therefore becomes the primary lever for reducing emissions. (Sections 3.1, 3.2)

Recent high-ambition 1.5°C overshoot pathways present a consistent picture of fossil fuel phase-down for 2035. By 2035, fossil fuel use declines by 36–62% relative to 2025 levels, equivalent to an annual decline of around 4–9% per year. Coal, oil and gas respectively decline by at least 64% (range 64–89%), 11% (range 11–44%) and 15% (range 15–61%) by 2035. Minimum values are not compatible with one another, meaning that slower reductions in one fuel requires faster reductions in others. Rates of fossil fuel phase-down are similar in recent high-ambition pathways from integrated assessment modelling and in the IEA's Net Zero Emissions by 2050 scenario. (Section 3.2)

Renewable power and electrification expand faster and further in recent high-ambition pathways, displacing fossil fuel use more rapidly. The recent high-ambition pathways start from the 2025 energy system and reflect the latest developments in clean energy and industrial technologies. The costs of solar and wind power generation, as well as batteries, have fallen faster than anticipated and often undercut those of fossil fuel-based alternatives. These technological breakthroughs have cut decarbonisation costs and are redefining what is feasible for the future. (Sections 3.1, 3.3.1, 3.3.2, 4.1)

Expanding renewable power generation is a key driver of the transition. Solar and wind power grow to produce 46–73% of electricity by 2035 in recent high-ambition pathways, up from 15% in 2024. As their share grows, it is important to establish and incentivize demand flexibility, and to expand energy storage and grid interconnections to allow cost-efficient operation of power systems (Section 3.3.1).

Electricity is the dominant global energy carrier in recent high-ambition pathways, supporting calls for a global electrification target of 35% by 2035. As the buildings, industry and transport sectors electrify, electricity's share in total final energy consumption rises from 23% in 2024 to 34–42% by 2035 and 53–71% by 2050. Global electricity demand grows roughly two- to three-fold by 2050. Energy access expands, yet total global energy demand remains stable due to overall efficiency improvements. Closing decent-living gaps is compatible with Paris-aligned pathways. Electric cooking and other clean options can expand access for the nearly 2 billion people still lacking clean cooking, while reducing reliance on fossil cooking fuels. (Sections 3.3.2, 3.4.2, Box 2)

Carbon capture and storage (CCS) plays a smaller role in recent high-ambition pathways than in AR6 pathways, both before 2035 and in the long term, but remains substantial and indispensable in the long term, mainly for industry and carbon dioxide removal (CDR). CCS technologies remain costly, and the existing project pipeline and long infrastructure lead times limit their contribution to emission reductions before 2035. All recent high-ambition pathways deploy at least 2 $GtCO_2$/yr of CCS by 2050, mostly for carbon dioxide removal and to abate industrial process emissions, such as from cement production. Fossil power generation with CCS plays a negligible role. (Sections 3.1, 3.3.1, 4.1).

Some end-uses such as aviation, shipping, and chemical feedstocks cannot be readily electrified, meaning there will be residual demand for liquid and gaseous hydrocarbons that is more difficult to defossilise. In recent high-ambition pathways, residual demand for hydrocarbons and other molecular energy amounts to 102–177 EJ/yr by 2050. Pathways show different approaches to abate or compensate for these emissions. Further research is needed to understand how novel electrification technologies, including indirect electrification through green hydrogen, circular economy approaches and behavioural change could further reduce residual fuel demand. (Section 3.3.3)

Pathways that phase out fully fossil fuels show lower reliance on CCS and CDR technologies and greater reliance on green molecular fuels. These pathways use synthetic fuels based on green hydrogen in addition to biomass to meet hydrocarbon demand in the aviation, shipping and chemical industries. This requires substantial additional investment in e-fuel production. (Section 3.3.4)

Identifying credible and acceptable transitions requires consideration of regional contexts as well as equity and justice dimensions. Moving from global pathways to national roadmaps requires accounting for differences in countries' starting points, available resources and common but differentiated responsibilities. New industries, commodities and economic opportunities will arise in all regions, particularly where clean energy is abundant and relatively cheap. At the same time, some fossil fuel producing countries face significant fiscal exposure as the world decarbonises, requiring economic diversification, which in some cases may include clean energy-based industries. International cooperation and long-term international support are crucial to allow all countries to benefit from clean economic development and prevent communities from being left behind. (Sections 2, 4.1.1, 4.2.2, 4.4, Box 2)

Reducing the reliance on fossil fuels and boosting domestic renewable generation allows fossil fuel importing countries to reap energy security, economic and health benefits. Volatile fossil fuel prices tied to geopolitical instability have raised living costs and many importing countries have already enacted policies to accelerate electrification and renewables deployment. (Section 2, Box 1, Box 2)

Each country's transition depends on the ability to scale up supporting infrastructure and secure low-cost finance. Developing countries face borrowing costs averaging about 14%, compared to 4% or lower for high income countries in recent years. These higher financing costs add about USD24–26/MWh to renewable electricity in low- and middle-income countries. Risk-reducing and concessional finance instruments can help reduce borrowing costs and narrow the gap between current annual finance flows of USD500–600 billion to emerging and developing economies excluding China and the USD1.3–1.7 trillion needed by 2030. (Sections 3.4.1, 4.1.3, 4.2.1, 4.2.2, Box 2)

Fair effort sharing in high-ambition pathways can be achieved by a combination of financial transfers from higher to lower responsibility countries and a regionally differentiated pace of emissions reductions. A recent study showed that scenarios with in-built fair effort-sharing assumptions deliver similar global emissions outcomes, but what changes is where emissions are reduced and how much finance flows between regions. Because of the tight remaining emissions space in high-ambition pathways, financial transfers are essential to realise ambitious global emission reductions and energy transition benchmarks. (Section 3.4)

Enablers of the transition span social, economic, technological, institutional domains, and can mutually reinforce one another to facilitate change. This is already happening for some clean energy technologies. A broadly supportive policy environment and adequate fiscal space are necessary to foster different enablers and align climate objectives with other societal priorities like health, security and development. (Section 4, Box 1)

Examples from different world regions show both differences and similarities for national energy transition strategies towards the collective global climate goal. Common elements include the strategy of decarbonising the power sector, electrifying energy demand and greening residual fuel use. Aligning regulation, planning, investment and regional cooperation is important in all regions. For African countries, fulfilling the urgent development needs in terms of broad electricity access, clean cooking, inclusive industrialisation and urban transformation is of overarching importance. ASEAN countries start from high fossil fuel shares in primary energy and electricity supply. They require stable sources of finance and investment in renewable energy and well-regulated markets for sustainable biofuels. Brazil already generates half of its domestic energy supply, and 87% of electricity, from renewables, but also derives a large economic value from oil and gas exports. Biofuels are central to Brazil's non-electric renewable supply. Their expansion requires sustainable feedstocks and safeguards for land use and food security. China illustrates how expanding low-carbon electricity generation is essential to supporting the growing adoption of clean energy technologies across sectors. For the EU, reaching net zero GHG emissions by 2050 requires complementing power sector decarbonization and electrification with a fast scale-up of green hydrogen-based fuels and carbon dioxide removal for the last steps of the transition. (Boxes on Africa, ASEAN, China, Brazil, the European Union)

1. INTRODUCTION



1. INTRODUCTION

Global average temperature rise is set to exceed 1.5°C in the next few years, pushing climate change into ever more dangerous territory (UNEP, 2026b). Fossil fuels are the main driver of climate change, accounting for 85% of global CO_2 emissions and around a third of methane emissions (Friedlingstein et al., 2026; IEA, 2026b). A global transition away from fossil fuels is urgently needed: the longer countries continue to fail to curb fossil fuel production and use, the longer and more severe the overshoot of 1.5°C will be, and the more difficult it will become to bring temperatures back down to 1.5°C by 2100 (Schleussner et al., 2024; UNEP, 2026b).

The energy transition is a central priority on the global climate agenda. At COP28 in 2023, governments agreed to transition away from fossil fuels, noting that it should be "just, orderly and equitable", with accelerated action this decade (UNFCCC, 2023b). Two years later, the Brazilian Presidency of COP30 set up a process for developing a global roadmap for the transition (COP30 Presidency, 2026); in 2026 a group of countries met in Santa Marta, Colombia, to discuss how to put this into action. The Science Panel for the Global Energy Transition (SP-GET) supports this process. The panel's first output is this policy brief on what Paris-aligned pathways for the energy transition look like.

The ongoing global energy crisis adds further impetus to a rapid shift to clean energy supplies that are less vulnerable to geopolitical instability (see Box 1). Crucially, the transition to clean, more renewable and electrified economies needs to unfold equitably, supporting sustainable development and expanded energy access. Different national contexts — including development needs, capabilities, responsibilities and constraints — need to be accounted for, in line with the Paris Agreement's core principles.

Given this urgent and global challenge, quantified, science-based information is needed to translate long-term climate goals into tangible energy transition milestones. Ultimately, this information needs to be available at the country level, but clarity is also needed on what the Paris Agreement's global temperature goal means for the global energy system.

In this policy brief we provide new evidence on what a transition away from fossil fuels looks like at the global level. This analysis is based on modelled pathways aligned with the Paris Agreement's long-term temperature goal that capture recent emissions trends and the latest state of development of clean energy and industrial technologies. The IPCC undertakes periodic assessments of published scenarios, but its last report draws on scenarios that were produced in or before 2021 and are out-of-date in many elements. This report draws on more recent scenarios that are consistent with the global energy system in 2025.

We focus on quantitative milestones for the transition away from fossil fuels — such as the percentage declines in coal, oil and gas use and the rise in electrification of end use sectors — to facilitate a more granular tracking of global progress, but we also outline how equity and sustainable development needs are factored into the scenarios, and where limitations lie.

To move from global milestones to national transitions, implementation challenges and opportunities at different scales need to be understood. In advance of more detailed national level work planned for next year, we complement our global analysis with examples from two major economies — China and the EU — based on recent energy system modelling analyses (see section 3). We also provide examples of implementation in practice from Brazil, the ASEAN region and Africa. Deep dives into specific regional and national contexts in greater detail are planned for the future.

The policy brief is structured as follows: Section 2 lays out the context in which global pathways should be considered, including questions around fairness, justice and national circumstances; Section 3 sets out the evidence provided by global scenarios, including the impact of equity considerations; Section 4 outlines key opportunities that an energy system transition can provide, as well as barriers that will need to be overcome, with examples from specific country contexts.

BOX 1:
THE CURRENT STATE OF THE TRANSITION AWAY FROM FOSSIL FUELS

Globally, clear signs of a shift towards clean energy are visible. A handful of countries including France, Germany and the Netherlands have published national roadmaps with fossil fuel phase-out dates. The power sector shows the greatest progress: renewable power projects are being deployed faster and at lower cost than fossil fuel plants, and in 2025 low-carbon power generation grew to make up 43% of the global electricity mix, while fossil fuel generation stagnated (Ember, 2026). This is also reflected in policy commitments — of the 55 countries still using coal, over half (28) include plans to phase down unabated coal power in their new Nationally Determined Contributions (NDCs) (Marshall et al., 2025).

There are signs that a peak in global fossil fuel emissions may be in reach due to the combined effect of accelerated renewables, energy efficiency measures and electrification of energy uses in large fossil fuel consuming countries. However, a slow-down in global climate policy momentum and growing energy demand from e.g., data centres and air conditioning, risk delaying such a peak, and political direction to reduce fossil fuel reliance remains weak. Governments provided more than USD725 billion in explicit fossil fuel subsidies in 2024; when unpriced negative externalities are included, the total rises to USD6.7 trillion (Black et al., 2025; IISD and OECD, n.d.). And projections based on current policies suggest that while coal is set to decrease, oil and gas are expected to increase slightly (UNEP, 2026a)

Meanwhile, geopolitical instability has caused fossil fuel prices to rise, exacerbating cost-of-living pressures and pushing potentially millions of people into extreme poverty (Guan et al., 2023). Climate impacts are worsening, placing additional burdens on sensitive energy infrastructure, and millions still lack access to basic energy. International public climate finance support, which forms a crucial element of the Paris Agreement, fell between 2023 and 2024 (Climate Policy Initiative, 2026), while major oil and gas companies have reaped record profits (Semieniuk et al., 2024).

2. PLACING GLOBAL ENERGY SYSTEM PATHWAYS IN CONTEXT

2. PLACING GLOBAL ENERGY SYSTEM PATHWAYS IN CONTEXT

Global mitigation scenarios show what an ambitious global energy transition looks like under specific climate goals and socio-economic conditions. They can inform policy processes at different scales — for example, international goals such as the tripling of renewable energy by 2030 were informed by IRENA's 1.5°C pathway (COP28, IRENA and GRA, 2023). But scenarios are only one line of evidence. Understanding the functions that scenarios serve and their limitations is necessary when considering how they can inform national roadmaps. While national pathways may broadly follow the dynamics of a global transition, translating global pathways to national contexts is complex and requires each country's specific circumstances to be factored in.

Under the Paris Agreement, governments agreed that each country's contribution is nationally determined, reflecting key principles. These include equity and "common but differentiated responsibilities and respective capabilities, in the light of different national circumstances" (CBDR-RC), as well as the need to undertake climate action in line with each country's "highest possible ambition" and "in the context of sustainable development and efforts to eradicate poverty". It follows that energy transition roadmaps need to reflect countries' different starting points, development priorities, historical responsibilities, capabilities and domestic resources.

A large body of literature has considered how equity and CBDR-RC can be incorporated into scenario analysis to support the definition and implementation of different regional or national mitigation benchmarks (Rajamani et al., 2021; Lecocq et al., 2022; Dekker et al., 2025; Pelz et al., 2025, 2026; Robiou du Pont et al., 2025) (see section 3.4.3). Such analyses show that for many countries with high historical per capita emissions, reducing domestic emissions in line with what could be considered a fair share of the remaining carbon budget would imply net zero emissions years that are no longer feasible to reach. Providing support to developing countries with less capability and historical responsibility can address this (Pelz et al., 2025). International finance support, trading mitigation units under Article 6, and technology transfer are the most widely discussed options for doing so, although these are not an alternative to reducing domestic emissions (Pelz et al., 2025; Robiou du Pont et al., 2025).

While global models can be designed to prioritise key development goals, such as to enhance energy access or share resources equitably (Soergel et al., 2024), many specific national circumstances and equity dimensions are not yet well captured (see section 3.4). These include changes to supply chains and trade flows, transition co-benefits and trade-offs, climate change impacts, adaptation, and implications for livelihoods, poverty and inequality (Klinsky and Winkler, 2018; Lecocq et al., 2022; Pachauri et al., 2026). Global pathways therefore need to be complemented by national modelling studies and research from other disciplines (Waisman et al., 2019; Briand et al., 2026; Daly et al., 2026).

At the national and sub-national levels, motivation for climate mitigation policy is increasingly linked to industrial strategy, job creation, energy access, security, and trade competitiveness (Mercure et al., 2021). Transitioning to a clean energy system will have long-term economic benefits compared to the status quo, but also near-term, unevenly distributed costs that need to be carefully managed. The need for a just transition has therefore come into focus in recent years.

Energy transition roadmaps will only be successful if they incorporate fundamental development needs and set out how the services that fossil fuels currently provide — from basic energy access through to advanced industrial processes — can be sustained and improved. They also need to factor in the risks and pervasive negative impacts associated with fossil fuel production and consumption, such as air and water pollution, negative distributional effects, financial risks and economic distortion (Clarke et al., 2022; Kemfert et al., 2022). In each context, the solution space of how to reduce fossil fuel production and use will look different (see Box 2).

If well governed, the transition away from fossil fuels can enable more distributed energy sources to power national economies, generating revenues for local or national businesses, and expanding energy access faster than large, centralised fossil fuel projects can (Foster et al., 2024). More efficient and decarbonised energy systems can meet decent living standards with lower per-capita energy use and associated emissions (Kikstra et al., 2025) (see Box 2 and section 3.4.2).

For each type of transition there is a need to better understand what works in different contexts, and planning will need to adapt to the rapidly evolving technology and policy landscape. Country-specific integrated energy system planning research co-created with local stakeholders is essential for all developing countries (Mulugetta et al., 2022; Chaturvedi et al., 2024). Continued support from developed countries is critical to ensure countries do not fall into the trap of following the fossil fuel-driven status quo, and that clean economic development presents an attractive and achievable alternative (see section 4) (Foster et al., 2024). The global milestones presented in this policy brief are contingent on such global solidarity.

BOX 2: DIFFERENT NATIONAL CONTEXTS FOR THE TRANSITION AWAY FROM FOSSIL FUELS

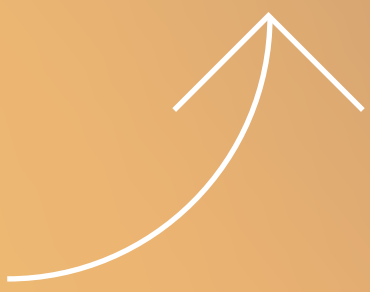
There is strong evidence that **fossil fuel importing countries** can reap energy security, economic and health benefits by reducing their reliance on fossil fuels and boosting domestic renewables generation (Mercure et al., 2021; Clarke et al., 2022; Meng et al., 2026; Ordonez et al., 2026). Volatile fossil fuel prices tied to geopolitical instability have raised living costs and many importing countries have already enacted policies to accelerate electrification and renewables deployment (UNEP, 2026a). The dynamics of each country's transition depend on the availability of natural resources and ability to scale up supporting infrastructure and secure low-cost finance (see section 4) (Mercure et al., 2021; Mulugetta et al., 2022).

Fossil fuel producing countries that rely on export revenues — in some cases for over a third of their GDP — will need to transition large parts of their economies (Mercure et al., 2021; Foster et al., 2024). Falling global demand for fossil fuels and shifting preferences towards less carbon-intensive production could cause export revenues to collapse, especially in countries where production costs are higher. Coal exporters and domestic coal users in particular face the challenge of highly localised impacts to workforces and in most cases need to simultaneously transition their energy systems (Strambo et al., 2019). In some contexts, the economic benefits of pursuing low-carbon development may not fully compensate for the losses in industrial output, strengthening the need for international support and a proactively designed industrial strategy (Mercure et al., 2021; Jones et al., 2026). The structure and pace of the transitions required depends on the maturity of alternative value-adding sectors (e.g. clean technologies, information services) and presence of strong governance and international support (Foster et al., 2024). Building up clean energy based export industries can be an important strategy to compensate for falling fossil fuel export revenues for countries that are rich in both fossil fuels and renewable energy potential (Burke et al., 2022).

Some low and lower-middle income countries have unexploited fossil fuel resources that they consider a potential asset for development. However, evidence from low-income countries with well-established fossil fuel industries suggests that fossil fuel wealth does not necessarily translate to improved energy access or other development gains, especially in the face of high financing costs and a market that is increasingly looking for cleaner and cheaper options (Mulugetta et al., 2022; Foster et al., 2024). The more resilient strategy would be to avoid fossil fuel dependence and pursue growth through a low-carbon industrial strategy that can be competitive in a carbon-constrained world (Muttitt and Winkler, 2026).

In developing countries where meeting basic energy services takes priority, demand-side initiatives that avoid lock-in through efficient appliances, buildings and cities are particularly important (Van Heerden et al., 2025). Ambient cooling needs have been projected to rise two- to sixteen-fold by 2040 in Brazil, India, Indonesia and Mexico in a very high emissions scenario above the level of more recent worst case scenarios (Van Vuuren et al., 2026), potentially leaving up to around 100 million households unable to afford adequate cooling by this time (Pavanello et al., 2021). Affordability interventions need to be combined with efficiency improvements, and behavioural change if the expansion of electricity services is to address energy poverty and improve well-being (Piai Paiva et al., 2024). Cooking energy needs illustrate the same point: nearly 2 billion people still lack access to clean fuels and efficient cooking appliances, about half of them in Africa (IEA, 2026a). LPG already supplies over 70% of those with access in Africa, but it is fossil-based and exposed to price shocks, so electric cooking and other options that can reduce emissions and improve affordability need to be explored (IEA, 2026a).

3. INSIGHTS FROM GLOBAL PATHWAYS TOWARDS LIMITING WARMING IN LINE WITH PARIS CLIMATE TARGETS



3. INSIGHTS FROM GLOBAL PATHWAYS TOWARDS LIMITING WARMING IN LINE WITH PARIS CLIMATE TARGETS

Global energy transition pathways can inform decision-makers about near-to-medium term energy transition benchmarks such as reductions in fossil fuel use or the deployment of low-carbon technology consistent with global long-term warming limits. Recent developments have changed the near-term outlook considerably as most of the high-ambition pathways assessed in the IPCC's Sixth Assessment Report (AR6) and published before 2022 no longer reflect current conditions.

The pathways assessed in this brief are drawn from the Scenario Compass Initiative (SCI; Riahi et al., 2026), an effort of the scientific community to collect, evaluate and assess global emissions scenarios generated with a variety of models. Building on the more than 1,200 global pathways assessed in AR6, the SCI has collected over 450 additional global scenarios published since then, bringing the total to nearly 1,700. Scenarios were systematically evaluated against historical observations and assessed for near-term feasibility and long-term sustainability concerns (Riahi et al., 2026).

From the full SCI ensemble (Huppmann et al., 2026), this brief focuses on the subset of high-ambition pathways that limit exceedance of 1.5°C and subsequently return to below that level, consistent with the long-term temperature goal of the Paris Agreement. These pathways assume substantially strengthened mitigation ambition by 2030 towards limiting peak warming at the lowest attainable warming level between 1.6–1.7°C, and returning below 1.5°C by 2100[1]. Insufficient global climate action in the decade since the Paris Agreement has rendered peak warming below 1.6°C unattainable (Riahi et al., 2026). In addition to the warming limit, the selected pathways meet the SCI evaluation criteria on consistency with energy system and emission statistics through 2025, as well as feasibility of 2030 energy system developments in terms of power system capacities and carbon capture and storage (CCS) upscaling[2] (see Technical Annex and Verpoort et al., 2026, for details).

The resulting set comprises eight recently published high-ambition pathways, stemming from three different modelling systems (AIM, IMAGE and REMIND-MAgPIE) based on three scenario studies (ScenarioMIP-CMIP7, Van Vuuren et al., 2026; NGFS, Richters et al., 2025; as well as Rescuing 1.5°C, Climate Analytics and PIK, 2025). These pathways, selected for consistency with historic developments and near-term feasibility, also meet the SCI sustainability criteria on biomass use and cumulative geological storage. For comparison, the analysis also considers pathways that exceed 1.7°C but remain below 2°C with greater than 67% likelihood.

Section 3.1 compares these SCI high-ambition pathways with corresponding AR6 pathways that also limit warming to below 1.7°C and return to below 1.5°C by 2100. Section 3.2 analyses the transition away from fossil fuels, while Section 3.3 explores the broader energy transition in these global pathways. Section 3.4 addresses equity considerations and the limitations of global pathways.

1 Warming projections use the simple climate model MAGICC 7.6.03a (Nicholls et al., 2025) driven by the modelled emissions for 2025–2100 after harmonising them with estimated historic emissions until 2023 (Hoesly et al., 2025). Temperature limits are imposed on the median warming projection of MAGICC, i.e., at each point in time there is equal probability that the projected warming is below or above the median value. Selected pathways correspond to category GW2a of the SCI Climate categorization. Uncertainty about the climate response to greenhouse gas emissions implies that these pathways can lead to lower or higher warming than the limits imposed on the median projection from a single climate model.

2 Near-term plausibility and feasibility is tested by comparing scenarios results with near-term projections from the bottom-up technology literature: BNEF (2024) for solar PV, GWEC (2026) for Wind Power, Kazlou et al. (2024), IEA (2024b) for CCS and IAEA (2024) for nuclear power. A detailed documentation of the criteria is provided at SCI/IAMC (2026).

3.1 COMPARISON OF RECENT HIGH-AMBITION SCENARIOS WITH LOWEST-WARMING SCENARIOS FROM THE IPCC'S LATEST ASSESSMENT (AR6)

New mitigation pathways incorporate trends that were not projected in 2020. Recently published pathways (called "SCI high-ambition pathways" below) differ from those assessed by the IPCC in its Sixth Assessment Report ("AR6 high-ambition pathways") in that they incorporate important recent trends. First, fossil fuel use kept increasing, which led to continued high greenhouse gas (GHG) emissions making warming above 1.5°C inevitable. The world is now on an overshoot pathway; the highest ambition pathways with no or limited overshoot of 1.5°C assessed in AR6 are no longer available. Second, technological breakthroughs in some low-carbon technologies led to faster-than-anticipated cost reductions that are redefining what is realistic for the future, while fossil CCS technologies are yet to scale sufficiently and remain costly. Third, integrated assessment models (IAMs) have improved their representation of the global energy system regarding near-term trends, technology readiness, sectoral granularity and regional specificities.

A notable difference between recent SCI high-ambition pathways and earlier AR6 high-ambition pathways is the role of CCS. The near-term scale-up of CCS is constrained by the existing project pipeline and long infrastructure development times, limiting its contribution to emission reductions before 2035 (Kazlou et al., 2024; Fuhrman et al., 2025). Nevertheless, CCS continues to play a substantial long-term role in SCI high-ambition pathways, although generally less than in AR6 1.5°C overshoot pathways (Figure 3.1). All SCI pathways deploy at least 2.0 $GtCO_2$/yr of geological carbon storage by 2050, in particular for emissions from industrial processes like cement production, and for carbon dioxide removal (CDR) through bioenergy or direct air capture. Future deployment remains uncertain and depends on continued investment, supportive policies and infrastructure development (Jewell et al., 2026). By contrast, solar PV, wind power, batteries and electrification technologies have experienced much faster deployment and cost reductions, supported by their relatively modular nature and rapid technological learning (Malhotra and Schmidt, 2020; Wilson et al., 2020; Dhakal et al., 2022; IEA, 2026b). Sustaining this momentum will require overcoming challenges related to technology access, supply chains, grid integration as well as timely and affordable finance (Sections 4.1.1–4.1.3 and 4.2.1).

The structure of a Paris-aligned energy system has become clearer since AR6. SCI high-ambition pathways show a much narrower solution space than corresponding AR6 pathways, with on average a faster reduction in fossil fuel use, a faster uptake of variable renewables, and a faster and larger electrification of the energy sector (see Figure 3.1). The IEA estimates that fossil primary energy use amounted to around 520 EJ in 2025 (IEA, 2026c), much higher than 390–475 EJ envisioned by most Paris-aligned AR6 pathways[3] that had assumed stringent mitigation efforts starting in 2020. With the objective of returning to 1.5°C of warming, this leaves less leeway for the energy system in SCI pathways. By 2050, fossil primary energy drops by 75–89% relative to 2025 to 58–130 EJ/yr in SCI high-ambition pathways, compared to 118–334 EJ/yr in AR6 pathways. The lower fossil fuel use is compensated for by higher combined shares of solar and wind power (46–73% by 2035 in SCI high-ambition pathways compared to 25–67% in AR6) and a higher share of electricity in energy end-uses (53–71% in 2050 compared to 42–65% in AR6).

Note that primary energy includes non-energy uses of fossil fuels for the production of plastics and other base materials, which currently account for about 8% of fossil fuel production and are closely coupled to energy uses (IEA, 2025b).

3 For AR6 ranges 10th-90th percentile levels were used to remove outliers.

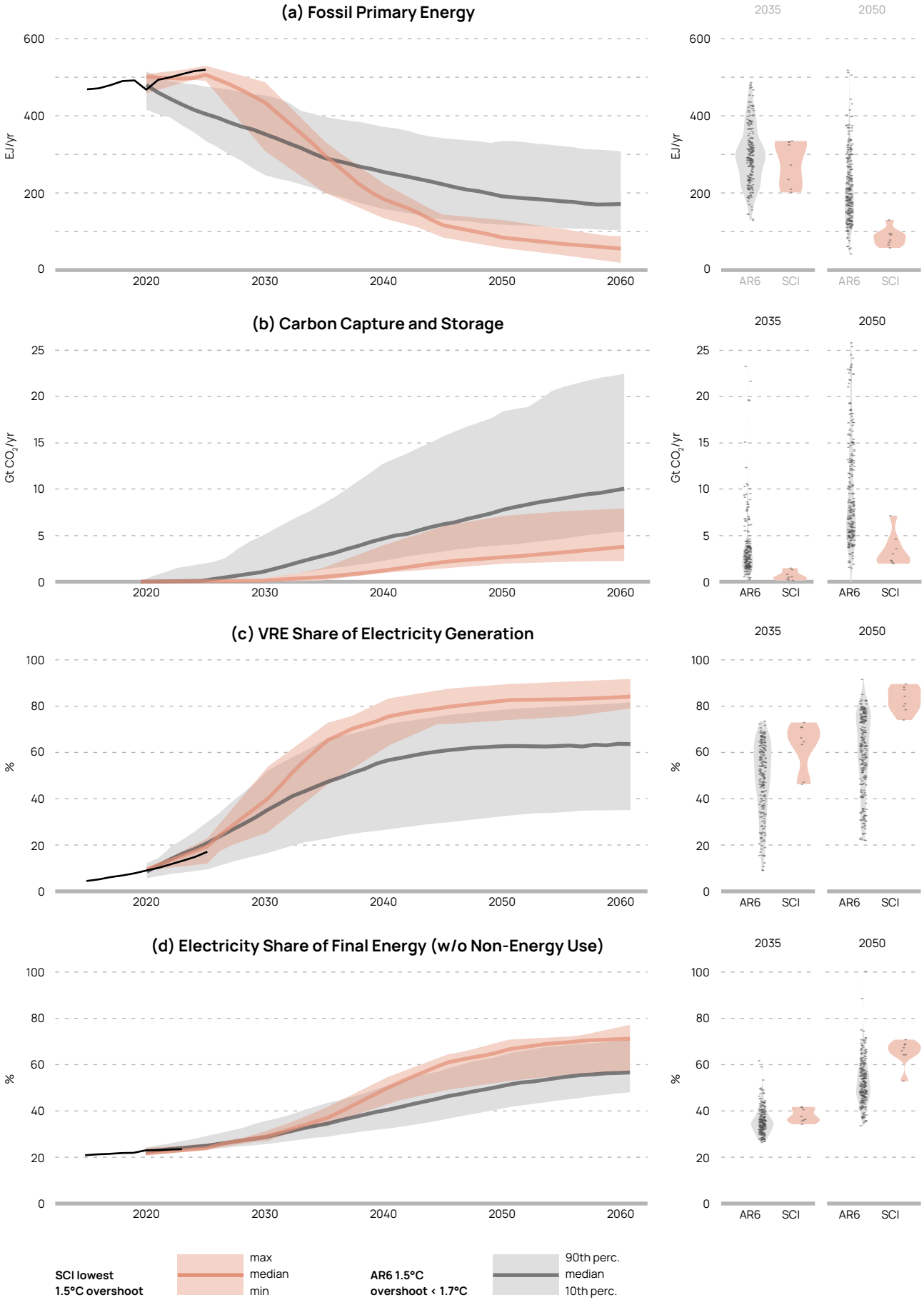


Figure 3.1: SCI high-ambition scenarios limiting peak warming to below 1.7°C and end-of-century warming to below 1.5°C, consistent with historic developments through 2025, near-term feasibility and sustainability criteria. Scenarios from AR6 meeting the same peak and end-of century warming limits are shown for comparison.

3.2 PHASE-DOWN OF FOSSIL FUEL ENERGY

There is a clear link between the pace of fossil fuel reduction and the level of peak warming. Global temperatures will keep increasing until net CO_2 emissions fall to zero. Given the high cost and upscaling challenges that carbon capture and storage technologies face (Kazlou et al., 2024; Fuhrman et al., 2025), the role that it can play in the coming decades is limited. This leaves cutting fossil fuels as the primary lever to rapidly reduce emissions.

Figures 3.2 and 3.3 illustrate the full range of SCI high-ambition pathways, as well as two illustrative scenarios from this set, high-ambition Pathway A (HAP A) and high-ambition Pathway B (HAP B) and the IEA's Net Zero Emissions by 2050 (NZE) scenario. HAP A and HAP B were developed as part of the ScenarioMIP/CMIP7 exercise (Van Vuuren et al., 2026) and reflect the latest science on global high-ambition transformation pathways. They are particularly useful for exploring the high end of feasible mitigation and the resulting low end of emissions (see Technical Annex): HAP A (REMIND-MAgPIE model, Very Low pathway realisation with Shared Socioeconomic Pathway 1 (SSP1) socio-economic assumptions) shows a transition to a fossil fuel-free future by 2070, assuming a trajectory of sustainable development focused on human well-being, international cooperation and resource efficiency; HAP B (AIM model, Very Low pathway realisation with SSP2 socio-economic assumptions) does not completely phase out fossil fuels, but keeps peak warming low by transitioning faster in the first fifteen years, and assumes that recent socioeconomic trends continue.

All SCI high-ambition pathways show a rapid phase-down in fossil fuel supply and use already by 2035, with a 36–62% reduction relative to 2025 levels (see Figure 3.2 and Table 3.1). As the most emissions-intensive fossil fuel factor, coal declines the fastest: it reduces by 64–89% by 2035 and is nearly phased out by 2045. Addressing impacts of such rapid phase-down on employment and livelihoods in coal-producing regions requires proactive just-transition policies, which are not represented in the underlying models, including social protection, support for affected workers and regional economic diversification (Strambo et al., 2019; see Sections 3.4.1, 4.2.2 and 4.4.1).

Gas and oil use decline steadily, respectively reaching 11–42 EJ and 44–68 EJ in 2050 compared to about 149 EJ and 195 EJ in 2025. In two of the pathways, including HAP A, fossil fuel use is completely phased out by around 2070, 10–20 years after net-zero CO_2 is achieved (see section 3.3.4). The levels of oil and gas retained in the high ambition SCI pathways in 2050 are below expected oil and gas production capacity from approved oil and gas extraction (IEA, 2026e), meaning that investments into new fossil production capacity may lead to higher overshoot unless existing capacities are retired.

SCI scenarios with higher peak warming (GW3, below 2°C with 67% likelihood) still imply a deep phase-down of coal and oil use, albeit with a slower rate than the SCI high ambition scenarios limiting peak warming to 1.7°C. For natural gas, around a third of these below 2°C scenarios project consumption broadly corresponding to current levels, mostly for use in the industry sector, while another third exhibits a phase down by 50% or more by 2050.

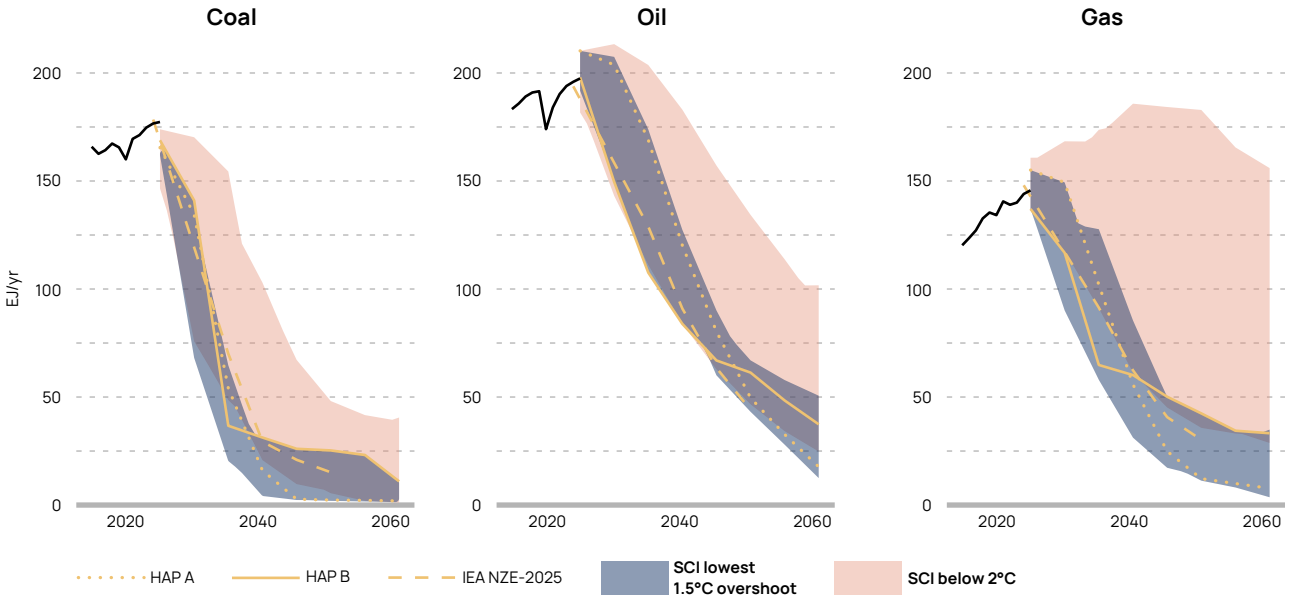


Figure 3.2: Primary energy demand of coal, oil and gas in the SCI high-ambition scenarios limiting peak warming to below 1.7°C, compared to SCI scenarios that limit warming to 2°C . Illustrative pathways from IAMs and IEA are shown in the foreground.

	2035 reduction vs 2025 [%]				2050 reduction vs 2025 [%]			
	Coal	Gas	Oil	Fossil	Coal	Gas	Oil	Fossil
SCI — Lowest 1.5 °C Overshoot (GW2a)	64–89	15–61	11–44	36–62	86–99	72–92	65–77	75–89
SCI — below 2 °C (GW3)	14–3	-16–39	-4–43	7–48	73–97	-22–76	31–75	45–78
IPCC AR6 1.5 °C overshoot below 1.7 °C	60–96	-2–56	-6–54	23–60	67–99	-10–72	17–83	36–77
High-ambition Pathway A	70	32	13	38	99	92	74	88
High-ambition Pathway B	80	57	44	60	86	72	68	75
IEA NZE (2025)	61	39	34	44	92	80	77	83

Table 3.1: Reduction of fossil primary energy [%] relative to 2025. SCI: full ranges for lowest 1.5°C overshoot scenarios (GW2a), n=8, and below 2°C scenarios (GW3), n=21. Both High Ambition Pathways A and B limit peak warming to below 1.7°C and return to below 1.5°C by 2100. 10th–90th percentile for IPCC AR6 1.5°C with peak warming below 1.7°C.

3.3 TRANSFORMING THE ENERGY SYSTEM

The SCI high-ambition pathways have three main shifts in common that characterise the transition away from fossil fuels and enable deep reductions in energy related emissions, as illustrated in Figure 3.3:

→ Electricity generation decarbonises rapidly through the uptake of renewable power generation and energy storage. This shift is already well under way in 2025, with over 30% of power generation coming from renewable sources and the share of fossil fuels in power generation declining (Ember, 2026).

→ The transport, buildings and industry sectors electrify at an accelerating pace, drastically reducing the end use demand for fossil fuels and leading to significant efficiency gains. Some progress has already been made — especially in buildings and electric vehicle sales — but two thirds of final energy consumption still comes directly from fossil fuel combustion.

→ Sectors that are harder to electrify, such as aviation, shipping and chemical industries, shift at least partly away from fossil fuels by adopting alternative molecular fuels that are not based on fossil carbon, in particular biofuels, hydrogen, or hydrogen-based synthetic fuels.

The subsections 3.3.1–3.3.4 provide a detailed perspective on these transformations.

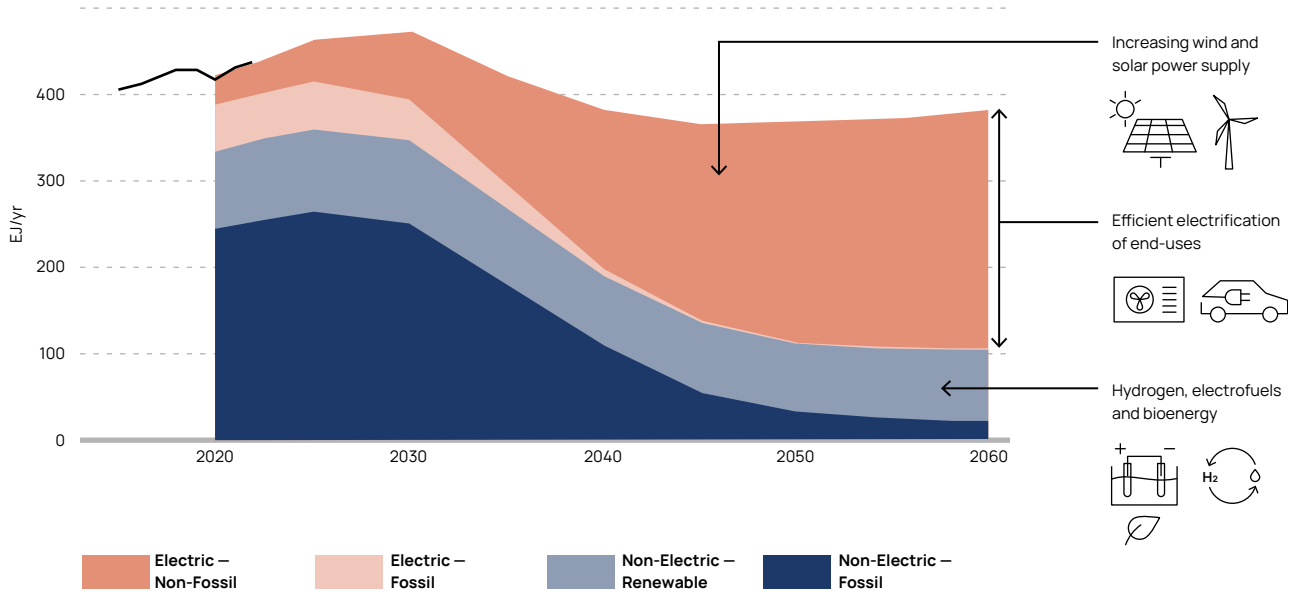


Figure 3.3: Illustration of key determinants of the energy transition away from fossil fuels in high ambition pathways in terms of evolution of final energy provision by energy carrier and primary energy source, based on illustrative pathway HAP A. Note that total final energy declines despite strongly increasing energy service provision due to efficiency gains.

	VRE share [%]			Electrification [%]			Green fuels [EJ/yr]		
	2024	2035	2050	2024	2035	2050	2024	2035	2050
SCI – Lowest 1.5°C Overshoot (GW2a)	15	46–73	74–90	23	34–42	53–71	21	17–38	17–67
SCI – below 2°C (GW3)		33–66	56–86		27–36	41–57		10–35	13–49
IPCC AR6 1.5°C overshoot below 1.7°C		25–67	33–79		29–43	42–65		24–46	21–72
High-ambition Pathway A		66	89		37	71		32	55
High-ambition Pathway B		71	74		36	53		38	48
IEA NZE (2025)		59	75		36	62		41	60

Table 3.2: Variable renewable energy (VRE; wind and solar) share of electricity generation, electricity share of final energy without non-energy use, and final energy from biomass, excluding traditional biomass and hydrogen (green fuels). SCI: full ranges for lowest 1.5°C overshoot scenarios (GW2a), n=8, and below 2°C scenarios (GW3), n=21. Both High Ambition Pathways A and B limit peak warming to below 1.7°C and return to below 1.5°C by 2100. 10th–90th percentile for IPCC AR6 1.5°C with peak warming below 1.7°C. 2024 values are based on IEA (2025d).

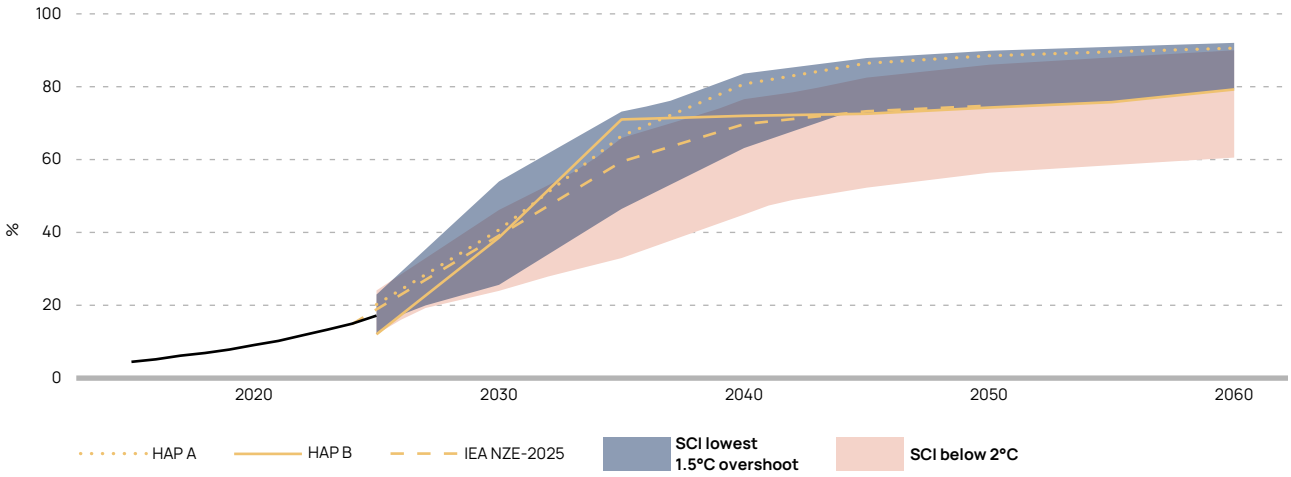
3.3.1 Decarbonising electricity

The power sector sees the fastest transition away from fossil fuels, reaching near-zero carbon intensity by the early 2040s. Coal power generation — the largest source of emissions in the sector — falls the fastest. Gas is also increasingly replaced by renewable electricity and nearly phased out by 2050, as non-fossil alternatives are increasingly deployed for dispatchable generation. Fossil power generation with CCS plays a negligible role globally in all SCI high-ambition scenarios, reflecting limited cost-competitiveness against renewables and the use of geological storage for industrial process emissions and carbon dioxide removal.

This transition is made possible by a rapid expansion in renewable power generation combined with storage, which meet all of the growth in electricity demand projected over the next few decades and displace fossil fuels. Solar PV, wind and batteries are the main drivers; these technologies have seen dramatic cost reductions over the past two decades, now competing with and often undercutting fossil power generation (Dhakal et al., 2022; IRENA, 2026a). In the SCI high-ambition pathways, the share of solar and wind in electricity generation grows from 15% in 2024 to 46–73% in 2035 and a median of 76% in 2040 and 83% in 2050. Half of these pathways project combined renewable power capacity to exceed 10 TW by 2030, broadly consistent with the tripling renewables target set in the COP28 UAE consensus.

Power systems worldwide increase in size by around 40% by 2035 relative to 2025 and two to three-fold by 2050 in the SCI high-ambition scenarios, reflecting demand growth due to economic development as well as accelerated electrification (section 3.3.2). This increase of power supply is consistent with rapidly improving access to energy services required for decent living, and declining gaps between regional energy consumption (Section 3.4).

(a) VRE share in Electricity



(b) Electricity

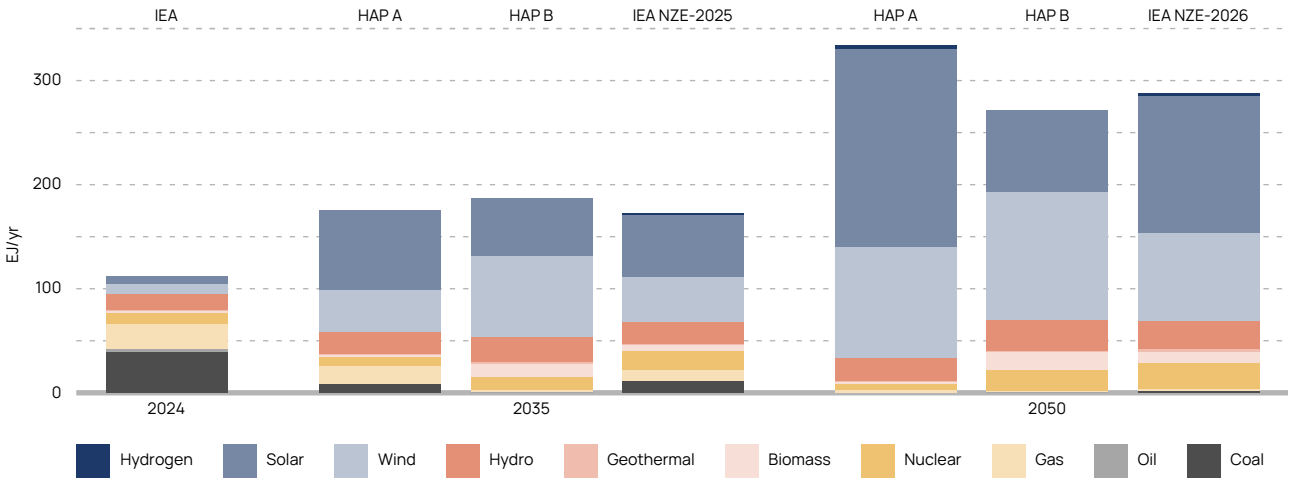


Figure 3.4: a) Share of variable renewable electricity (VRE) from wind and solar power in total electricity generation in pathways limiting peak warming to below 1.7°C, compared to SCI scenarios that limit warming to below 2°C. Illustrative pathways from IAMs and IEA are shown in the foreground. **b)** Electricity generation mix for for 2035 and 2050, as well as historical electricity generation for 2024 (IEA, 2025d).

Integrating rapidly increasing shares of solar and wind power requires a more interconnected and flexible energy system (Clarke et al., 2022). Demand-side flexibility, including through electric vehicles, heat pumps and industrial processes, along with battery storage systems helps to balance supply and demand while achieving lower system costs and consumer prices (IEA, 2025c). Non-fossil dispatchable generation (e.g. from hydropower, geothermal or biomass), together with long-duration storage, can complement variable renewable energy during extended periods of low wind and solar generation (Clarke et al., 2022; Brown and Hampp, 2023). Coordinated development of capacity expansion with grid infrastructure and market design are essential for maintaining reliable and low-cost electricity supply as renewable generation and electrification advances (IEA, 2024d; see Sections 3.3.2 and 4.1.3).

3.3.2 Efficient Electrification of End Use

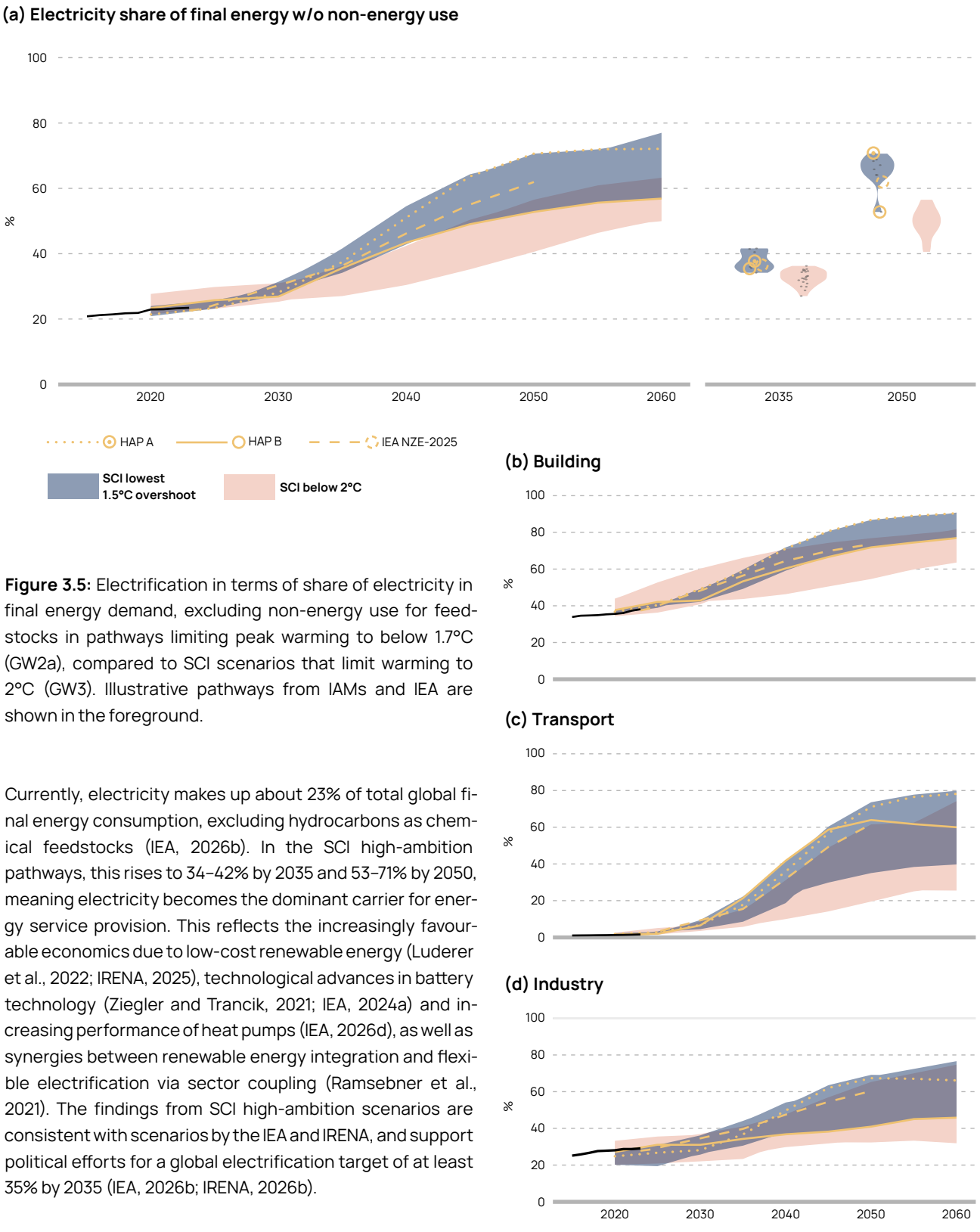


Figure 3.5: Electrification in terms of share of electricity in final energy demand, excluding non-energy use for feedstocks in pathways limiting peak warming to below 1.7°C (GW2a), compared to SCI scenarios that limit warming to 2°C (GW3). Illustrative pathways from IAMs and IEA are shown in the foreground.

Currently, electricity makes up about 23% of total global final energy consumption, excluding hydrocarbons as chemical feedstocks (IEA, 2026b). In the SCI high-ambition pathways, this rises to 34–42% by 2035 and 53–71% by 2050, meaning electricity becomes the dominant carrier for energy service provision. This reflects the increasingly favourable economics due to low-cost renewable energy (Luderer et al., 2022; IRENA, 2025), technological advances in battery technology (Ziegler and Trancik, 2021; IEA, 2024a) and increasing performance of heat pumps (IEA, 2026d), as well as synergies between renewable energy integration and flexible electrification via sector coupling (Ramsebner et al., 2021). The findings from SCI high-ambition scenarios are consistent with scenarios by the IEA and IRENA, and support political efforts for a global electrification target of at least 35% by 2035 (IEA, 2026b; IRENA, 2026b).

Transport sees the fastest acceleration in electrification, reflecting the availability and cost effectiveness of electric cars, two-three wheelers, buses and trucks. By 2050, road transport is almost fully electrified. The feasibility of this rapid transition is supported by progress already seen in some countries where a tipping point has been reached, resulting in a self-propelling uptake of electric vehicles (Mercure et al., 2025).

In the buildings sector, electrification is already at 40% and rises to 49–60% in 2035 and 72–87% in 2050 due to the replacement of fossil heating by electric heat pumps, the electrification of cooking and water heating, and the expansion of electric space cooling.

In the industry sector, which currently makes up almost 38% of global final energy consumption, SCI high-ambition pathways show an increase in electrification from 28% today to 31–44% by 2035 to 41–69% by mid-century. Electricity increasingly replaces coal and gas combustion for low- and medium-temperature industrial processes. Many high-temperature industrial processes can also be electrified (Madeddu et al., 2020; Fraunhofer ISI, 2024), although typically with lower potential for efficiency gains and therefore greater CO_2 abatement costs. Electrified steel recycling also grows and is economically attractive, but some high quality steel demands will continue to rely on primary steel.

Electrification is also a major driver for energy efficiency improvements. A large share of today's energy consumption is highly inefficient: burning fossil fuels to obtain mechanical work loses around two thirds of the primary energy as waste heat. For example, electric drivetrains are 2–4 times more efficient than combustion engines, and heat pumps can use one unit of electricity to supply 3–4 units of heat (IEA, 2026b). When combined with an increasingly decarbonised power sector (see above), end use electrification dramatically reduces fossil fuel reliance and associated emissions while maintaining and improving energy services.

Electrification and other efficiency measures are major contributors to a doubling in the energy efficiency by 2050 relative to 2025 in terms of final energy consumption per unit GDP. Other measures include insulation and district heating in the buildings sector. Multi-model analysis shows that activity, efficiency and electrification strategies can cut direct emissions by 51–85% in buildings and 37–91% in transport by 2050 relative to current policies, and that combining them lowers electricity demand beyond electrification alone, easing generation, storage and grid investment (Van Heerden et al., 2025); a UK study finds technology-focused systems cost 20–100% more than lower-demand ones (Sharmina et al., 2025).

BOX 3: HOW IS CHINA SCALING UP CLEAN ENERGY TECHNOLOGIES ACROSS SECTORS?

Authors: Hancheng Dai, Biying Yu, Da Zhang, Eduardo Andres Pardo-Piñashca

China illustrates how expanding low-carbon electricity generation is essential to supporting the growing adoption of clean energy technologies across sectors. Figure B3 highlights selected transition pathways across four sectors. The overall direction is broadly similar, although the pace and structure of the transitions in each sector differ.

A recent analysis using the Integrated Model of Energy, Environment, and Economy for Sustainable Development (IMED) shows that electricity is projected to account for around 60% of transport energy consumption by 2060 as electric vehicle adoption expands (Fang et al., 2023). A similar expansion of electric technologies is projected in rural households (Ma et al., 2023). Under their carbon-neutrality scenario, electric cooking could meet around 94% of rural cooking demand by 2060, while air-to-air heat pumps could supply around 72% of heating demand. Industry follows a different trajectory (Liu et al., 2026). Across nine major industrial subsectors, energy-efficiency improvements drive early progress, while electrification and emerging low-carbon technologies gain importance after 2035.

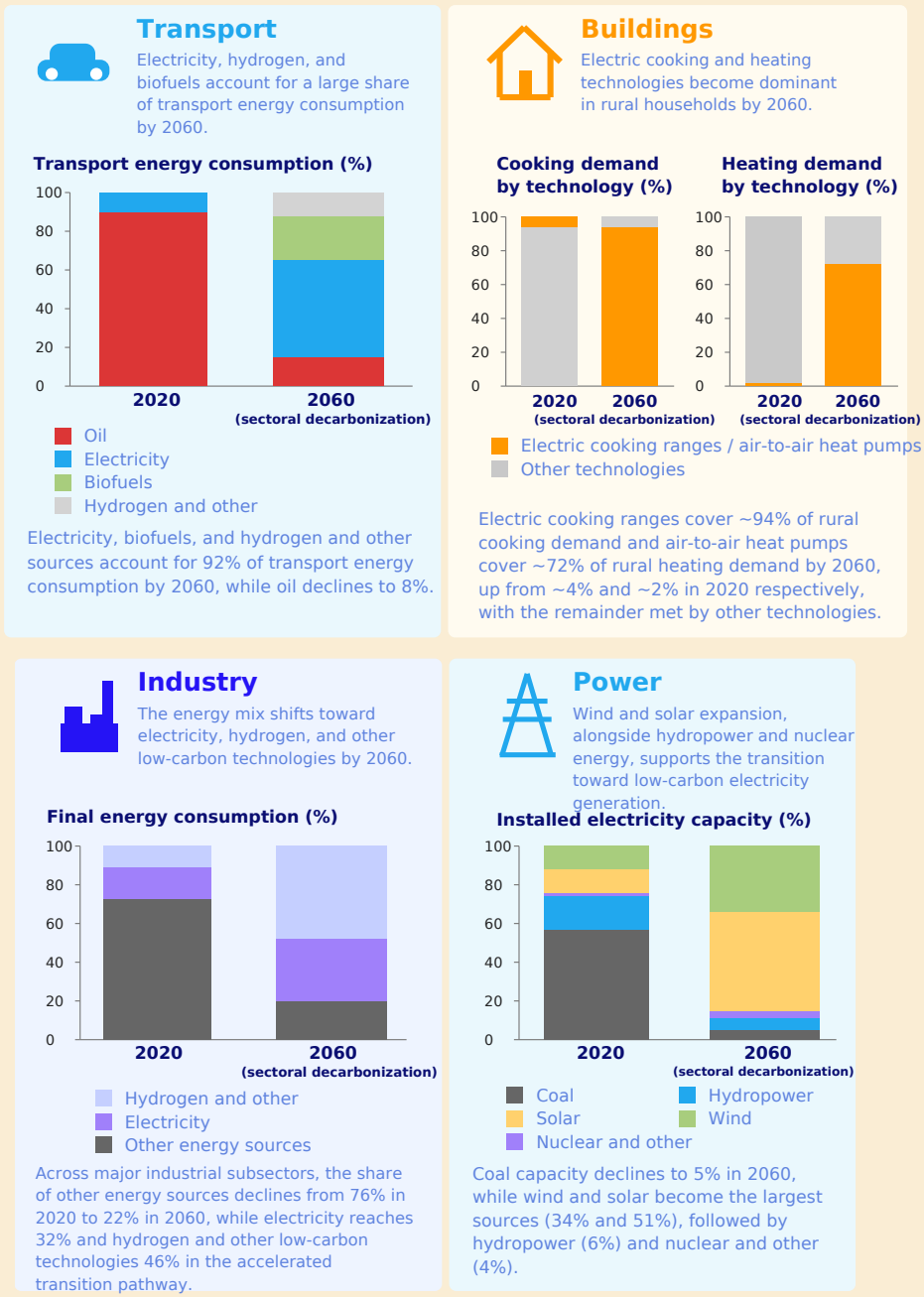


Figure B3: Towards a low-carbon energy system: sectoral transition pathways in China. Selected modelling studies project substantial energy transitions across transport, buildings, industry, and power by 2060, with electrification and low-carbon energy technologies playing complementary roles.

While these technologies offer potential energy efficiency and air-quality benefits, their ability to reduce emissions depends critically on the carbon intensity of the electricity used to power them. Recognizing the need to support growing electrification with low-carbon electricity, China is expanding its clean power supply. As highlighted by Chui et al. (n.d.), wind and solar power are expected to account for more than 50% of electricity generation by 2060. A broader multi-model assessment further reinforces the central role of power-sector transformation in aligning China's near-term climate commitments with its long-term carbon neutrality target (Kong et al., 2023; Sun et al., n.d.). Coordinating clean electricity expansion with end use electrification may also reduce transition costs, with lower GDP losses (Liu et al., 2025; Liu et al., n.d.). For policymakers, these developments highlight the importance of expanding low-carbon electricity supply as transport, buildings, and industry increasingly adopt electric technologies.

REFERENCES

Chui, T.K. et al. (no date) 'Technology diffusion and learning as enablers of firm-level decarbonization: Insights from China's thermal power sector'. Manuscript under review.

Fang, Y.R. et al. (2023) 'Neutralizing China's transportation sector requires combined decarbonization efforts from power and hydrogen supply', Applied Energy, 349, p. 121636. Available at: https://doi.org/10.1016/j.apenergy.2023.121636.

Kong, L.-S. et al. (2023) 'Significance of achieving carbon neutrality by 2060 on China's energy transition pathway: A multi-model comparison analysis', Advances in Climate Change Research, 14(1), pp. 32–42. Available at: https://doi.org/10.1016/j.accre.2023.01.010.

Liu, X. et al. (2026) 'Accelerated pathways for China's industrial decarbonization lower system costs and preserve the carbon budget', Joule, p. 102542. Available at: https://doi.org/10.1016/j.joule.2026.102542.

Liu, X. et al. (no date) 'Assessing costs and mitigation strategies for China's new nationally determined contribution: A multi-model comparison'. Manuscript under review.

Liu, Yu et al. (2025) 'Mitigation policies interactions delay the achievement of carbon neutrality in China', Nature Climate Change, 15(2), pp. 147–152. Available at: https://doi.org/10.1038/s41558-024-02237-2.

Ma, T. et al. (2023) 'Costs and health benefits of the rural energy transition to carbon neutrality in China', Nature Communications, 14(1), p. 6101. Available at: https://doi.org/10.1038/s41467-023-41707-7.

Sun, Y. et al. (no date) 'Pursuing enhanced climate pledges: Consistency between updated NDCs and net zero'. Manuscript under review.

3.3.3 Hydrocarbon molecules demands and green molecules supply

Electrification can replace the bulk of fossil fuel use, but some applications remain difficult to electrify (Ueckerdt et al., 2021; Bachorz et al., 2025). While direct electrification is generally more energy- and cost-efficient, these applications continue to require hydrocarbons as fuels because of their high energy density, or as feedstocks with specific chemical properties. In particular, plastic production and liquid fuels for aviation and shipping require molecules that contain carbon. With increasing electrification of end uses, the remaining challenge of transitioning away from fossil fuels becomes increasingly concentrated in these applications.

Residual demand for liquid, gaseous and solid hydrocarbons and hydrogen in the SCI high-ambition pathways amounts to 102–177 EJ/yr by 2050. Biomass-based fuels and feedstocks provide an important alternative to fossil hydrocarbons, but their sustainable supply is limited: expanding bioenergy production can increase competition for land and water, threaten biodiversity and food security, and cause additional greenhouse gas emissions from land-use change (Clarke et al., 2022). Green hydrogen, produced using renewable electricity, offers another route to replacing fossil fuels. It can be used directly in some industrial processes such as primary steel making via direct reduction, or ammonia production for fertilizers. It can also be combined with captured CO_2 to produce synthetic hydrocarbons (e-fuels). However, producing these fuels requires large amounts of renewable electricity and sustainable carbon sources, which remains substantially more costly than conventional fossil fuels (Tonelli et al., 2023; Schreyer et al., 2025). In view of these technological and economic challenges, the deployment levels of hydrogen and e-fuels remain relatively small in high-ambition scenarios. However, with fast technological progress in electrolyser technology, the significance of hydrogen in future energy systems could potentially increase.

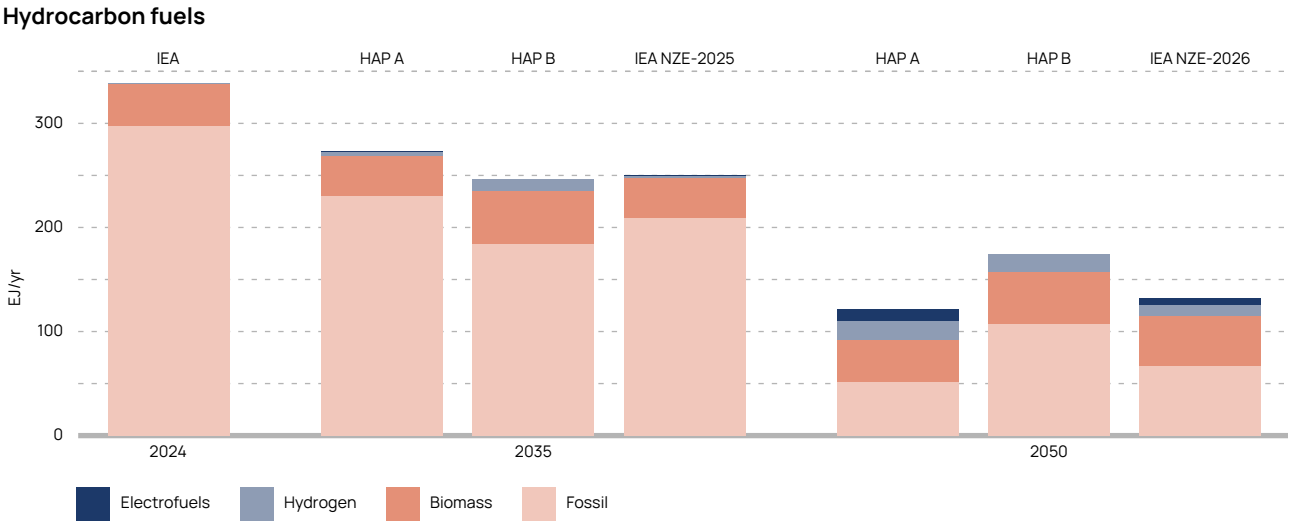


Figure 3.6: Evolution of hydrocarbon and hydrogen fuel demand in the energy demand sectors for three illustrative for 2035 and 2050, as well as historical fuel demand for 2024 (IEA, 2025d).

BOX 4: THE EU'S PATH TO NET ZERO BY 2050

Authors: Felix Schreyer, Robert Pietzcker, Claire Fyson, Keywan Riahi, Elena Verdolini, Gunnar Luderer

The EU occupies a particular position in the global transition: with the European Climate Law it has committed to greenhouse gas neutrality by 2050, leaving less than 25 years to restructure an industrialised energy system. Because the target is so near and stringent, the EU needs to deploy strategies in parallel that elsewhere are consecutive: deep electrification, carbon dioxide removal, and green molecules for hard-to-electrify sectors. The EU thus functions as a testbed for the late stages of decarbonisation.

The EU has already made substantial headway, cutting energy CO_2 emissions by almost 40% since 1990 (EEA 2026). Ambitious economy-wide emissions reduction targets (-55% in 2030, -90% in 2040 incl. up to 5% international credits, net zero in 2050) will require an even more fundamental transformation across all sectors, driven by increasingly stringent climate policy instruments. A key instrument is the EU emissions trading scheme (ETS) that will cover most energy-related emissions once the ETS2 for road transport and buildings starts by 2028. This is complemented by sector-specific policies (e.g. emissions standards for light-duty vehicles) and industrial policy measures. While many of the core building blocks point towards an ambitious transformation, there is growing pressure from some industrial and political actors to weaken the EU's climate measures. However, recent geopolitical tensions and disruptions of global fossil fuel markets have given European energy discourse a new focus: the transition is increasingly motivated by gaining energy independence.

Modelling studies have drawn a robust picture of how the EU could reach net zero emissions by 2050 (Boitier et al. 2023; Schreyer et al., 2025; Mikropoulos et al., 2025; Rodrigues et al., 2026). The core elements of the energy transition are similar to those in global pathways but generally faster: rapid power sector decarbonisation, widespread electrification, and use of green molecules (green hydrogen, biofuels, e-fuels), material circularity or carbon dioxide removal (CDR) in hard-to-electrify sectors (Figure B4). In typical EU net-zero pathways, these strategies jointly reduce fossil fuel consumption by 85–100% in 2050 (Figure B4a). The amount of residual fossil energy at net zero depends on how far energy demand in the hard-to-electrify sectors can be reduced (efficiency, material circularity, mode shift) and on how far either carbon capture and storage (CCS) and CDR, or green molecules can be scaled up by 2050.

Acceleration of renewable power expansion and roll-out of demand-side electrification are the two main levers for substantial, cost-efficient reductions of energy-related emissions up to 2050. A more rapid deployment of wind and solar power sits at the heart of the EU power sector decarbonization (Figure B4b). With high shares of these weather-dependent technologies, challenges such as energy storage, grid expansion, smart meter roll-out and regulation for demand-side flexibility need to be tackled (Brown et al., 2018). Electrification of cars and trucks as well as low- and medium-temperature heat provision can replace most hydro-carbon fuel demand by electricity (Figure B4c). This is a huge mitigation lever, as together these sectors currently account for around 60% of EU energy CO_2 emissions (EEA, 2026). EU-wide sales shares of battery-electric vehicles (BEV) have grown considerably in recent years, driven by policies, strong cost reductions, and the energy price crises in 2022 and 2026, with several Member States reaching sales shares of 40–80%. Key requirements for further acceleration include grid upgrading, adjusting regulatory frameworks to lower electricity prices, and transferring successful deployment policies to lagging Member States.

Enabling the last step of the transition in hard-to-electrify sectors is particularly relevant in the EU as net-zero GHG emissions is to be achieved in less than 25 years and Europe's potential for low-cost renewable energy is limited. The hard-to-electrify sectors currently account for about 450 Mt/yr CO_2 emissions (EEA, 2026) including energy-intensive industries (steel, cement, chemicals), aviation, shipping and waste incineration. One option is to deploy CCS or carbon dioxide removal (CDR) to abate or compensate for these emissions. Given the technological, infrastructural and institutional challenges, scaling CDR fast enough to compensate for both residual non-CO_2 emissions in agriculture (about 300–400 $MtCO_2eq/yr$) and fossil emissions from hard-to-electrify sectors by 2050 will be hardly feasible (Rosa et al., 2021; Kazlou et al., 2024). The less carbon storage can be realized, the more green molecules such as green hydrogen, biofuels and e-fuels will be needed (Figures B4d, B4e). The optimal mix of green molecules is somewhat uncertain and varies across scenarios and studies (Li et al. 2026; Liu et al. 2026; Schreyer et al. 2025; Mikropoulos et al. 2025; Glaum et al. 2026). However, it is clear that green molecules will remain expensive, so their use should be confined to hard-to-electrify sectors and complemented by circular economy measures to reduce demand (Musonda et al. 2024; Stegmann et al. 2022). Green molecule production and carbon management are currently at negligible scale in the EU. To enable this last step of the transition, it is key to plan the required infrastructure (H_2, CO_2 grids) and to reduce business uncertainty so that novel technologies survive the "valley of death" in early development and scale up rapidly.

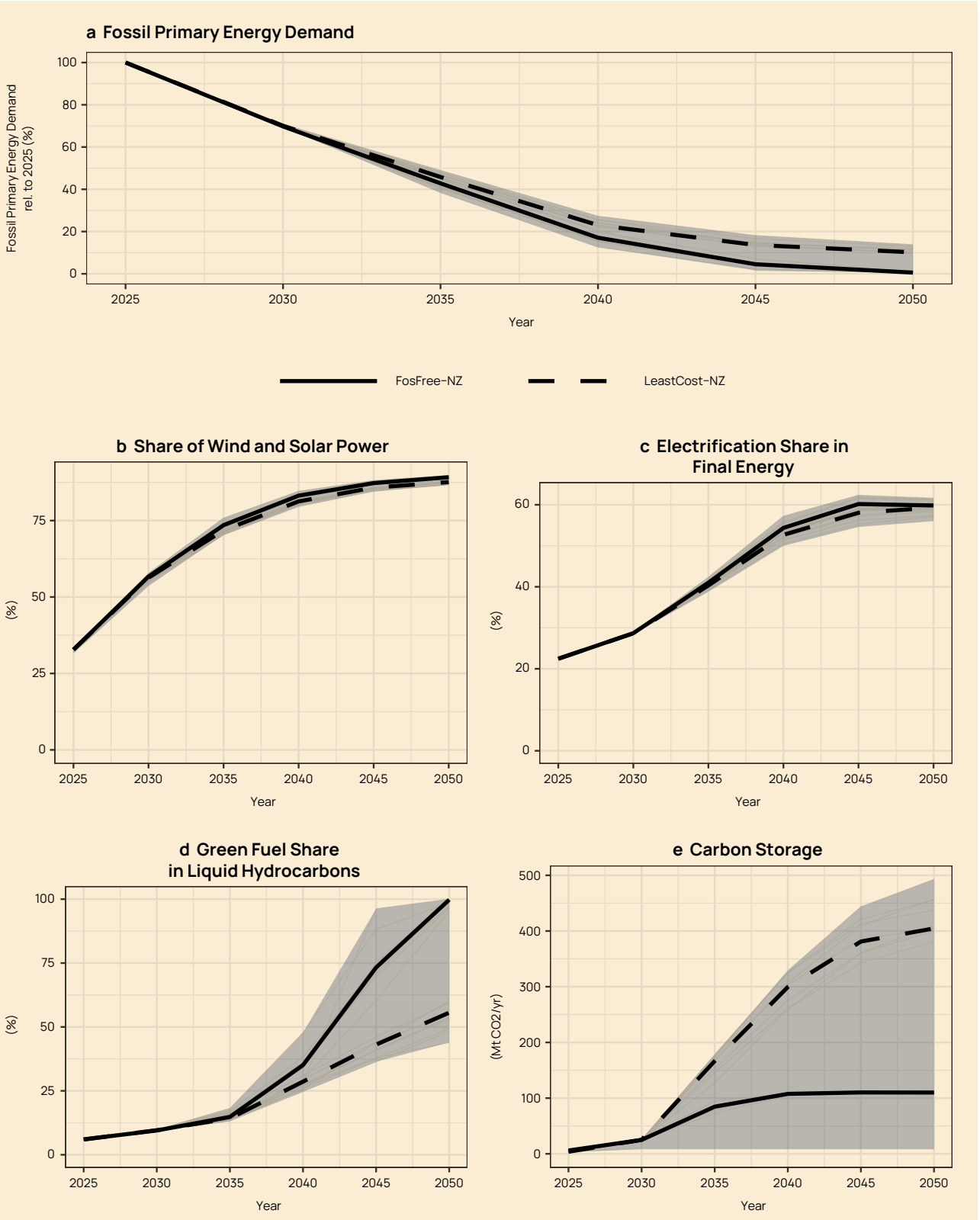


Figure B4: Transition indicators in EU net-zero scenarios from Schreyer et al. (2025). The LeastCost-NZ scenario represents a least-cost pathway to net-zero under substantial deployment of carbon storage. The FosFree-NZ scenario is a net-zero scenario with a full fossil phase-out and limited use of carbon storage. Funnels show sensitivity scenarios. Figures are for EU27 totals. Panels: **a)** Fossil primary energy consumption relative to 2025, **b)** Share of wind and solar power in total electricity generation, **c)** Share of electricity in final energy (incl. bunker fuels and non-energy use), **d)** Share of green (non-fossil) fuels in liquid hydrocarbon supply, e) Annual carbon capture and storage.

REFERENCES

Boitier, Baptiste, Alexandros Nikas, Ajay Gambhir, et al. 2023. "A Multi-Model Analysis of the EU's Path to Net Zero." Joule 7 (12): 2760–82. https://doi.org/10.1016/j.joule.2023.11.002.

Brown, T., D. Schlachtberger, A. Kies, S. Schramm, and M. Greiner. 2018. "Synergies of Sector Coupling and Transmission Reinforcement in a Cost-Optimised, Highly Renewable European Energy System." Energy 160 (October): 720–39. https://doi.org/10.1016/j.energy.2018.06.222.

EEA. 2026. "GovReg: National Emissions Reported to the UNFCCC and to the EU under the Governance Regulation, 2026 Ver. 3.0." Version 03.00. European Environment Agency, September 15. https://doi.org/10.2909/F6A252A6-1BDE-43A8-9E6A-F58146FD691E.

Glaum, Philipp, Fabian Neumann, Markus Millinger, and Tom Brown. 2026. "A Minimal Methanol Backstop for High-Electrification Scenarios." Joule 10 (9): 102464. https://doi.org/10.1016/j.joule.2026.102464.

Kazlou, Tsimafei, Aleh Cherp, and Jessica Jewell. 2024. "Feasible Deployment of Carbon Capture and Storage and the Requirements of Climate Targets." Nature Climate Change 14 (10): 1047–55. https://doi.org/10.1038/s41558-024-02104-0.

Li, Yunfei, Nathan Gray, Richard O'Shea, et al. 2026. "A Decision-Making Process to Compare Renewable Fuel Production Pathways for Shipping." Cell Reports Sustainability 3 (9): 100834. https://doi.org/10.1016/j.crsus.2026.100834.

Liu, Zipeng, Tom Terlouw, Patrick Frey, Christian Bauer, and Russell McKenna. 2026. "Global Cost Drivers and Regional Trade-Offs for Low-Carbon Fuels: A Prospective Techno-Economic Assessment." Energy & Environmental Science 19 (7): 2246–72. https://doi.org/10.1039/D5EE05591A.

Mikropoulos, Efstratios, Mark Roelfsema, Hsing-Hsuan Chen, et al. 2025. "Examining Pathways for a Climate Neutral Europe by 2050; A Model Comparison Analysis Including Integrated Assessment Models and Energy System Models." Energy 319 (March): 134809. https://doi.org/10.1016/j.energy.2025.134809.

Musonda, Frazer, Markus Millinger, and Daniela Thrän. 2024. "Modelling Assessment of Resource Competition for Renewable Basic Chemicals and the Effect of Recycling." GCB Bioenergy 16 (4): e13133. https://doi.org/10.1111/gcbb.13133.

Rodrigues, Renato, Robert Pietzcker, Joanna Sitarz, et al. 2026. "2040 Greenhouse Gas Reduction Targets and Energy Transitions in Line with the EU Green Deal." Nature Communications 17 (1): 3417. https://doi.org/10.1038/s41467-026-71159-8.

Rosa, Lorenzo, Daniel L. Sanchez, and Marco Mazzotti. 2021. "Assessment of Carbon Dioxide Removal Potential via BECCS in a Carbon-Neutral Europe." Energy & Environmental Science, 10.1039.D1EE00642H. https://doi.org/10.1039/D1EE00642H.

Schreyer, Felix, Falko Ueckerdt, Robert Pietzcker, et al. 2025. From Net-Zero to Zero-Fossil in Transforming the EU Energy System. Nature Communications 16: 10700. https://doi.org/10.1038/s41467-025-66682-z

Stegmann, Paul, Vassilis Daioglou, Marc Londo, Detlef P. van Vuuren, and Martin Junginger. 2022. "Plastic Futures and Their CO_2 Emissions." Nature 612 (7939): 272–76. https://doi.org/10.1038/s41586-022-05422-5.

3.3.4 Reaching (near-)zero fossil fuel use

Two of the SCI pathways, HAP A and the 1.5°C scenario from Climate Analytics and PIK (2025) feature a near full-scale phase-out of fossil fuel use in the second half of this century. Other studies with this feature (Schreyer et al., 2025; Mori et al., 2026) are not included in the SCI set here due to lack of consistency with historic developments through 2025, or lack of global coverage. For the same global end-of-century carbon budget, full phase-out pathways also rely less on carbon capture and storage and carbon dioxide removal, and result in lower peak temperatures (Mori et al., 2026).

The key difference between scenarios that phase out fossil fuels entirely and those where residual use is significant resides in the supply of molecular fuels to aviation, shipping and chemical industries. In fossil phase-out scenarios like HAP A, molecular fuel demand is met by hydrogen, biomass and synthetic fuels. The low efficiency of converting electricity into hydrogen and synthetic fuels results in additional electricity demand in these pathways (see Figure 3.4a), requiring a rapid growth in wind, solar, energy storage, electrolysers and hydrogen-powered technologies. Total energy infrastructure investments are therefore higher, and supply chain bottlenecks may arise (Mori et al., 2026).

By contrast, scenarios with residual fossil fuel use like HAP B rely on carbon capture and storage (CCS) and carbon dioxide removal (CDR) to mitigate or offset fossil emissions. Scaling up these technologies is also costly and remains a technological challenge (Schreyer et al., 2025). These pathways also risk resulting in higher peak temperatures, as fossil emissions continue in the near term and are only compensated later on (Mori et al., 2026). Importantly, fossil phase-out pathways reduce but do not eliminate the need for CDR, since compensation of residual industrial process emissions GHGs other than CO_2 as well as net-negative emissions to reverse exceedance of 1.5°C remain essential.

There are further options to reduce long-term molecular fuel demand that are not widely explored in the SCI high-ambition pathways. First, demand reduction through circular economy, material efficiency and behavioural changes can relieve pressure on the bottleneck sectors. Second, a deeper electrification may be possible, with evidence that as much as 90% of non-feedstock industrial energy demand could be electrified through existing and emerging technologies (Etter-Wenzel and Rosenow, 2026). Further research is needed to assess the potential of these options and develop them at a large scale.

3.4 EQUITY IN GLOBAL ENERGY TRANSITION SCENARIOS

3.4.1 Distributional implications of global pathways

The SCI high-ambition pathways presented in Sections 3.1, 3.2, and 3.3 indicate the global pace of mitigation needed to meet the Paris temperature goal, but do not determine who should bear the costs of mitigation. Most pathways pursue a least cost approach, many include sustainability constraints, and some apply regionally differentiated carbon prices (see Technical Annex). Moderate carbon price differentiation, combined with moderate financial transfers, can share mitigation effort more equally at a small loss of efficiency (Bauer et al., 2020). A growing literature extends or post-processes pathways to assess their effects on household incomes, poverty and inequality (Soergel et al., 2021; Emmerling, Andreoni and Tavoni, 2024; Emmerling et al., 2024; Zhao et al., 2025; Young-Brun et al., 2025) and on energy-sector jobs (Malik et al., 2021). Carbon pricing can disproportionately affect low income households. Redistributing carbon revenues as equal per-capita transfers can offset this in some countries (Soergel et al., 2021; Emmerling, Andreoni and Tavoni, 2024; Emmerling et al., 2024; Young-Brun et al., 2025), although domestic redistribution alone may not be enough to eradicate poverty in many African countries (Zhao et al., 2025).

Three issues remain largely outside the scope of global pathways. The first is distribution within countries, as higher energy prices, subsidy reform, job losses in fossil fuel producing regions and competing demands for land affect households and communities unevenly (Box 1, Section 2 and Section 4). The second concerns the exposure of economies dependent on fossil fuels to declining export earnings and public revenues (Box 2 and Section 4). The third is which countries capture the opportunities arising from clean industries and commodities produced with low emissions (Section 4).

Financing conditions also matter. Most pathways still assume a uniform cost of capital across all regions. In reality, higher financing costs add on average about USD26/MWh to the cost of solar and USD24/MWh to onshore wind electricity in low- and middle-income countries, compared with high-income financing terms (Hatton et al., 2026). Models that represent these differences find higher global mitigation costs and a shift of mitigation towards lower-risk, mostly industrialised regions (Iyer et al., 2015; Waidelich et al., 2026). In a 2°C cost-minimising pathway, green electricity generation in Africa reduces by 35% if higher financing costs are taken into account (Ameli et al., 2021). Conversely, lowering financing costs in developing regions brings more renewable and affordable energy (Calcaterra et al., 2024; Frilingou et al., 2026) and moves Africa's net zero forward by about a decade (Ameli et al., 2021). Global pathways may therefore overestimate the pace of clean investments in low- and middle-income countries unless financing conditions improve.

All global pathways in this brief exceed 1.5°C before returning to it by 2100 and therefore depend on CDR to bring temperatures back down, which imposes costs, land demands and other risks onto later generations and the regions that host CDR.

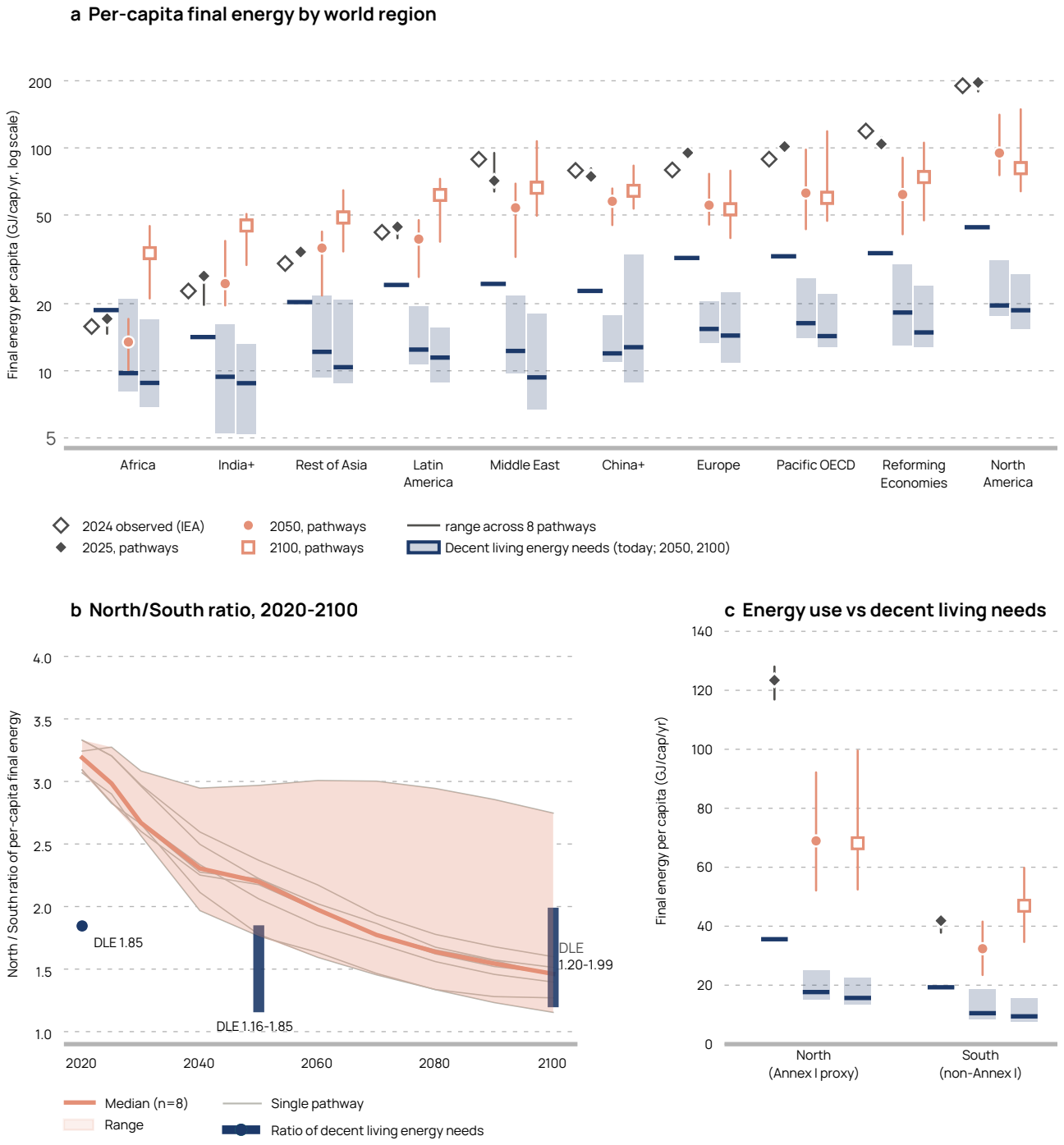
3.4.2 Development needs and convergence of living conditions

Fossil fuels serve different needs, from basic energy access and early industrialisation to advanced industrial processes (see Section 2). Bottom-up estimates suggest these needs are modest, and that building the infrastructure to close decent-living gaps worldwide by 2040 requires about 290 EJ in total, less than three-quarters of one year's current global final energy demand (Kikstra et al., 2021). Decent living for all does not in itself threaten climate goals. For many countries, however, the growth in energy supply required to meet decent living standards by 2040 would be substantially above historical rates (Kikstra et al., 2021). Newer work links these thresholds to mitigation pathways directly and finds that pathways combining reduced inequality, efficient service provision and higher energy services can close most residential and commercial energy deprivation by 2040 while staying in line with the Paris Agreement (Kikstra et al., 2025).

Regional gaps in energy use become much narrower in the SCI high-ambition pathways (Figure 3.7). An average person in the Global North (approximated here by Annex I countries) today uses about three times as much final energy as a person in the Global South. In the eight SCI high-ambition pathways, this ratio falls to about 2.2 by 2050 (range 1.8–3.0) and to about 1.5 by 2100 (range 1.2–2.8). Two shifts drive this convergence. In the North, per-capita final energy use falls by more than 40% by 2050, as electrification and efficiency deliver the same services with less energy. In the South, energy use per person grows as incomes rise, by 70–100% in Africa and South Asia by 2100.

Energy equity does not imply equal energy consumption for everyone, but rather equitable access to the energy services needed for a decent standard of living, including heating and cooling, cooking, mobility, lighting and communication. The energy required to provide these services varies across regions, depending on climate, settlement patterns and the efficiency of buildings, vehicles and appliances. Taking this into account, a decent standard of living requires approximately 1.85 times more energy per person in the Global North than in the Global South today, and 1.2–2.0 times more by 2100 (Kikstra et al., 2025). Measured against these needs,

the North-South gap in energy use beyond decent living narrows substantially by 2050 and closes in seven of the eight pathways by 2100 (Figure 3.7b). Remaining regional differences in energy use thus increasingly reflect differences in service provisioning rather than unequal access to energy. However, regional averages can mask substantial inequalities within countries, which these pathways do not resolve (Section 3.4.1).



8 high ambition SCI pathways (GW2a: peak warming below 1.7°C, return below 1.5°C by 2100). North = R10 North America, Europe, Pacific OECD, Reforming Economies (Annex I proxy); South = other R10 regions. Decent living energy (DLE): Kikstra et al. (2025), SHAPE scenarios. 2024 observed: IEA World Energy Outlook 2025, UN population. Markers in panel c as in panel a.

Figure 3.7. Regional energy inequalities decline, and average energy use exceeds decent living needs across all regions. (a) Per-capita final energy use by world region in eight SCI high-ambition pathways for 2025, 2050 and 2100 (markers: median; lines: range), compared with 2024 observed values (IEA, 2025d) and decent living energy requirements (green). (b) Ratio of per-capita final energy use between the Global North (Annex I) and the Global South (non-Annex I); green markers and bars show the same ratios for decent living energy requirements. (c) Per-capita final energy use in the Global North and South compared with their respective decent living energy needs. Calculations based on Kikstra et al. (2025).

3.4.3 Embedding fair shares into scenarios

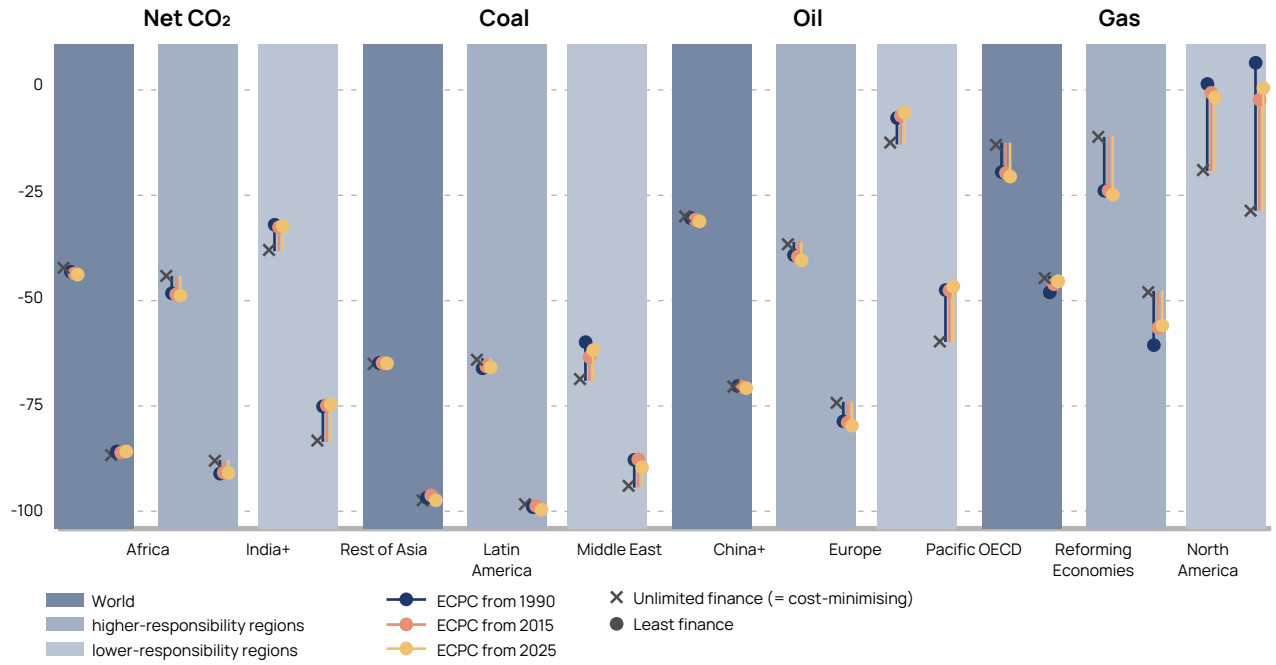
An important dimension of common but differentiated responsibilities for collective mitigation action is fair effort sharing. A variety of fair effort sharing approaches have been formulated, e.g., based on principles like responsibility (polluter / beneficiary pays) and capability (ability to pay) (Caney, 2010). Those approaches were also applied to mitigation pathways in numerous studies, but mostly for the analysis of the financial flows that would be required to make the regional distribution of actual emissions reductions consistent with regional fair shares of emissions allowance (Van Den Berg et al., 2020; Pachauri et al., 2022). Pelz et al. (2026) are among the first to build principle-based fair shares into scenario generation itself. Using MESSAGE-ix-GLOBIOM (SSP2), they allocate the remaining 1.5°C carbon budget, assumed to be 500 $GtCO_2$ from 2020 to 2100, by equal cumulative per-capita emissions from 2015 and let regions meet their shares through domestic mitigation or financial transfers, keeping global peak and end-of-century temperatures unchanged. Regions whose emissions in the cost-minimising pathway exceed their fair share form a higher-responsibility group (North America, Europe, China, the Middle East, the Reforming Economies, Pacific OECD and the rest of centrally planned Asia); the rest form a lower-responsibility group.

A key finding is that fair effort sharing leaves the global emissions and energy transition benchmarks largely unchanged. Global net CO_2 emissions and coal, oil and gas use in 2035 and 2050 are almost the same with and without fair shares (Figure 3.8a). The largest difference is seen for global gas use that falls somewhat faster by 2035 (about 20% rather than 13%). Global renewables deployment and electrification are nearly identical (Pelz et al., 2026). What changes is the regional distribution of effort. Even in the least cost pathway, lower-responsibility regions, where energy needs are growing, reduce oil and gas use more slowly than higher-responsibility regions by 2050. Fair shares widen this difference. Higher-responsibility regions cut net CO_2 and oil slightly faster, and gas markedly faster. Lower-responsibility regions phase down more slowly: with responsibility counted from 2015, their gas use stays close to 2025 level through 2050 rather than falling by around 30%, and their oil use falls by about half rather than 60%. Coal falls by around 90% or more by 2050 in both groups.

The stringency of the 1.5°C budget is what makes finance central. Under equal per capita shares the remaining emissions allowances of high responsibility regions are smaller than even very deep domestic cuts can meet. They cover the gap by buying allowances from lower-responsibility regions, whose fair shares exceed their emissions. Even the lowest feasible transfers, i.e., the smallest amounts with which each region can meet its fair share, sum to about USD18 trillion (present value, 2026–2100) with responsibility counted from 2015. The choice of start date alone moves this from about USD8 trillion (2025) to about USD38 trillion (1990), and to as much as USD57 trillion if transfers are unlimited (Figure 3.8b). These figures rest on normative choices about allocation principles and start dates, which are a matter for political agreement rather than modelling.

Effort-sharing schemes imply similar global migitation but different regional obligations and finance transfers

a Emissions reductions and fossil-fuel phase-down
Percentage change from 2025, 1.5°C pathways



b Financial transfers from higher- to lower-responsibility regions

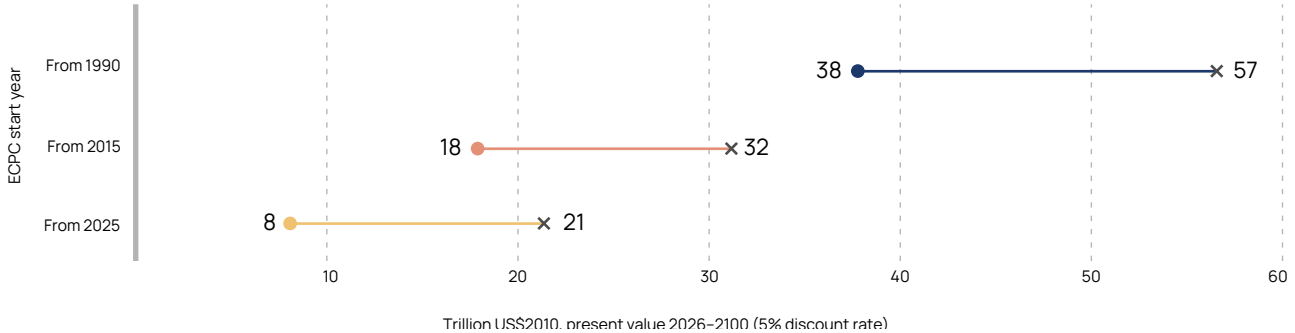


Figure 3.8. Fair effort sharing changes who mitigates, not the global pace. **a)** Change in net CO_2 emissions and in coal, oil and gas use in 2035 and 2050 relative to 2025, for the world and for higher- and lower-responsibility regions (shaded), under a 1.5°C carbon budget (500 $GtCO_2$ net from 2020, allowing temporary overshoot). Crosses show the cost-minimizing pathway, which is identical to fair shares met with unlimited finance. Dots show fair shares met with the lowest feasible finance, for equal cumulative per-capita (ECPC) allocations with responsibility counted from 1990, 2015 (central case) or 2025. Lowest feasible finance is the smallest cap on transfers, as a share of GDP, at which every region can still meet its ECPC share within the 1.5°C budget; below that cap, the model finds no pathway. **b)** Financial transfers to net recipient regions for each start year, from lowest feasible (dot) to unlimited (cross) finance, in USD2010 trillion, present value 2026–2100 at a 5% discount rate. Global results barely change, while lower-responsibility regions phase down fossil fuels more slowly when finance is limited. Changes are relative to 2025; Pelz et al. (2026) report changes relative to 2020. Scenarios rerun for this brief based on Pelz et al. (2026).

4. TAFF IMPLEMENTATION: ENABLERS AND BARRIERS

4. TAFF IMPLEMENTATION: ENABLERS AND BARRIERS

Delivering the first Global Stocktake commitment (Decision 1/CMA.5, para. 28(d)) to transition from fossil fuels "in a just, orderly and equitable manner" requires countries to identify and address interconnected economic, technological, institutional and distributional barriers (UNFCCC, 2023a, 2025a). While global modelling illustrates plausible overshoot pathways that limit warming to 1.7°C at peak and below 1.5°C by 2100, techno-economic feasibility alone does not imply that regions or countries can practically implement these pathways. A variety of barriers exist at the country level which will need to be addressed and overcome to transition away from fossil fuels and align with these global pathways. A wide variety of enablers spanning the social, economic, technological and institutional domain have been implemented across regions to overcome these barriers, and there is much to learn from these efforts. Further, enablers are dynamic, interact with each other, and can produce non-linear change — as we are now seeing for some important mitigation options. A clear policy implication is that there is no single silver bullet to overcome the complex and multiple challenges that countries face. A broadly supportive environment is necessary for specific and often multiple enablers to effectively overcome barriers. Importantly, having multiple societal priorities — not only climate but also health, security, development and natural resource sustainability — can make enablers more robust where those objectives align. Overcoming barriers requires domestic reforms as well as international support to enable nationally determined decarbonisation pathways that align with development priorities.

The following overview identifies common barriers and enablers; their relevance, interactions and implications for implementation require careful assessment in each national context.

4.1 TECHNOLOGICAL ENABLERS AND BARRIERS

Improvements in clean technology in the past several years have been dramatic and are continuing. Batteries and solar are exceptional in both their diffusion and cost reductions and are quickly becoming core components of energy systems (Dhakal et al., 2022). They are in stark contrast to high potential technologies that are diffusing slowly with more static costs: low-carbon industry, CCS, novel CDR, and advanced nuclear. In particular, CCS deployment has remained well below the levels envisaged in many earlier climate-mitigation pathways (Kazlou et al., 2024). Some options, notably CCS and direct air capture (DAC), also require substantial energy inputs, which can reduce net energy delivered to the wider system or increase its energy requirements. Although technological improvements can reduce these energy requirements, cost reductions alone do not eliminate the underlying energy demand (Clarke et al., 2022; Bashmakov et al., 2023; Herzog et al., 2024).

Not only are rapidly improving clean technologies making low-carbon pathways more affordable and more feasible, they are underpinning other enablers. The pathways results show that improvements in electric vehicles, renewables and battery storage are effective in reducing fossil fuel use substantially (Section 3.2, 3.3). The decreasing costs of clean technologies is enhancing institutional enablers, such as making climate policy more affordable. The granular scale of these technologies is making behavioural change more feasible. It is also making public preferences for energy security more aligned with climate protection goals than in the past, even if the two still create some trade-offs. However, the rapid adoption of clean technologies is also surfacing new issues, which will require enablers to overcome — such as, domestic capabilities, supply chain reliability, and access to critical minerals. System integration and capacity for implementation (social, institutional, infrastructural) are becoming crucial constraints on the transition and decision makers will need to evaluate specific regional issues and contexts to evaluate the practicality of choices and implement a broad suite of supportive conditions to enable scaling up of the emerging technological opportunities.

4.1.1. Technology access and domestic capabilities

For expanding mitigation technology, apart from availability of adequate and affordable finance, the most prominent enabler is capacity building, which includes enhancing social, institutional, financial, technical, and labour market capacity.

Large-scale clean technology deployment requires the capacity to adapt, operate, maintain and develop/manufacture technologies. Finance and equipment imports alone cannot overcome gaps in research, skills and innovation, particularly for emerging technologies such as green hydrogen and advanced storage. Restrictive intellectual property regimes, licensing costs and limited technology-transfer arrangements further constrain access (Blanco et al., 2022; UNCTAD, 2023). Without domestic capabilities, developing countries risk remaining technology importers, capturing few jobs, industrial benefits or learning opportunities (Blanco et al., 2022; UNCTAD, 2023; IRENA, 2026b)

Joint research, affordable technology access, flexible intellectual property arrangements and South–South cooperation can support domestic manufacturing and skills development (Songwe et al., 2022). Cooperation across the value chain can enable developing countries to participate more meaningfully in clean technology industries (Lema et al., 2018; IEA, 2024c).

4.1.2. Supply-chain concentration and critical minerals

Clean energy transition could introduce new supply chain vulnerabilities especially with regard to critical minerals and manufacturing inputs. Adequate availability of reliable critical mineral supplies at affordable prices is crucial for ensuring energy security as countries transition towards higher renewable energy (Hotchkiss et al., 2024). Global production of critical minerals is concentrated in a few countries with China being the largest supplier; IEA analysis indicates that China is the leading refiner for 19 of the 20 energy-related strategic minerals with an average market share of around 70% (Berahab, 2022; Nygaard, 2023; IEA, 2025a). Apart from the recent geopolitical turmoil affecting critical mineral supply chains, geopolitical risks also remain high for countries which depend on critical minerals production based in Africa and South America due to civil conflicts and other non-technical risks which impact investments and lead to price volatility (Trench et al., 2014; Saadaoui et al., 2025). However, the overall issue is less about scarcity than concentration of processing and know-how.

Scaling up clean energy transitions could reduce fuel import dependencies for several countries, but may shift the concerns of energy security towards building more resilient energy systems that can withstand geopolitical disruptions, price shocks and long-term structural changes. Diversifying supply chains and strengthening local processing can enhance energy security while helping countries distribute economic benefits more widely (Mohan et al., 2026).

4.1.3. Energy security, grid integration and system costs

Rapid end use electrification can significantly alter the shape of the load curve and impact electricity system operations, but the extent of this variation in net zero systems is uncertain (Bistline et al., 2021). Developing countries undergoing economic restructuring could be impacted more, especially as access and availability of reliable energy improves and new demand from AI driven data centres may evolve. While rapid digitalisation led growth could spur electricity needs significantly, a sudden reduction in dispatchable fossil fuel capacity could compromise reliability and affordability. Managing the rapidly changing electricity loads requires grids to be strengthened.

Rapid electrification and renewable energy deployment requires substantial upfront investment in grids, storage and backup capacity, although these costs are often overlooked in technology-level comparisons (Songwe et al., 2022). Very rapid increase in renewable generation capacity requires grid strengthening and expansion to keep pace with growth in renewable generation capacity for renewable heavy electricity systems to reliably supply the increasing needs. Grid infrastructure typically takes 5–15 years to develop, compared with 1–5 years for renewable energy projects (IEA, 2023).

Digital technologies can however also be a key enabler to developing resilient energy systems that operate quite differently from those of the past. As developing countries expand energy access and face rapidly rising electricity growth, variable renewable energy, energy storage technologies, transmission/trade and demand side management would need to play a larger role; their uptake would however depend on policies, markets and technology. Coordinated infrastructure development and regional grids can support integration and mitigate dependencies.

BOX 5: ACCELERATING ASEAN'S ENERGY TRANSITION: FINANCE, TECHNOLOGY, AND REGIONAL COOPERATION

Authors: Ambiyah Abdullah, Claire Fyson, Frank Jotzo, Joni Jupesta, Ho Wai Shin, Haslenda Hashim, Nuwong Chollacoop, Silva Kampanart

The Association of Southeast Asian Nations (ASEAN)'s transition towards a low-carbon economy offers significant opportunities to mobilise investment, strengthen energy security, and enhance regional energy resilience. Although the region comprises approximately 9% of the global population, it attracts only 3% of global energy investment (IEA, 2026a). Furthermore, its share of global clean energy investment (3%) is lower than that of fossil fuels (4%) (IEA, 2026b). In 2025, annual energy investment surpassed USD100 billion, with fossil fuels constituting just over half of this amount (IEA, 2026a). However, investments in renewable energy and the grid in 2026 are expected to be USD22 billion and USD15 billion, respectively (IEA, 2026b). With transition needs expected to reach up to USD170 billion each year by 2030, frameworks must address political, regulatory, and offtaker risks (ACE, 2026b). The 2026 oil shock further highlights the need for resilient financing structures, as inflation and currency depreciation raise foreign-currency borrowing costs and limit investment in grids and energy storage (Abdullah et al., 2026; ADB, 2026).

Indonesia's Just Energy Transition Partnership (JETP) illustrates both the scale of existing international financing commitments and the gap between what has been pledged and what has been approved for deployment. Of the USD21.4 billion pledged, only around USD3.1 billion has been approved, with grants constituting only 2.6% of international partners' commitments. This underscores the need to enhance finance mobilisation, improve access to concessional resources, and expedite project implementation (Yustika and Iyer, 2026). Low grant shares have been identified as misalignment between recipient country expectations for early concessional finance and international partners' emphasis on reform conditionality (Do et al., 2026).

Under the baseline scenario, fossil fuels still supply around 85% of total primary energy supply (TPES) and 78% of electricity in 2060, with gas the largest source at around 37% and 61%, respectively. Under the ASEAN Coordinated Transition Scenario (ACTS), the fossil-fuel share falls to 47% in both (ACE, 2026a). Transition planning must therefore account for existing plants, long-term power purchase agreements (PPAs), financing obligations and regulatory frameworks, as Indonesia's planned early retirement of the 660 MW Cirebon-1 coal plant (Yustika and Iyer, 2026). Each retirement should be coordinated with replacement capacity to safeguard energy security (ACE, 2026a), while the ASEAN Mineral Cooperation Action Plan (ACMAP-IV) and the ASEAN Plan of Action for Energy Cooperation (APAEC), both covering 2026–2030, help align critical minerals, industry, and energy planning (APEC Drafting Committee, 2025; ASEAN Secretariat, 2025b).

Battery energy storage systems (BESS) support greater integration of variable renewable energy (VRE) by shifting surplus renewable electricity to periods of high demand or low generation and by providing frequency regulation and other grid services. This improves reliability, reduces curtailment and displaces fossil-fuel generation. However, deployment is restricted by high upfront and replacement costs and uncertain revenues for storage services. Addressing these barriers requires integrated planning, transparent procurement, bankable financing and regional cooperation on standards and recycling (ACE & IEA, 2026).

In road transport, fuel subsidies continue to preferentially support internal combustion engine vehicles (ICEVs). Except in Singapore, electric buses and trucks generally have a higher total cost of ownership (TCO) than ICE equivalents (about USD1.21 versus USD0.87 per km for buses), mainly due to higher purchase and financing costs. Converting motorcycles to electric, however, lowers TCO from 1.66 to 1.16 US cents per km, which is significant for a fleet projected to reach 254 million units by 2040, around 61% in Indonesia. Key strategies include purchase incentives, the gradual elimination of fuel subsidies, reduced charging tariffs, concessional finance for fleet operators and battery leasing for electric buses. Indonesia's USD645 conversion subsidy has had limited uptake owing to high type-testing and re-registration costs for small workshops. Additionally, the development of regional battery recycling ecosystems will be necessary (Al Irsyad et al., 2025).

For hard to electrify sectors, such as aviation and heavy industry, palm oil mill effluent (POME) from the 23.97 million hectares of oil palm in ASEAN could potentially produce 7,342 million m^3 of biogas by 2060, according to a Net Zero scenario. This biogas could be converted into 4,588 million m^3 of biomethane, equivalent to approximately 16.13 TWh of electricity, thereby replacing natural gas. Additionally, it could yield 5.06 million tonnes of biogenic CO_2 for bioenergy with carbon capture and storage (BECCS) and up to 36.69 billion US gallons of e-SAF, contingent upon the availability of sufficient green hydrogen. The cost of e-SAF is projected to decrease from USD1.20–2.30 to USD0.25–0.77 per litre by 2060. Achieving these outcomes necessitates technology trans-

fer, mandates for SAF blending, carbon accounting in accordance with Article 6 of the Paris Agreement, blended finance, and the involvement of smallholders, who manage approximately 40% of the oil palm land (Jupesta et al., 2026). Biofuels, including sustainable aviation fuel (SAF) and sustainable maritime fuel (SMF), can complement electric vehicles in decarbonising transport by drawing on the region's agricultural resources. By 2050, ASEAN's demand could reach 20–22 billion litres of bioethanol, 40 billion litres of biodiesel and 12–13 billion litres of SAF. Complementary production profiles, with biodiesel surpluses in Indonesia and Malaysia and bioethanol deficits in importers such as the Philippines, create scope for intra-ASEAN trade that could lower fuel costs and create over 5,000 jobs. This requires harmonised standards and mutually recognised sustainability certification, potentially through a proposed ASEAN Biofuel Taskforce (ERIA and ACE, 2025). Nuclear energy, including small modular reactors, could provide firm, low-carbon supply for industrial heat and data centres, in line with the ACTS (ACE, 2026a), but public acceptance, regulatory readiness, safety, waste management and high upfront costs require nuclear literacy, public engagement and regional cooperation under APAEC.

Unlocking this potential requires a stable regulatory framework, integrated power-sector planning and risk-adjusted financing, supported by bankable PPAs, guarantees and blended finance (ACE, 2026b). The ASEAN Taxonomy for Sustainable Finance includes criteria for early coal retirement that could enhance its bankability, such as those proposed for Cirebon-1 (ASEAN Taxonomy Board, 2025). However, classification alone is insufficient to bridge the financing gap. Concessional finance is essential to address outstanding Power Purchase Agreement (PPA) obligations and to fund replacement capacity and grid infrastructure. For example, the ASEAN Power Grid Financing (APGF) Initiative brings together regional stakeholders, including the Heads of ASEAN Power Utilities/Authorities (HAPUA), ASEAN energy developers, the World Bank, and the Asian Development Bank (ADB), to support this through cross-border connectivity, renewable integration and coordinated investment (ASEAN Secretariat, 2025a). ASEAN's experience highlights the importance of aligning regulation, planning, investment and regional cooperation. It also illustrates the magnitude of the challenge in achieving rapid transitions.

REFERENCES

Abdullah, A., Oktaqiara, R. and Rahmat, S. N. J. (2026). Global Oil Supply Disruptions and ASEAN Energy Investment: Inflation and Financing Cost Pressures (Policy Brief No. 11). ASEAN Centre for Energy (ACE).

ACE (2026a). 9th ASEAN Energy Outlook 2026–2060. ASEAN Centre for Energy (ACE). https://aseanenergy.org/publications/the-9th-asean-energy-outlook

ACE (2026b). ASEAN Energy Investment 2026. ASEAN Centre for Energy (ACE). https://aseanenergy.org/publications/asean-energy-investment-2026

ACE and IEA (2026). Accelerating Battery Energy Storage System for VRE Integration. ASEAN Centre for Energy (ACE). https://aseanenergy.org/publications/accelerating-battery-energy-storage-system-for-vre-integration

ADB (2026). Asian Development Outlook April 2026: The Middle East Conflict Challenges Resilience in Asia and the Pacific (0 edn). Asian Development Bank. https://doi.org/10.22617/FLS260098-3

Al Irsyad, M. I., Firmansyah, A. I., Harisetyawan, V. T. F., Supriatna, N. K., Gunawan, Y., Jupesta, J., Yaumidin, U. K., Purwanto, J. and Inayah, I. (2025). Comparative total cost assessments of electric and conventional vehicles in ASEAN: Commercial vehicles and motorcycle conversion. Energy for Sustainable Development, 85, 101599. https://doi.org/10.1016/j.esd.2024.101599

APEC Drafting Committee (2025). ASEAN Plan of Action for Energy Cooperation (APAEC) 2026-2030. ASEAN Centre for Energy (ACE). https://aseanenergy.org/publications/asean-plan-of-action-for-energy-cooperation-apaec-2026-2030

ASEAN Secretariat (2025a). ADB and World Bank Group Launch the ASEAN Power Grid Financing Initiative with the ASEAN Secretariat and the ASEAN Centre for Energy (ACE). ASEAN. https://asean.org/adb-and-world-bank-group-launch-the-asean-power-grid-financing-initiative-with-the-asean-secretariat-and-the-asean-centre-for-energy-ace/

ASEAN Secretariat (2025b). ASEAN Minerals Cooperation Action Plan (AMCAP-IV) 2026-2030. The ASEAN Secretariat. https://asean.org/book/asean-minerals-cooperation-action-plan-amcap-iv-2026-2030/

ASEAN Taxonomy Board (2025). ASEAN Taxonomy for Sustainable Finance (Version 4). https://www.sfinstitute.asia/wp-content/uploads/2025/11/ASEAN-Taxonomy-Sustainable-Finance-V4_06Nov25.pdf

Do, T. N., Halimatussadiah, A., Burke, P. J. and Jotzo, F. (2026). Just Energy Transition Partnerships at Risk in Indonesia and Vietnam. Journal of Southeast Asian Economies, 43(1), 100–109. https://doi.org/10.1355/ae43-1e

ERIA and ACE (2025). Biofuel Market Potential for Regional Cooperation in ASEAN. https://www.eria.org/publications/biofuel-market-potential-for-regional-cooperation-in-asean

IEA (2026a). Southeast Asia Energy Outlook 2026. International Energy Agency (IEA). https://www.iea.org/reports/southeast-asia-energy-outlook-2026

IEA (2026b). World Energy Investment 2026. International Energy Agency (IEA). https://www.iea.org/reports/world-energy-investment-2026

Jupesta, J., Akimoto, K., Sahari, B., Wiloso, E. I., Boer, R., Gheewala, S. H. and Dohong, A. (2026). Innovation and technology for bioeconomy transition: Assessing BECCS and e-fuel potential from oil palm residues in Southeast Asia. United Nations Economic and Social Commission for Asia and the Pacific (ESCAP).

Yustika, M. and Iyer, R. N. (2026). Building credibility in Indonesia's energy transition: Insights from the ETM and JETP Indonesia [Briefing Note]. Institute for Energy Economics and Financial Analysis (IEEFA). https://ieefa.org/resources/building-credibility-indonesias-energy-transition-insights-etm-and-jetp-indonesia

4.2 ECONOMIC ENABLERS AND BARRIERS

4.2.1. Adequate, predictable and affordable finance

Access to stable and affordable finance varies significantly across countries. Developing countries face a deficit in adequate, predictable and affordable climate finance. Moreover, the higher cost of capital is also a potential barrier (Calcaterra et al., 2024; Nor and Mohamed, 2024). Developing countries face borrowing costs averaging approximately 14%, compared with 1–4% for reserve-currency issuers, disproportionately impacting capital-intensive clean energy projects. With one-third of developing countries at high risk of debt distress, debt-servicing pressures also constrain public investment in grids, storage and social protection (Songwe et al., 2022).

The commitment to mobilise USD100 billion annually by 2020 was met only in 2022 (Songwe et al., 2022; OECD, 2026). At COP29, it was superseded by the New Collective Quantified Goal (NCQG) of at least USD300 billion annually by 2035, led by developed countries, alongside a broader effort to scale finance from all sources to USD1.3 trillion annually (UNFCCC, 2025b). However, there are challenges both at the macro and micro levels in enabling clean finance flows. While the ability to undertake larger public expenditure on clean energy investments in developing countries is partly constrained by the requirements for expenditure on other national development priorities such as public health, education etc., apart from additional costs of clean technologies, costs of re-skilling/ training etc. are also needed for supporting rapid transitions. Capacity across sectors to projectize climate finance flows also remains weak in developing countries.

The terms and distribution of finance also matter. Between 2016 and 2020, loans constituted 72% of public climate finance and grants only 26% (Songwe et al., 2022). Support remains concentrated in middle-income countries: assistance to low-income countries declined from USD11.1 billion in 2022 to USD9.6 billion in 2024 (OECD, 2026).

Increased grants and concessional finance, larger bilateral contributions, expanded multilateral development bank lending and debt-for-climate swaps can help address these constraints (Songwe et al., 2022). Stable funding aligned with recipients' needs improves predictability (Nor and Mohamed, 2024), while guarantees and local-currency lending can reduce financing costs (ACE, 2026). Financing for R&D for adoptive technologies to scale operation is also necessary. Reforms to the multilateral financial architecture are needed to prevent transition costs falling disproportionately on countries least equipped to bear them.

4.2.2. Economic restructuring and development opportunities

Fossil fuels have contributed to growth, industrialisation, employment, export earnings and tax revenues across economies. However, rapid shifts at scale at a country level can have very different implications for some developing countries which might require transitioning to new sources of economic activity and public revenue, or managing the impacts on existing supply chains and extraction-dependent communities (Songwe et al., 2022). Moreover, new economic activities such as setting up of data centres are associated with additional resource sustainability issues cutting across land, water and clean energy considerations (Xiao et al., 2025). Countries must also manage potentially stranded assets, including recently constructed infrastructure, through repurposing or retirement to prevent carbon lock-in. Early coal phase-out entails lost revenues, decommissioning expenses and just transition support, particularly in major producing countries such as South Africa, Indonesia and India (Songwe et al., 2022).

Transition initiatives can support restructuring by improving energy access, generating employment and reducing fuel import costs. Transition costs however entail not only the clean technology costs, but also the costs of providing the supporting infrastructure. Annual finance flows for energy transformation in emerging and developing economies excluding China remain at USD500–600 billion, compared with estimated requirements of USD1.3–1.7 trillion by 2030 (Songwe et al., 2022). Predictable external support should reflect countries' differing capacities to bear the full transition costs, not limited to technology costs alone, but the ecosystem to support the transition.

Managing existing assets requires assessing whole-system costs, including flexible plant operation, co-firing, sequenced retirement and backup capacity during the transition (Songwe et al., 2022)

Affordability continues to remain a key factor driving the transition. As countries strive to provide access to clean and affordable energy to all, shifting subsidies to promote cleaner energy can enable faster shifts to cleaner choices. Additionally, higher upfront costs of low carbon options can become an affordability issue for consumers and would need to be managed innovatively. There is also a risk of making currently affordable energy services unaffordable, suppressing real incomes of people. Innovative policies and measures could help overcome such hurdles by spreading the costs as payment for services, or providing incentives for cleaner technology choices such as buy-back schemes for ICE vehicles.

One-third of all developing countries and two-thirds of low-income countries are at high risk of debt distress. Addressing these challenges requires a comprehensive approach with a suite of solutions including expanded access to low-cost official liquidity facilities, expanding the envelope of low-cost and debt-free finance, managing the risks of adequate liquidity, strengthening the role of central banks and regulators in the drive to net zero and creating more partnerships to scale up green finance. High-integrity cooperation under Article 6 can also mobilise debt-free finance (Songwe et al., 2022)

Closing the investment gap depends not only on mobilising more supply-side finance, demand-side options can reduce the new supply needs that must be financed and the affordability pressures it creates. Low energy demand scenarios indicate that final energy could fall by about 40% by 2050 while living standards rise, particularly in the Global South, and that this would reduce reliance on carbon dioxide removal (Grubler et al., 2018; Edelenbosch et al., 2024); similar magnitudes appear in other work, such as a 50% reduction for Europe (Wiese et al., 2024), and are consistent with the decent-living estimates in Section 3.4.

BOX 6: AFRICA'S ENERGY CROSSROADS: TAFF, DEVELOPMENT AND THE DOUBLE TRANSITION

Authors: Youba Sokona, Yacob Mulugetta, Meron Tesfamichael, Philipp Trotter, Benard Wabukala, Mark Akrofi, Nibwene Mwakibinga, Jesse Burton, Vera Songwe

The key role of national context for African energy transition pathways. Africa's 54 countries enter the transition away from fossil fuels (TAFF) from widely varied starting points. Some are major oil and gas exporters whose public finances depend on hydrocarbon revenues, such as Nigeria, Angola and Algeria; others, such as Kenya and Ethiopia, depend on imported fuels. South Africa's power system is dominated by coal, while Ethiopia, the Democratic Republic of Congo and Zambia rely largely on hydropower, and Kenya draws much of its electricity from geothermal. North African countries and Mauritius have near-universal electricity access, while in countries such as South Sudan and Chad most people remain without it. What unites them is a development paradox. Africa possesses exceptional solar, wind, hydropower and geothermal resources plus substantial oil and gas (IEA, 2022, 2025a). Yet millions of Africans lack electricity to power their development aspirations and cook with polluting fuels, contributing to an estimated 815,000 premature deaths annually (IEA, 2025b, 2025c). These energy deficits sit alongside high climate vulnerability, constrained fiscal space and substantial unmet wellbeing needs (IEA, 2022).

Recent solar growth makes the paradox more striking. Africa is set to install a record 17 GW of solar in 2026, 45% more than in 2025 (Ember and African Tech Futures Lab, 2026). Much of it is distributed solar, installed by households and businesses outside formal planning systems and poorly captured in official statistics. Yet this dynamism does not automatically deliver universal access, stronger public electricity systems or displace charcoal and fuelwood.

African countries thus confront two connected but distinct transitions. The first is TAFF within established energy systems. Oil products account for roughly two-thirds of Africa's final fossil-fuel consumption, linking TAFF in many countries to lower import bills and electrified mobility, as illustrated by Ethiopia's 2024 ban on combustion-vehicle imports (AFREC, 2025; IEA, 2026). For fossil-fuel producers, it also requires economic diversification and an equitable transition for producing regions (Foster et al., 2024). Pathways will therefore reflect national starting points, endowments and capabilities (Figure B6). Development needs do not create an automatic case for fossil-fuel expansion (IEA, 2022). In South Africa, high fossil-fuel consumption coexists with energy poverty and inequality, while low emissions elsewhere may reflect deprivation rather than decarbonisation (Mulugetta et al., 2022). Second, energy transition in Africa goes beyond TAFF. Expanding modern energy services to replace traditional biomass for cooking is a fundamental development imperative in Africa, with transformative health and livelihood benefits, even though assessed pathways include LPG as a fossil fuel alongside electricity (IEA, 2025b).

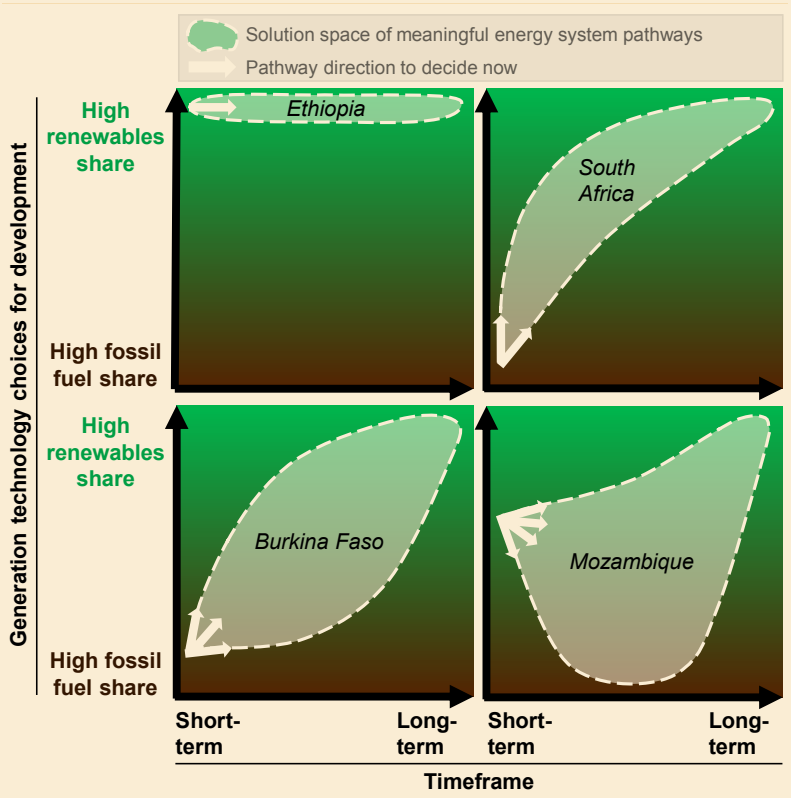


Figure B6. Different starting points, different pathway uncertainties Schematic energy-generation pathways and solution spaces for Ethiopia, South Africa, Burkina Faso and Mozambique; larger shaded areas indicate greater uncertainty about development-oriented pathways. Pathways are illustrative, not forecasts. Source: Mulugetta et al. (2022).

Context-specific TAFF as a development opportunity. Many NDC actions across Africa depend on limited international finance, technology and capacity support, leaving countries reliant on scarce domestic resources. The African Union (AU)'s Climate Change and Resilient Development Strategy and Action Plan (2022–2032) calls for equitable and transformative low-emission, climate-resilient development, supported by stronger governance, finance, technology and regional cooperation (AU, 2022b). Together with the AU Common Position, it places energy access within a wider agenda of adaptation, low-emission development and regional integration (AU, 2022a, 2022b). The first global stocktake calls for a just, orderly and equitable TAFF (UNFCCC, 2024). TAFF should therefore be judged not only through emissions but by its contribution to three broad development outcomes: livelihoods, inclusive industrialisation and urban transformation (Sokona et al., 2023).

→ **Powering livelihoods.** For households and small enterprises, TAFF means replacing diesel, kerosene and biomass with reliable renewable energy and clean cooking that enable irrigation, cold storage, milling, lighting and electric mobility. Income gains depend not simply on being connected to the grid, but on reliable, affordable and adequate electricity that can be used productively (Ngowi et al., 2019).

→ **Inclusive industrialisation.** Cost-effective and rapidly scalable renewable energy is a competitive input for African economies that creates substantial economic opportunity, especially when combined with their mineral endowments and expanding regional markets. Opportunities include local value chains in agro-processing, electric appliances, grid equipment, mineral processing and low-emissions materials that reduce raw-material export dependence (IEA, 2025a; Sokona et al., 2023).

→ **Urban transformation.** Africa's rapidly growing cities can avoid locking in energy-intensive and unequal development if TAFF-informed energy planning is integrated with housing, mobility, land use and public services. Evidence supports compact development, public transport, walking, cycling and low-carbon electrification, with paratransit vital to poorer residents' livelihoods (Jaramillo et al., 2023; Randall et al., 2023; Stokenberga et al., 2025).

Shaping the transition for development. Realising these opportunities requires more than mobilising capital. It depends on where investment goes. Livelihoods, industrialisation and urban transformation each need finance directed to specific energy services: productive uses and clean cooking in rural and informal economies, reliable and competitively priced power for industrial zones and regional value

chains, and integrated energy, housing and mobility infrastructure in growing cities. These areas generate substantial social and developmental value but are often poorly served by prevailing investment criteria, which favour lower-risk, quicker-return projects (Moses, 2023; Ngowa et al., 2024; SEforALL and Climate Policy Initiative, 2020). Africa receives only about 2% of global clean-energy investment (IEA, 2025c), reflecting high financing costs, debt burdens, currency risks and wider inequalities in the allocation of international capital. Concessional and grant-based finance, guarantees and appropriate risk-sharing mechanisms can lower financing costs, while debt restructuring, local-currency lending and stronger domestic financial institutions can expand the room for public and productive investment (Calcaterra et al., 2024; IEA, 2024; Sokona et al., 2023; UNECA, 2024). But lower-cost capital alone will not reach these priorities. Small, dispersed productive-use investments need aggregation and blended finance; industrial energy needs development-bank lending tied to industrial policy and local value retention; and cities need access to municipal and subnational infrastructure finance.

Directing these flows depends on the capacity of African states and institutions to steer finance, technology and infrastructure towards development priorities and retain more of the value they create. Continued fossil investment carries revenue and stranded-asset risks (IEA, 2022; Müller et al., 2023), while an externally oriented transition could reproduce extractive patterns without building domestic capabilities (de Sousa et al., 2026). National strategies should therefore connect energy and climate goals with industrial development, urban planning, technological learning and local and regional value creation (AU, 2022a, 2022b; IEA, 2024; IRENA, 2024). Stronger African-owned research and institutions are equally important for defining priorities and shaping these choices (Mulugetta et al., 2022).

Africa illustrates why TAFF must be guided by equity and differentiation. Where access deficits are severe, early fossil-fuel reductions may be more gradual while investment in clean electricity, networks and institutions accelerates; higher-consuming, more capable countries should move faster. A credible Paris-aligned pathway must combine faster fossil-fuel reductions by historically high-emitting countries with the finance, technology and policy space for African countries to pursue context-specific low-carbon structural transformation.

REFERENCES

AFREC (2025). Key Africa Energy Statistics 2025. African Energy Commission (AFREC). https://au-afrec.org/sites/default/files/2026-02/KAES_English_2025_1.pdf

AU (2022a). Africa Speaks with Unified Voice as AU Executive Council Adopts African Common Position on Energy Access and Just Energy Transition. African Union. https://au.int/en/pressreleases/20220722/africa-speaks-unified-voice-au-executive-council-adopts-african-common

AU (2022b). African Union Climate Change and Resilient Development Strategy and Action Plan (2022-2032). African Union. https://au.int/en/documents/20220628/african-union-climate-change-and-resilient-development-strategy-and-action-plan

Calcaterra, M., Aleluia Reis, L., Fragkos, P., Briera, T., De Boer, H. S., Egli, F., Emmerling, J., Iyer, G., Mittal, S., Polzin, F. H. J., Sanders, M. W. J. L., Schmidt, T. S., Serebriakova, A., Steffen, B., Van De Ven, D. J., Van Vuuren, D. P., Waidelich, P. and Tavoni, M. (2024). Reducing the cost of capital to finance the energy transition in developing countries. Nature Energy, 9(10), 1241–1251. https://doi.org/10.1038/s41560-024-01606-7

de Sousa, N., Klug, T., Mbwette, S., Mwakibinga, N., Ndaw, A. C. and Nweke-Eze, C. (2026). New Visions to Replace Fossil Fuel Revenues in Angola, Senegal and Tanzania. Fossil Fuel Treaty Initiative. https://www.fossilfueltreaty.org/s/New-Visions-to-Replace-Fossil-Fuel-Revenues-in-Angola-Senegal-and-Tanzania.pdf

Ember, and African Tech Futures Lab (2026). The take-off in African solar that official statistics can't yet see. Ember. https://ember-energy.org/latest-insights/the-take-off-in-african-solar-that-official-statistics-cant-yet-see/

Foster, V., Trotter, P. A., Werner, S., Niedermayer, M., Mulugetta, Y., Achakulwisut, P., Brophy, A., Dubash, N. K., Fankhauser, S., Hawkes, A., Hirmer, S., Jenkins, S., Loni, S., McGivern, A., Nanthavong, K., Probst, B., Pye, S., Russo, V., Semieniuk, G., … Yang, P. (2024). Development transitions for fossil fuel-producing low and lower-middle income countries in a carbon-constrained world. Nature Energy, 9(3), 242–250. https://doi.org/10.1038/s41560-023-01440-3

IEA (2022). Africa Energy Outlook 2022: Key findings. International Energy Agency. https://www.iea.org/reports/africa-energy-outlook-2022/key-findings

IEA (2024). Clean Energy Investment for Development in Africa: Status and opportunities. International Energy Agency (IEA). https://www.iea.org/reports/clean-energy-investment-for-development-in-africa/executive-summary

IEA (2025a). Stepping Up the Value Chain in Africa: Minerals, materials and manufacturing. International Energy Agency (IEA). https://www.iea.org/reports/stepping-up-the-value-chain-in-africa/executive-summary

IEA (2025b). Universal Access to Clean Cooking in Africa: Progress Update and Roadmap to Implementation. International Energy Agency (IEA). https://www.iea.org/reports/universal-access-to-clean-cooking-in-africa/executive-summary

IEA (2025c). World Energy Investment 2025. International Energy Agency (IEA). https://www.iea.org/reports/world-energy-investment-2025/africa

IEA (2026). Ban on import of internal combustion engine vehicles: Policies database entry (Ethiopia). International Energy Agency (IEA). International Energy Agency. https://www.iea.org/policies/30386

IRENA (2024). Sub-Saharan Africa: Policies and finance for renewable energy deployment. International Energy Agency (IEA). https://www.irena.org/Publications/2024/Jul/Sub-Saharan-Africa-Policies-and-finance-for-renewable-energy-deployment

Jaramillo, P., Kahn Ribeiro, S., Newman, P., Dhar, S., Diemuodeke, E. O., Kajino, T., Lee, D. S., Nugroho, S. B., Ou, X., Hammer Strømman, A. and Whitehead, J. (2023). Transport. In Climate Change 2022 — Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (1st edn, pp. 1049–1160). Cambridge University Press. https://doi.org/10.1017/9781009157926.012

Moses, O. (2023). Who Finances Energy Projects in Africa? [Working Paper]. Carnegie Endowment for International Peace. https://carnegieendowment.org/research/2023/11/who-finances-energy-projects-in-africa

Müller, M., Schulze, M. and Schöneich, S. (2023). The energy transition and green mineral value chains: Challenges and opportunities for Africa and Latin America. South African Journal of International Affairs, 30(2), 169–175. https://doi.org/10.1080/10220461.2023.2230957

Mulugetta, Y., Sokona, Y., Trotter, P. A., Fankhauser, S., Omukuti, J., Somavilla Croxatto, L., Steffen, B., Tesfamichael, M., Abraham, E., Adam, J.-P., Agbemabiese, L., Agutu, C., Aklilu, M. P., Alao, O., Batidzirai, B., Bekele, G., Dagnachew, A. G., Davidson, O., Denton, F., … Yussuff, A. (2022). Africa needs context-relevant evidence to shape its clean energy future. Nature Energy, 7(11), 1015–1022. https://doi.org/10.1038/s41560-022-01152-0

Ngowa, A., Chen, X. and Ireri, B. (2024). Unlocking Local Private Capital to Finance the Productive Use of Renewable Energy (PURE) Sector — a Look at East African Local Financial Institutions (LFIs). World Resources Institute. https://doi.org/10.46830/wriwp.23.00102

Ngowi, J. M., Bångens, L. and Ahlgren, E. O. (2019). Benefits and challenges to productive use of off-grid rural electrification: The case of mini-hydropower in Bulongwa-Tanzania. Energy for Sustainable Development, 53, 97–103. https://doi.org/10.1016/j.esd.2019.10.001

Randall, L., Brugulat-Panés, A., Woodcock, J., Ware, L. J., Pley, C., Abdool Karim, S., Micklesfield, L., Mukoma, G., Tatah, L., Dambisya, P. M., Matina, S. S., Hambleton, I., Okello, G., Assah, F., Anil, M., Kwan, H., Awinja, A. C., Pujol-Busquets Guillén, G. and Foley, L. (2023). Active travel and paratransit use in African cities: Mixed-method systematic review and meta-ethnography. Journal of Transport & Health, 28, 101558. https://doi.org/10.1016/j.jth.2022.101558

SEforALL and Climate Policy Initiative. (2020). Energizing Finance: Understanding the Landscape 2020. Sustainable Energy for All (SEforALL). https://www.seforall.org/system/files/2020-11/EF-2020-UL-SEforALL_0.pdf

Sokona, Y., Mulugetta, Y., Tesfamichael, M., Kaboub, F., Hällström, N., Stilwell, M., Adow, M. and Besaans, C. (2023). Just Transition: A Climate, Energy and Development Vision for Africa. https://justtransitionafrica.org/wp-content/uploads/2023/05/Just-Transition-Africa-report-ENG_single-pages.pdf

Stokenberga, A., Saïsset, E., Kerzhner, T. and Espinet Alegre, X. (2025). Connecting through public transport: Accessibility to health and education in major African cities. Area Development and Policy, 10(2), 210–227. https://doi.org/10.1080/23792949.2024.2364619

UNECA (2024). Economic Report on Africa 2024: Investing in a Just and Sustainable Transition in Africa. United Nations Economic Commission for Africa. https://doi.org/10.18356/9789213589373

UNFCCC (2024). Report of the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement on its fifth session, held in the United Arab Emirates from 30 November to 13 December 2023 (FCCC/PA/CMA/2023/16/Add.1). United Nations Framework Convention on Climate Change (UNFCCC). https://unfccc.int/sites/default/files/resource/cma2023_16a01_adv_0.pdf

4.3 INSTITUTIONAL ENABLERS AND BARRIERS

4.3.1. Implementation capacity and coordination

Rapid transitions require developing capabilities across several domains to create a supportive ecosystem of supply networks, strong governance systems, and efficient coordination across multiple national and sub-national departments. Discrepancies across government levels can foster local resistance (Shen and Tai, 2024), while complex international financing procedures disadvantage countries with limited administrative resources (Nor and Mohamed, 2024). Transition challenges may also arise due to resistance by labour unions, dominance of state enterprises that resist change, power sector market design and dependence of (sub-national) governments on revenues and jobs from the fossil industry (Chaturvedi, 2021).

Institutional weaknesses also limit the provision of training, skilling and reskilling, constraining workforce availability and slowing clean technology adoption (Pereira et al., 2025). Accordingly, weak administrative capacity and coordination can prevent financially supported, technically viable plans from being implemented. While affecting feasibility of implementation, state capacity remains insufficiently recognised in transition policymaking (Singh, 2023). Strengthening technical and administrative capacity, alongside multi-level governance that supports national implementation and public participation, can address these barriers. International cooperation and learning from best practices across regions could also be useful.

Challenges may also arise with government-imposed limits on production of fossil fuels as this could lead to claims from investors for compensation, including for lost future profits in investor-state dispute settlements. It is estimated that global action on climate change could lead to more than USD340 billion in legal claims from oil and gas investors (Tienhaara et al., 2022).

4.3.2. International trade and policy space

International trade, environmental and technology regulations interact with each other in shaping the policy space for developing countries to pursue low carbon development pathways and for developed countries to pursue green growth strategies. Policy measures such as trade and technology restrictions, subsidies exclusive to domestic industries, and privileged access to markets and technologies can have a variety of motivations and multiple effects on the global energy transition.

Border carbon adjustment mechanisms in conjunction with emissions pricing for industry, such as the CBAM implemented by the EU (Böhringer et al., 2022) are motivated by the idea of leveling the playing field for emissions intensive trade exposed industries between domestic and international producers to address carbon leakage risks, the desire to reduce or eliminate free allocation of emissions permits to industry, and also as a mechanism to incentivise low-carbon technology adoption. Groups of countries could benefit from graduated yet harmonised carbon pricing for heavy industry combined with border carbon adjustments, including in coalitions that might include developing countries (Wolfram et al., 2026)

Border carbon adjustments are contested. The EU's CBAM is often viewed as a protectionist measure. Particular modes of implementation may not be WTO compatible, and developing countries have raised concerns regarding accounting challenges related with implementing the CBAM, as well as

regarding compatibility with the UNFCCC principle of common but differentiated responsibilities. While border carbon adjustments could reduce competitiveness of emissions intensive exporting producers, domestic carbon pricing mechanisms implemented gradually could help reduce these impacts (Ren et al., 2025). Carbon pricing provides comprehensive incentives to invest in low-emissions production facilities which can achieve competitive advantages in export markets with emissions pricing and border adjustments.

An open, rules-based trading system can facilitate implementation of the Paris Agreement. It can help countries progressively raise their national climate commitments, aligned with CBDR-RC and long-term climate goals, preventing a split between high- and low-ambition regions and reducing the need for trade measures to protect domestic climate action. Retaining open, rules-based trading globally would also mitigate broader concerns about weaponisation of trade and economic exchange.

BOX 7: BRAZIL: A RENEWABLE-RICH ENERGY SYSTEM FACING THE CHALLENGE OF TRANSITIONING AWAY FROM FOSSIL FUELS

Authors: Gilberto de Martino Jannuzzi, Mayara Melo, Alexandre Szklo, Luiz Bernardo Baptista, Andre Lucena

Brazil enters the transition away from fossil fuels (TAFF) from a distinctive position among major economies. In 2025, renewables accounted for 49.4% of domestic energy supply and 86.8% of electricity supply, with wind and solar providing 26.4% of electricity generation (EPE, 2026a). This renewable-rich power system offers a strong foundation for electrification and sector coupling, although significant structural challenges remain.

Policy and development objectives. Brazil's Nationally Determined Contribution (NDC) targets net greenhouse gas (GHG) emission reductions of 53% by 2030 and 59–67% by 2035, relative to 2005, and net-zero emissions by 2050 (BRASIL, 2024a). The National Energy Transition Policy (PNTE), National Energy Transition Plan (Plante), and Climate Plan provide an institutional framework for these objectives (EPE, 2026b).

Barriers. Brazil's central challenge is the coexistence of renewable-energy expansion and continued fossil-fuel production. In 2025, petroleum production averaged 3.8 million barrels per day, while natural-gas production increased by 16.7% (ANP, 2026a). Oil and petroleum products accounted for 33.7% of domestic energy supply, and natural gas for another 10.3%. Despite Brazil's established biofuel industry, renewables supplied only 26.1% of transport energy consumption (EPE, 2026a). Road freight remains heavily dependent on diesel, while electric passenger vehicles represent an emerging but still limited alternative.

Economic dependence extends beyond energy consumption. Oil and gas support exports, employment, industrial activity, taxation and innovation financing. Oil royalties alone reached BRL62.2 billion in 2025 (ANP, 2026b). Fossil-fuel phase-down therefore requires economic diversification, fiscal adaptation and alternative revenue sources, while safeguarding energy affordability, security and climate resilience (Jannuzzi, 2026a).

Opportunities. Brazil can leverage its low-carbon electricity system to accelerate transport and industrial electrification, supported by energy efficiency, demand-side management and sustainable fuels for hard-to-abate sectors. Promising pathways include biogas, biomethane, advanced biofuels, low-carbon hydrogen and bioenergy with carbon capture and storage (BECCS) (Jannuzzi, 2026b; EPE, 2021; EPE, 2022; Meneghini et al., 2021; Tagomori et al., 2018). The Fuel of the Future Law (Law No. 14,993/2024) supports low-carbon fuels, including sustainable aviation fuels and renewable diesel (BRASIL, 2024b). Beyond energy uses, reducing petroleum dependence in petrochemicals requires alternative feedstocks, material efficiency and circular-economy solutions (IEA, 2018). National Energy Plan 2055 scenarios also suggest that collective transport could increase from 29% to up to 50% of passenger transport activity by 2055 (EPE, 2026c).

Biomass in transport and industry. Biomass remains central to Brazil's non-electric renewable supply. In 2025, ethanol and biodiesel provided approximately 19.6% and 6.3% of transport energy consumption, respectively, while biomass accounted for roughly 44% of industrial energy use (EPE, 2026a). However, substantial industrial biomass consumption occurs within biomass-processing industries themselves, particularly sugar and ethanol production, and does not necessarily indicate widespread fossil-fuel substitution across industrial subsectors (Fioranelli and Bizzo, 2023). Further expansion requires sustainable feedstocks and

safeguards for land use and food security.

Critical minerals and industrial development. Brazil's substantial reserves of niobium, graphite, nickel, manganese and other critical minerals offer opportunities to develop domestic processing, battery materials and renewable-energy equipment manufacturing (CGEP, n.d.; PwC BRASIL, 2025). Capturing these opportunities requires industrial policy, financing, technological capabilities and regulatory stability (PIIE, 2026).

Implications for TAFF. Brazil demonstrates that a high renewable-energy share does not necessarily translate into declining fossil-fuel dependence. A successful transition requires coordinated changes in energy demand, infrastructure, industrial production and fiscal governance. Electrification, efficiency, sustainable biomass and critical-mineral value chains can support decarbonization, but addressing petroleum dependence and ensuring social equity remain essential for a just and economically sustainable transition (Jannuzzi, 2024).

REFERENCES

ANP (2026a). Brazilian Statistical Yearbook of Petroleum, Natural Gas and Biofuels 2026. ANP — Agência Nacional do Petróleo, Gás Natural e Biocombustíveis. https://www.gov.br/anp/pt-br/centrais-de-conteudo/publicacoes/anuario-estatistico/anuario-estatistico-brasileiro-do-petroleo-gas-natural-e-biocombustiveis-2026

ANP (2026b). Royalties. Tables of monthly royalties distributed to beneficiaries, 2025. Brasília: ANP. ANP — Agência Nacional do Petróleo, Gás Natural e Biocombustíveis. https://www.gov.br/anp/pt-br/assuntos/royalties-e-outras-participacoes/royalties

BRASIL, Law No. 14,993, of 8 October 2024. Establishes the Fuel of the Future Program and Related measures for low-Carbon fuels and Energy transition (2024b). mbustiveis/combustivel-do-futuro/law-no-14-993-of-october-8-2024

BRASIL (2024a). Brazil's Nationally Determined Contribution (NDC): National determination to contribute and transform. Brasília: Government of Brazil. https://www.gov.br/mma/pt-br/assuntos/noticias/nova-ndc-do-brasil-representa-paradigma-para-o-desenvolvimento-do-pais-diz-marina-na-cop29/apresentacao-sobre-a-nova-ndc.pdf

CGEP (n.d.). Brazil's Potential Role in Diversifying US Critical Mineral Supply. CGEP — Center on Global Energy Policy, Columbia University SIPA. New York: Columbia University SIPA. Retrieved https://www.energypolicy.columbia.edu/publications/brazils-potential-role-in-diversifying-us-critical-mineral-supply/

EPE (2021). Bases para a Consolidação da Estratégia Brasileira do Hidrogênio (Foundations for the Consolidation of the Brazilian Hydrogen Strategy). EPE — Empresa de Pesquisa Energética. Rio de Janeiro: MME/EPE. https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-569/Hidroge%CC%82nio_23Fev2021NT%20%282%29.pdf

EPE (2022). Hidrogênio Turquesa: Produção a partir da pirólise do gás natural (Turquoise Hydrogen: Production from Natural Gas Pyrolysis). EPE — Empresa de Pesquisa Energética. Nota Técnica EPE/DPG/SPG/01/2022. Rio de Janeiro: MME/EPE. https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-663/Nota%20Tecnica%20Hidrogenio%20Turquesa_12.04.22.pdf

EPE (2026a). Brazilian Energy Balance 2026: Summary Report — Base Year 2025. EPE — Empresa de Pesquisa Energética. Rio de Janeiro: EPE. https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/Balanco-Energetico-Nacional-2026

EPE (2026c). National Energy Plan 2055: Perspectives for Brazil's Future Energy System — Summary Report. EPE — Empresa de Pesquisa Energética. Rio de Janeiro: EPE. https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-865/topico-844/PNE%202055_Caderno%20S%C3%ADntese_Fevereiro%202026_Vers%C3%A3o%20Consulta%20P%C3%BAblica.pdf

EPE (2026b). Prepared with technical support from EPE, the National Energy Transition Plan is open for public consultation. EPE — Empresa de Pesquisa Energética. Rio de Janeiro: EPE. https://www.epe.gov.br/pt/imprensa/noticias/elaborado-com-apoio-tecnico-da-epe-plano-nacional-de-transicao-energetica-e-aberto-a-consulta-publica

Fioranelli, A. and Bizzo, W. A. (2023). Renewable and Sustainable Energy Reviews. Generation of Surplus Electricity in Sugarcane Mills from Sugarcane Bagasse and Straw: Challenges, Failures and Opportunities, 186, 113647. https://doi.org/https://doi.org/10.1016/j.rser.2023.113647

IEA (2018). The future of petrochemicals: Towards more sustainable plastics and fertilisers. IEA - International Energy Agency. https://doi.org/https://doi.org/10.1787/9789264307414-en

Jannuzzi, G. M. (2024). Ciência & Cultura. Transição Energética No Brasil (Energy Transition in Brazil), 76(3). http://cienciaecultura.bvs.br/scielo.php?script=sci_arttext&pid=S0009-67252024000300004

Jannuzzi, G. M. (2026a). Ciência & Cultura. Recursos Humanos Para Uma Transição Energética Justa e Ambientalmente Sustentável (Human Resources for a Just and Environmentally Sustainable Energy Transition), 77(4). https://cienciaecultura.bvs.br/scielo.php?script=sci_arttext&pid=S0009-67252025000400004

Jannuzzi, G. M. (2026b). O Planejamento de Oportunidades para a Expansão de Serviços Energéticos, Eficiência e Transição no Brasil (Planning Opportunities for the Expansion of Energy Services, Efficiency, and Energy Transition in Brazil).

Meneghini, J. R. et al. (2021). Desenvolvimento de Hidrogênio de Baixo Carbono no Brasil: Hidrogênio Azul e Turquesa (Development of Low-Carbon Hydrogen in Brazil: Blue and Turquoise Hydrogen). Relatório Técnico BEP / RCGI / Governo do Reino Unido.

PIIE (2026). Geology is not destiny: Brazil must establish an infrastructure to exploit its critical minerals wealth [PIIE — Peterson Institute for International Economics]. Realtime Economics Blog. https://www.piie.com/blogs/realtime-economics/2026/geology-not-destiny-brazil-must-establish-infrastructure-exploit-its

PwC BRASIL (2025). Brazil in the age of critical minerals: A new energy order. PwC BRASIL. https://www.pwc.com.br/pt/estudos/setores-atividades/mineracao-e-siderurgia/2025/tl-cop30-minerais-criticos-EN.pdf

Tagomori, I. S. et al. (2018). Designing an optimum carbon capture and transportation network by integrating ethanol distilleries with fossil-fuel processing plants in Brazil. Designing an Optimum Carbon Capture and Transportation Network by Integrating Ethanol Distilleries with Fossil-Fuel Processing Plants in Brazil, 68, 112–127. https://doi.org/10.1016/j.ijggc.2017.10.013

4.4 DISTRIBUTIONAL ENABLERS AND BARRIERS

4.4.1. Social protection and access to opportunities

Just transition requires decarbonising economies in a fair and inclusive manner, creating decent livelihood opportunities and leaving no one behind. However, transition costs and benefits are unevenly distributed across countries, regions and social groups (Carballo et al., 2026). Where institutions and social protection are weak, employment losses, income reductions and energy-price changes become more pronounced, undermining public support.

Coal workers can face particular barriers to reskilling because many come from underprivileged castes/classes and lack access to formal education (Prajapati et al., 2026). Limited training infrastructure and alternative employment opportunities can deepen social and regional inequalities.
Just transition strategies integrating social protection, accessible reskilling and community engagement can help maintain public support (Songwe et al., 2022). Institutional networks must reflect socioeconomic realities and include underrepresented and excluded groups (Ahmed et al., 2025).

4.4.2. Natural resources and competing land uses

Renewable energy and transmission infrastructure require land and water that may compete with agriculture, food security, urbanisation and conservation. Siting conflicts arise even where land is abundant (Richardson et al., 2022), and nationally supported transitions can encounter local opposition (Shen and Tai, 2024). In densely populated, agrarian developing countries, these conflicts can increase costs and delay projects. Community engagement is therefore relevant to infrastructure siting as well as the wider distribution of transition costs and benefits.

4.4.3. Equitable access to the remaining carbon budget

Developed countries have historically consumed a disproportionate share of the carbon budget, while many developing countries have low per capita emissions and substantial unmet development needs. This creates differentiated responsibilities under climate justice principles (Songwe et al., 2022; Nor and Mohamed, 2024). Requiring countries to meet equitable allocations solely through domestic action creates a pronounced trade-off between equity and efficiency, highlighting the need for international cooperation and financial support (Pelz et al., 2026) This is also quantified in section 3.4.3 (see figure 3.8).

TECHNICAL ANNEX: SCENARIO PATHWAYS EVALUATION AND SELECTION

Scenario source. The pathways in Section 3 are drawn from the Scenario Compass Initiative (SCI), a community effort to continuously collect, curate and assess global emissions scenarios, with annual updates and transparent vetting against observations (Riahi et al., 2026). Building on the ~1,200 pathways compiled for IPCC AR6, SCI adds ~450 scenarios published since then (~1,700 total). These are **new relative to AR6** in that they start from the energy system as observed in 2025, reflect recent clean-technology cost declines and the limited scale-up of fossil CCS, and use models with improved near-term, sectoral and regional detail. Because post-2020 emissions kept rising, the lowest-warming AR6 pathways are no longer attainable and the resulting solution space is narrower.

Scenarios shown in the figures. The main figures use the SCI "high-ambition" set: scenarios that pass historical vetting against 2025 data, raise no major feasibility, and fall into the warming category **GW2a** (peak warming below 1.7°C with 50% likelihood, return to below 1.5°C by 2100 with 50% likelihood; see Riahi et al for full definition). This yields **eight pathways** from three modelling systems (AIM, IMAGE, REMIND-MAgPIE) across three studies — ScenarioMIP/CMIP7 (van Vuuren et al., 2026), NGFS (2025) and Rescuing 1.5°C (Climate Analytics and PIK, 2025). Two are highlighted as illustrative: **HAP A** (REMIND-MAgPIE, Very Low/SSP1; fossil-free) and **HAP B** (AIM, Very Low/SSP2), shown alongside the IEA Net Zero Emissions by 2050 (IEA, 2025e) reference. There is a total of 239 AR6 pathways meeting the same peak-warming definition (below 1.7°C, returning to 1.5°C by 2100), which are shown for comparison in Figure 3.1 and Tables 3.1, 3.2. For comparison, also scenarios with peak warming exceeding 1.7°C but limiting warming to below 2°C with >67% likelihood (GW3) are considered (N = 21).

Scenario evaluation criteria (Verpoort et al., 2026; see also documentation) comprise

→ Historical vetting for consistency with observed CO_2 emissions, primary energy (coal, gas, oil, nuclear) and final energy in 2020 and 2025;

→ Feasibility concerns raised if near-term pace of deployment (to 2030; CCS to 2035/40) is not within empirically grounded upper (scale-up) and lower (plausibility) bounds for solar PV, wind, hydropower, nuclear and CCS, derived from installed capacity and market/ project pipelines.

→ Sustainability concerns raised if century-scale deployment does not stay within resource/environmental limits for bioenergy (below 245 EJ/yr) and cumulative 2020–2100 geological CO_2 storage (below 1,460 Gt CO_2) or if food availability is outside reasonable ranges of nutritional needs.

Warming categories (Riahi et al., 2026). Each pathway is classified by peak warming (PW) and end-of-century warming (EoCW) relative to 1850–1900, refining the AR6 categories C1–C8 by distinguishing whether warming returns to 1.5°C by 2100. Categories up to GW3 are treated as Paris-consistent; the high-ambition scenario set is GW2a.

A full list of the **scenarios** considered in the assessment is available at https://spget.org/products/cop31-policy-brief

REFERENCES

ACE (2026) 9th ASEAN Energy Outlook 2026-2060. Jakarta: ASEAN Centre for Energy (ACE). Available at: https://aseanenergy.org/publications/the-9th-asean-energy-outlook.

Ahmed, M., Araral, E. and Khan, M.A. (2025) 'Barriers to just energy transition: Institutional and infrastructure challenges in developing countries', Sustainable Futures, 10, p. 101414. Available at: https://doi.org/10.1016/j.sftr.2025.101414.

Ameli, N. et al. (2021) 'Higher cost of finance exacerbates a climate investment trap in developing economies', Nature Communications, 12(1), p. 4046. Available at: https://doi.org/10.1038/s41467-021-24305-3.

Bachorz, C. et al. (2025) 'Exploring techno-economic landscapes of abatement options for hard-to-electrify sectors', Nature Communications, 16(1), p. 3984. Available at: https://doi.org/10.1038/s41467-025-59277-1.

Bashmakov, I.A. et al. (2023) 'Industry', Climate Change 2022 - Mitigation of Climate Change. 1st edn. Cambridge University Press, pp. 1161–1244. Available at: https://doi.org/10.1017/9781009157926.013.

Bauer, N. et al. (2020) 'Quantification of an efficiency–sovereignty trade-off in climate policy', Nature, 588(7837), pp. 261–266. Available at: https://doi.org/10.1038/s41586-020-2982-5.

Berahab, R. (2022) The Energy Transition Amidst Global Uncertainties: A Focus on Critical Minerals. Policy Brief. Policy Center for the New South. Available at: https://www.policycenter.ma/publications/energy-transition-amidst-global-uncertainties-focus-critical-minerals.

Bistline, J. et al. (2021) 'Modeling variable renewable energy and storage in the power sector', Energy Policy, 156, p. 112424. Available at: https://doi.org/10.1016/j.enpol.2021.112424.

Black, S. et al. (2025)'Underpriced and Overused: Fossil Fuel Subsidies Data 2025 Update', 2025(270). International Monetary Fun (IMF). Available at: https://doi.org/10.5089/9798229034715.001. A001.

Blanco, G. et al. (2022) 'Innovation, Technology Development and Transfer', Climate Change 2022 - Mitigation of Climate Change. IPCC. Cambridge University Press, Cambridge, UK and New York, NY, USA. Available at: https://doi.org/10.1017/9781009157926.018

BNEF (2024) 3Q 2024 Global PV Market Outlook. Available at: https://about.bnef.com/insights/clean-energy/3q-2024-global-pv-market-outlook/.

Böhringer, C. et al. (2022) 'Potential impacts and challenges of border carbon adjustments', Nature Climate Change, 12(1), pp. 22–29. Available at: https://doi.org/10.1038/s41558-021-01250-z.

Briand, Y. et al. (2026) 'Net-zero compatible development pathways in Argentina, Brazil, China, India, Indonesia, Mexico and South Africa: lessons for short-term actions', Climate Policy, 26(5), pp. 709–725. Available at: https://doi.org/10.1080/14693062.2026.2624246.

Brown, T. and Hampp, J. (2023) 'Ultra-long-duration energy storage anywhere: Methanol with carbon cycling', Joule, 7(11), pp. 2414–2420. Available at: https://doi.org/10.1016/j.joule.2023.10.001.

Burke, P.J. et al. (2022) 'Contributing to regional decarbonization: Australia's potential to supply zero-carbon commodities to the Asia-Pacific', Energy, 248, p. 123563. Available at: https://doi.org/10.1016/j.energy.2022.123563.

Calcaterra, M. et al. (2024) 'Reducing the cost of capital to finance the energy transition in developing countries', Nature Energy, 9(10), pp. 1241–1251. Available at: https://doi.org/10.1038/s41560-024-01606-7.

Caney, S. (2010) 'Climate change and the duties of the advantaged', Critical Review of International Social and Political Philosophy, 13(1), pp. 203–228. Available at: https://doi.org/10.1080/13698230903326331.

Carballo, I.H. et al. (2026) 'The Economics of a Just Transition', Review of Environmental Economics and Policy, 20(2), pp. 260–282. Available at: https://doi.org/10.1086/742029.

Chaturvedi, V. et al. (2024) 'India's pathway to net zero by 2070: status, challenges, and way forward', Environmental Research Letters, 19(11), p. 112501. Available at: https://doi.org/10.1088/1748-9326/ad7749.

Chaturvedi, V. (2021) 'A vision for a net-zero energy system for India', Energy and Climate Change, 2, p. 100056. Available at: https://doi.org/10.1016/j.egycc.2021.100056.

Clarke, L. et al. (2022) 'Energy Systems', Climate Change 2022 — Mitigation of Climate Change. IPCC. Cambridge University Press, pp. 613–746. Available at: https://doi.org/10.1017/9781009157926.008.

Climate Analytics and PIK (2025) 'Rescuing 1.5°C: new evidence on the highest possible ambition to deliver the Paris Agreement'. Zenodo. Available at: https://doi.org/10.5281/ZENODO.18234421.

Climate Policy Initiative (2026) Global Landscape of Climate Finance 2026. Available at: https://glcf.climatepolicyinitiative.org/.

COP28, IRENA and GRA (2023) Tripling renewable power and doubling energy efficiency by 2030: Crucial steps towards 1.5°C. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2023/Oct/Tripling-renewable-power-and-doubling-energy-efficiency-by-2030.

COP30 Presidency (2026) Transitioning Away from Fossil Fuels Roadmap. Available at: https://cop30.br/en/2026-priorities/transitioning-away-from-fossil-fuels-roadmap .

Daly, M. et al. (2026) 'Addressing context-specific energy modelling risks and dynamics in low- and middle-income countries', Nature Energy, 11(4), pp. 526–533. Available at: https://doi.org/10.1038/s41560-025-01962-y.

Dekker, M.M. et al. (2025) 'Navigating the black box of fair national emissions targets', Nature Climate Change, 15(7), pp. 752–759. Available at: https://doi.org/10.1038/s41558-025-02361-7.

Dhakal, S. et al. (2022) 'Emissions Trends and Drivers', Climate Change 2022 — Mitigation of Climate Change. IPCC Cambridge University Press, pp. 215–294. Available at: https://doi.org/10.1017/9781009157926.004.

Edelenbosch, O.Y. et al. (2024) 'Reducing sectoral hard-to-abate emissions to limit reliance on carbon dioxide removal', Nature Climate Change, 14(7), pp. 715–722. Available at: https://doi.org/10.1038/s41558-024-02025-y.

Ember (2026) Global Electricity Review 2026. Available at: https://ember-energy.org/latest-insights/global-electricity-review-2026.

Emmerling, J. et al. (2024) 'A multi-model assessment of inequality and climate change', Nature Climate Change, 14(12), pp. 1254–1260. Available at: https://doi.org/10.1038/s41558-024-02151-7.

Emmerling, J., Andreoni, P. and Tavoni, M. (2024) 'Global inequality consequences of climate policies when accounting for avoided climate impacts', Cell Reports Sustainability, 1(1), p. 100008. Available at: https://doi.org/10.1016/j.crsus.2023.100008.

Etter-Wenzel, C. and Rosenow, J. (2026): High voltage: the global potential for electrifying industry. Oxford: Environmental Change Institute, University of Oxford.

Foster, V. et al. (2024) 'Development transitions for fossil fuel-producing low and lower-middle income countries in a carbon-constrained world', Nature Energy, 9(3), pp. 242–250. Available at: https://doi.org/10.1038/s41560-023-01440-3.

Fraunhofer ISI (2024) Direct electrification of industrial process heat: An assessment of technologies, potentials and future prospects for the EU. Available at: https://doi.org/10.24406/PUBLICA-3407.

Friedlingstein, P. et al. (2026) 'Global Carbon Budget 2025', Earth System Science Data, 18(5), pp. 3211–3288. Available at: https://doi.org/10.5194/essd-18-3211-2026.

Frilingou, N. et al. (2026) 'Regional impacts on decarbonisation under evolving financing conditions for energy technologies', Nature Communications, 17(1), p. 6611. Available at: https://doi.org/10.1038/s41467-026-73522-1.

Fuhrman, J. et al. (2025) 'Rate and growth limits for carbon capture and storage', Environmental Research Letters, 20(6), p. 064034. Available at: https://doi.org/10.1088/1748-9326/add9af.

Grubler, A. et al. (2018) 'A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies', Nature Energy, 3(6), pp. 515–527. Available at: https://doi.org/10.1038/s41560-018-0172-6.

Guan, Y. et al. (2023) 'Burden of the global energy price crisis on households', Nature Energy, 8(3), pp. 304–316. Available at: https://doi.org/10.1038/s41560-023-01209-8.

GWEC (2026) Global Wind Report 2026. Global Wind Energy Council (GWEC). Available at: https://www.gwec.net/reports/globalwindreport.

Hatton, L. et al. (2026) 'High costs of capital shape the mitigation effects of renewable energy deployment globally', Nature Communications, 17(1), p. 9733. Available at: https://doi.org/10.1038/s41467-026-75666-6.

Herzog, H. et al. (2024) 'Getting real about capturing carbon from the air', One Earth, 7(9), pp. 1477–1480. Available at: https://doi.org/10.1016/j.oneear.2024.08.011.

Hoesly, R., Smith, S. J., Ahsan, H., Prime, N., O'Rourke, P., Crippa, M., Klimont, Z., Guizzardi, D., Feng, L., Harkins, C., McDonald, B., and Wang, S.: CEDS v_2025_03_18 Aggregate Data, Zenodo [data set], https://doi.org/10.5281/zenodo.15059443, 2025.

Hotchkiss, E., Urdaneta, M.P. and Bazilian, M.D. (2024) 'Comparing methods for criticality and security in minerals for clean energy', The Extractive Industries and Society, 17, p. 101402. Available at: https://doi.org/10.1016/j.exis.2023.101402.

Huppmann, D. et al. (2026) 'Scenario Compass Initiative — Pathways Ensemble 2025 (v1.2)'. Zenodo. Available at: https://doi.org/10.5281/ZENODO.23188984.

IEA (2023) Electricity Grids and Secure Energy Transitions. Paris: International Energy Agency (IEA). Available at: https://www.iea.org/reports/electricity-grids-and-secure-energy-transitions.

IEA (2024a) Batteries and Secure Energy Transitions. Paris: International Energy Agency (IEA). Available at: https://www.iea.org/reports/batteries-and-secure-energy-transitions.

IEA (2024b) 'CCUS Projects Database'. Available at: https://www.iea.org/data-and-statistics/data-product/ccus-projects-database.

IEA (2024c) Energy Technology Perspectives 2024. Paris: International Energy Agency (IEA). Available at: https://www.iea.org/reports/energy-technology-perspectives-2024.

IEA (2024d) Integrating Solar and Wind. Paris: International Energy Agency (IEA). Available at: https://www.iea.org/reports/integrating-solar-and-wind.

IEA (2025a) Global Critical Minerals Outlook 2025. Paris: International Energy Agency (IEA). Available at: https://www.iea.org/reports/global-critical-minerals-outlook-2025.

IEA (2025b) Global Energy Review 2025. Paris: International Energy Agency (IEA). Available at: https://www.iea.org/reports/global-energy-review-2025.

IEA (2025c) The Value of Demand Flexibility. Available at: https://www.iea.org/reports/the-value-of-demand-flexibility.

IEA (2025d) World Energy Outlook 2025. Paris: International Energy Agency (IEA). Available at: https://www.iea.org/reports/world-energy-outlook-2025.

IEA (2025e) Global Energy and Climate Model. Paris: International Energy Agency (IEA). The Impl icat ions of Oil and Gas Field De-cline Rates. Available at: https://www.iea.org/reports/the-implications-of-oil-and-gas-field-decline-rates

IEA (2026a) Clean Cooking in Africa 2026. Paris: IEA. Available at: https://www.iea.org/reports/clean-cooking-in-africa-2026 (Accessed: 26 October 2026).

IEA (2026b) Electrification. International Energy Agency (IEA). Available at: https://www.iea.org/reports/electrification.

IEA (2026c) Global Energy Review 2026. Paris: International Energy Agency (IEA). Available at: https://www.iea.org/reports/global-energy-review-2026

IEA (2026d) Heat Pump Monitor 2026: Key findings, International Energy Agency. Available at: https://www.iea.org/reports/heat-pump-monitor-2026/key-findings.

IEA (2026e) The Implications of Oil and Gas Field Decline Rates.

IISD and OECD (n.d.) Fossil Fuel Subsidy Tracker, FossilFuelSubsidyTracker.org. Available at: https://fossilfuelsubsidytracker.org/.

IRENA (2025) Renewable power generation costs in 2024. Abu Dhabi: International Renewable Energy Agency (IRENA) Available at: https://www.irena.org/Publications/2025/Jun/Renewable-Power-Generation-Costs-in-2024.

IRENA (2026a) Renewable power generation costs in 2025. Abu Dhabi: International Renewable Energy Agency (IRENA). Available at: https://www.irena.org/Publications/2026/Jul/Renewable-Power-Generation-Costs-in-2025.

IRENA (2026b) Transitioning Away from Fossil Fuels: A Roadmap Based on Renewables, Electrification and Grid Enhancement. Abu Dhabi: International Renewable Energy Agency (IRENA). Available at: https://www.irena.org/Publications/2026/May/Transitioning-away-from-fossil-fuels.

Iyer, G.C. et al. (2015) 'Improved representation of investment decisions in assessments of CO_2 mitigation', Nature Climate Change, 5(5), pp. 436–440. Available at: https://doi.org/10.1038/nclimate2553.

Jewell, J. et al. (2026) 'Policy-driven growth of technologies to accelerate climate action', Nature Reviews Earth & Environment, 7(4), pp. 235–252. Available at: https://doi.org/10.1038/s43017-026-00765-3.

Jones, N. et al. (2026) 'Leading the Transition Locally: A policy toolkit to address fossil fuel production for subnational states and regions'. IISD. : Available at: https://www.iisd.org/publications/report/fossil-fuel-production-subnational-states.

Kazlou, T., Cherp, A. and Jewell, J. (2024) 'Feasible deployment of carbon capture and storage and the requirements of climate targets', Nature Climate Change, 14(10), pp. 1047–1055. Available at: https://doi.org/10.1038/s41558-024-02104-0.

Kemfert, C. et al. (2022) 'The expansion of natural gas infrastructure puts energy transitions at risk', Nature Energy, 7(7), pp. 582–587. Available at: https://doi.org/10.1038/s41560-022-01060-3.

Kikstra, J.S. et al. (2021) 'Decent living gaps and energy needs around the world', Environmental Research Letters, 16(9), p. 095006. Available at: https://doi.org/10.1088/1748-9326/ac1c27.

Kikstra, J.S. et al. (2025) 'Closing decent living gaps in energy and emissions scenarios: introducing DESIRE', Environmental Research Letters, 20(5), p. 054038. Available at: https://doi.org/10.1088/1748-9326/adc3ad.

Klinsky, S. and Winkler, H. (2018) 'Building equity in: strategies for integrating equity into modelling for a 1.5°C world', Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 376(2119), p. 20160461. Available at: https://doi.org/10.1098/rsta.2016.0461.

Lecocq, F. et al. (2022) 'Mitigation and development pathways in the near- to mid-term', Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Edited by P.R. Shukla et al. Cambridge, UK and New York, NY, USA: Cambridge University Press. Available at: https://doi.org/10.1017/9781009157926.006.

Lema, R. et al. (2018) 'Renewable electrification and local capability formation: Linkages and interactive learning', Energy Policy, 117, pp. 326–339. Available at: https://doi.org/10.1016/j.enpol.2018.02.011.

Luderer, G. et al. (2022) 'Impact of declining renewable energy costs on electrification in low-emission scenarios', Nature Energy, 7(1), pp. 32–42. Available at: https://doi.org/10.1038/s41560-021-00937-z.

Madeddu, S. et al. (2020) 'The CO_2 reduction potential for the European industry via direct electrification of heat supply (power-to-heat)', Environmental Research Letters, 15(12), p. 124004. Available at: https://doi.org/10.1088/1748-9326/abbd02.

Malhotra, A. and Schmidt, T.S. (2020) 'Accelerating Low-Carbon Innovation', Joule, 4(11), pp. 2259–2267. Available at: https://doi.org/10.1016/j.joule.2020.09.004.

Malik, A. et al. (2021) 'Climate policy accelerates structural changes in energy employment', Energy Policy, 159, p. 112642. Available at: https://doi.org/10.1016/j.enpol.2021.112642.

Marshall, S., Gompertz, D. and Senlen, O. (2025) 'NDC Energy Commitments Tracker', 10 September. Available at: https://www.e3g.org/publications/ndc-3-0-energy-commitments-tracker/.

Meng, W. et al. (2026) 'Rethinking energy transition strategies for the European Union amid rising energy prices', Proceedings of the National Academy of Sciences, 123(23), p. e2609606123. Available at: https://doi.org/10.1073/pnas.2609606123.

Mercure, J.-F. et al. (2021) 'Reframing incentives for climate policy action', Nature Energy, 6(12), pp. 1133–1143. Available at: https://doi.org/10.1038/s41560-021-00934-2.

Mercure, J.-F. et al. (2025) 'Evidence of a cascading positive tipping point towards electric vehicles', Nature Communications, 17(1) Available at: https://doi.org/10.1038/s41467-025-66945-9.

Mohan, D.S. et al. (2026) How Secure is India's Energy Future? New Delhi: Council on Energy, Environment and Water (CEEW). Available at: https://www.ceew.in/publications/how-secure-is-india-energy-future.

Mori, S. et al. (2026) 'Challenges and opportunities of the full phase-out of fossil fuels under the 1.5 °C goal', Nature Communications, 17(1), p. 4379. Available at: https://doi.org/10.1038/s41467-026-72841-7.

Mulugetta, Y. et al. (2022) 'Africa needs context-relevant evidence to shape its clean energy future', Nature Energy, 7(11), pp. 1015–1022. Available at: https://doi.org/10.1038/s41560-022-01152-0.

Muttitt, G. and Winkler, H. (2026) 'Transitioning away from fossil fuels in a just, orderly and equitable manner: A quantitative overview of countries' different national circumstances, fossil fuel dependence and opportunities for flourishing post-fossil economies.', PRISM Working Paper 2026-2 [Preprint].

Nicholls, Z. et al. (2025) 'Model for the Assessment of Greenhouse gas Induced Climate Change (MAGICC)'. Zenodo. Available at: https://doi.org/10.5281/ZENODO.17054564.

Nor, M.I. and Mohamed, A.A. (2024) 'Investigating the complex landscape of climate finance in least developed countries (LDCs)', Discover Environment, 2(1), p. 76. Available at: https://doi.org/10.1007/s44274-024-00102-9.

Nygaard, A. (2023) 'The Geopolitical Risk and Strategic Uncertainty of Green Growth after the Ukraine Invasion: How the Circular Economy Can Decrease the Market Power of and Resource Dependency on Critical Minerals', Circular Economy and Sustainability, 3(2), pp. 1099–1126. Available at: https://doi.org/10.1007/s43615-022-00181-x.

OECD (2026) Developed countries exceed USD 100 billion climate finance goal for third consecutive year, OECD. Available at: https://www.oecd.org/en/about/news/press-releases/2026/05/developed-countries-exceed-usd-100-billion-climate-finance-goal-for-third-consecutive-year.html.

Ordonez, J.A. et al. (2026) 'Low-carbon technologies support energy security by buffering energy price shocks', Communications Earth & Environment, 7(1), p. 843. Available at: https://doi.org/10.1038/s43247-026-04131-5.

Pachauri, S. et al. (2022) 'Fairness considerations in global mitigation investments', Science, 378(6624), pp. 1057–1059. Available at: https://doi.org/10.1126/science.adf0067.

Pachauri, S. et al. (2026) 'Advancing representations of equity and justice in climate mitigation futures', PLOS Climate. Edited by D.G. Vidal, 5(2), p. e0000763. Available at: https://doi.org/10.1371/journal.pclm.0000763.

Pavanello, F. et al. (2021) 'Air-conditioning and the adaptation cooling deficit in emerging economies', Nature Communications, 12(1), p. 6460. Available at: https://doi.org/10.1038/s41467-021-26592-2.

Pelz, S. et al. (2025) 'Using net-zero carbon debt to track climate overshoot responsibility', Proceedings of the National Academy of Sciences, 122(13), p. e2409316122. Available at: https://doi.org/10.1073/pnas.2409316122.

Pelz, S. et al. (2026) 'Equitable cooperation deepens the solution space for high ambition pathways', Environmental Research Letters, 21(18), p. 184019. Available at: https://doi.org/10.1088/1748-9326/aea34d.

Pereira, S., Silva, C. and Ferreira, L.M.D.F. (2025) 'Barriers to energy transition: Comparing developing with developed countries', Energy for Sustainable Development, 87, p. 101753. Available at: https://doi.org/10.1016/j.esd.2025.101753.

Piai Paiva, J.C. et al. (2024) 'Improving the Expansion of Electricity Services Considering Affordability Issues: A Case Study in Brazilian Low-Income Households', Energies, 17(17), p. 4231. Available at: https://doi.org/10.3390/en17174231.

Prajapati, P. et al. (2026) 'Navigating the energy transition in India: challenges and opportunities towards sustainable energy goal', Water-Energy Nexus, 9, pp. 1–18. Available at: https://doi.org/10.1016/j.wen.2025.07.004.

Rajamani, L. et al. (2021) 'National "fair shares" in reducing greenhouse gas emissions within the principled framework of international environmental law', Climate Policy, 21(8), pp. 983–1004. Available at: https://doi.org/10.1080/14693062.2021.1970504.

Ramsebner, J. et al. (2021) 'The sector coupling concept: A critical review', WIREs Energy and Environment, 10(4), p. e396. Available at: https://doi.org/10.1002/wene.396.

Ren, L. et al. (2025) 'Quantitative Assessment of the Carbon Border Adjustment Mechanism: Impacts on China–EU Trade and Provincial-Level Vulnerabilities', Sustainability, 17(4), p. 1699. Available at: https://doi.org/10.3390/su17041699.

Riahi, K. et al. (2026) 'Mitigation benchmarks from the 2025 community update of global emissions pathways'. In Review. Available at: https://doi.org/10.21203/rs.3.rs-8891091/v1.

Richardson, J., Kirk Hall, P. and Morgan, W. (2022) 'Land Use Conflicts Between Wind and Solar Renewable Energy and Agricultural Uses', (2022–004). Available at: https://ssrn.com/abstract=4042235.

Richters, O. et al. (2026) 'NGFS Climate Scenarios Data Set'. Zenodo. Available at: https://doi.org/10.5281/ZENODO.17901363.

Robiou du Pont, Y. et al. (2025) 'Effect of discontinuous fair-share emissions allocations immediately based on equity', Nature Communications, 16(1), p. 8020. Available at: https://doi.org/10.1038/s41467-025-62947-9.

Saadaoui, J., Smyth, R. and Vespignani, J. (2025) 'Ensuring the security of the clean energy transition: Examining the impact of geopolitical risk on the price of critical minerals', Energy Economics, 142, p. 108195. Available at: https://doi.org/10.1016/j.eneco.2025.108195.

Schleussner, C.-F. et al. (2024) 'Overconfidence in climate overshoot', Nature, 634(8033), pp. 366–373. Available at: https://doi.org/10.1038/s41586-024-08020-9.

Schreyer, F. et al. (2025) 'From net-zero to zero-fossil in transforming the EU energy system'. Nature Communications 16, 10700. Available at: https://doi.org/10.1038/s41467-025-66682-z

SCI/IAMC (2026) Summary, Scenario Evaluation Criteria. Available at: https://scenario-evaluation-criteria.iamconsortium.org/2026.08.03/summary/.

Semieniuk, G. et al. (2024) 'Distributional Implications and Share Ownership of Record Oil and Gas Profits'. PERI Working Paper Series, Number 611. Political Economy Research Institute.

Sharmina, M. et al. (2025) 'Policymaker-led scenarios and public dialogue facilitate energy demand analysis for net-zero futures', Nature Energy, 10(12), pp. 1482–1492. Available at: https://doi.org/10.1038/s41560-025-01898-3.

Shen, C.-L. and Tai, H.-S. (2024) 'National goal, local resistance: How institutional gaps hinder local renewable energy development in Taiwan', Energy for Sustainable Development, 83, p. 101586. Available at: https://doi.org/10.1016/j.esd.2024.101586.

Singh, M.K. (2023) 'What is state capacity and how does it matter for energy transition?', Energy Policy, 183, p. 113799. Available at: https://doi.org/10.1016/j.enpol.2023.113799.

Soergel, B. et al. (2021) 'Combining ambitious climate policies with efforts to eradicate poverty', Nature Communications, 12(1), p. 2342. Available at: https://doi.org/10.1038/s41467-021-22315-9.

Soergel, B. et al. (2024) 'Multiple pathways towards sustainable development goals and climate targets', Environmental Research Letters, 19(12), p. 124009. Available at: https://doi.org/10.1088/1748-9326/ad80af.

Songwe, V., Stern, N. and Bhattacharya, A. (2022) Finance for climate action: Scaling up investment for climate and development. London: Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science.

Strambo, C., Burton, J. and Atteridge, A. (2019) The end of coal? Planning a "just transition" in South Africa. Stockholm Environment Institute (SEI). Available at: https://www.sei.org/wp-content/uploads/2019/02/planning-a-just-transition-in-south-africa.pdf.

Tienhaara, K. et al. (2022) 'Investor-state disputes threaten the global green energy transition', Science, 376(6594), pp. 701–703. Available at: https://doi.org/10.1126/science.abo4637.

Tonelli, D. et al. (2023) 'Global land and water limits to electrolytic hydrogen production using wind and solar resources', Nature Communications, 14(1), p. 5532. Available at: https://doi.org/10.1038/s41467-023-41107-x.

Trench, A., Packey, D. and Sykes, J. (2014) 'Non-Technical Risks and Their Impact on the Mining Industry', Mineral Resource and Ore Reserve Estimation: The AusIMM Guide to Good Practice. 2. ed. Carlton: AusIMM (Monograph, 30).

Ueckerdt, F. et al. (2021) 'Potential and risks of hydrogen-based e-fuels in climate change mitigation', Nature Climate Change, 11(5), pp. 384–393. Available at: https://doi.org/10.1038/s41558-021-01032-7.

UNCTAD (ed.) (2023) Opening green windows: technological opportunities for a low-carbon world. Geneva: United Nations (Technology and innovation report, 2023).

UNEP (2026a) Emissions Gap Report 2026: The point of return - Urgent emissions cuts needed to come back from overshoot of 1.5°C. Edited by A. Olhoff (chief ed.) et al. Nairobi: United Nations Environment Programme. Available at: https://doi.org/10.59117/20.500.11822/50038.

UNEP (2026b) Limiting Overshoot — Navigating exceedance of 1.5°C and pathways towards return | UNEP — UN Environment Programme. Available at: https://www.unep.org/resources/limiting-overshoot-navigating-exceedance.

UNFCCC (2023a) 'Decision 1/CMA.5', Outcome of the first global stocktake. Available at: https://unfccc.int/sites/default/files/resource/1_CMA.5.pdf.

UNFCCC (2023b) Matters relating to the global stocktake under the Paris Agreement | UNFCCC. Available at: https://unfccc.int/documents/636584.

UNFCCC (2025a) Nationally determined contributions under the Paris Agreement. Synthesis report by the secretariat. United Nations Framework Convention on Climate Change (UNFCCC). Available at: https://unfccc.int/documents/650664.

UNFCCC (2025b) Report of the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement on its sixth session, held in Baku from 11 to 24 November 2024. FCCC/PA/CMA/2024/17/Add.1. Available at: https://unfccc.int/sites/default/files/resource/cma2024_17a01E.pdf.

Van Den Berg, N.J. et al. (2020) 'Implications of various effort-sharing approaches for national carbon budgets and emission pathways', Climatic Change, 162(4), pp. 1805–1822. Available at: https://doi.org/10.1007/s10584-019-02368-y.

Van Heerden, R. et al. (2025) 'Demand-side strategies enable rapid and deep cuts in buildings and transport emissions to 2050', Nature Energy, 10(3), pp. 380–394. Available at: https://doi.org/10.1038/s41560-025-01703-1.

Van Vuuren, D.P. et al. (2026) 'The Scenario Model Intercomparison Project for CMIP7 (Scenario-MIP-CMIP7)', Geoscientific Model Development, 19(7), pp. 2627–2656. Available at: https://doi.org/10.5194/gmd-19-2627-2026.

Verpoort, P.C. et al. (2026) 'Scenario Evaluation Criteria'. Zenodo. Available at: https://doi.org/10.5281/ZENODO.21771914.

Waidelich, P. et al. (2026) 'The impact of financing cost differences on global energy and industry decarbonization', Nature Climate Change, 16(10), pp. 1178–1186. Available at: https://doi.org/10.1038/s41558-026-02756-0.

Waisman, H. et al. (2019) 'A pathway design framework for national low greenhouse gas emission development strategies', Nature Climate Change, 9(4), pp. 261–268. Available at: https://doi.org/10.1038/s41558-019-0442-8.

Wiese, F. et al. (2024) 'The key role of sufficiency for low demand-based carbon neutrality and energy security across Europe', Nature Communications, 15(1), p. 9043. Available at: https://doi.org/10.1038/s41467-024-53393-0.

Wilson, C. et al. (2020) 'Granular technologies to accelerate decarbonization', Science, 368(6486), pp. 36–39. Available at: https://doi.org/10.1126/science.aaz8060.

Wolfram, C. et al. (2026) 'Building a scalable climate coalition for heavy industry', Science, 393(6815), pp. 984–987. Available at: https://doi.org/10.1126/science.aef7190.

Xiao, T. et al. (2025) 'Environmental impact and net-zero pathways for sustainable artificial intelligence servers in the USA', Nature Sustainability, 8(12), pp. 1541–1553. Available at: https://doi.org/10.1038/s41893-025-01681-y.

Young-Brun, M. et al. (2025) 'Within-country inequality and the shaping of a just global climate policy', Proceedings of the National Academy of Sciences, 122(39), p. e2505239122. Available at: https://doi.org/10.1073/pnas.2505239122.

Zhao, S. et al. (2025) 'The multi-faceted global poverty and income inequality landscape in a decarbonizing world', Cell Reports Sustainability, 2(10), p. 100487. Available at: https://doi.org/10.1016/j.crsus.2025.100487.

Ziegler, M.S. and Trancik, J.E. (2021) 'Re-examining rates of lithium-ion battery technology improvement and cost decline', Energy & Environmental Science, 14(4), pp. 1635–1651. Available at: https://doi.org/10.1039/D0EE02681F.