Science of the Total Environment 977 (2025) 179409

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Short Communication

Empty promises: Some requirements for a successful implementation of decarbonisation strategies in developing countries

Walter Leal Filho [a,b,c], Tarek Ben Hassen [d,*], Newton Matandirotya [e,f], Artie Ng [g,h,i]

[a] Hamburg University of Applied Sciences, Research and Transfer Centre "Sustainable Development and Climate Change Management", Ulmenliet 20, D-21033 Hamburg, Germany
[b] WSB Merito University, Wroclaw, Poland
[c] School of Science and the Environment. Manchester Metropolitan University. All Saints Building. Oxford Road. Manchester M15 6BH. UK
[d] Department of International Affairs, College of Arts and Sciences, Qatar University. Doha. Qatar
[e] Climate Change Adaptation and Resilience Centre, P.O. Box 5, Beitbridge, Zimbabwe
[f] Kgotso Development Trust, P.O. Box 5, Beitbridge, Zimbabwe
[g] Centre for Sustainable Business, International Business University, Toronto, Canada
[h] The Balsillie School of International Affairs (BSIA), Waterloo, Canada
[i] Department of Industrial & Systems Engineering, Hong Kong Polytechnic University, Hong Kong SAR

HIGHLIGHTS

- Strong and stable policies are key for sustaining decarbonisation initiatives.
- Inclusive stakeholder engagement fosters support for climate policies.
- International cooperation and capacity building empower developing nations.
- Harmonising climate strategies with development goals ensures just transitions.
- Case studies from industrialised and developing countries offer valuable insights.

GRAPHICAL ABSTRACT

ARTICLE INFO

Editor: Kuishuang Feng

Keywords:
Decarbonisation
Climate change mitigation
Developing countries
Strategies
Paris agreement

ABSTRACT

Decarbonisation strategies are crucial for mitigating the adverse effects of climate change and achieving sustainable development. However, the successful implementation of these strategies in developing countries remains a significant challenge due to resource constraints, competing development priorities, and institutional barriers. This paper provides a comprehensive overview of decarbonisation efforts and impacts through an extensive review of existing research, reports, and case studies. The research includes a detailed examination of decarbonisation initiatives, complemented by case studies from seven industrialised (USA, EU27, Germany, Italy, France, Finland, and Australia) and six developing countries (China, Brazil, South Africa, India, Mexico, and Kenya). These case studies showcase practical efforts and illustrate current trends in decarbonisation. The findings underscore the importance of political will, financial resources, technological capacity, and social acceptance as critical requirements for the successful implementation of decarbonisation strategies in developing

* Corresponding author.
E-mail addresses: walter.leal2@haw-hamburg.de (W. Leal Filho), thassen@qu.edu.qa (T. Ben Hassen), ang@ibu.ca (A. Ng).

https://doi.org/10.1016/j.scitotenv.2025.179409
Received 20 May 2024; Received in revised form 2 April 2025; Accepted 9 April 2025
Available online 15 April 2025

countries. The paper emphasises the need for international cooperation, capacity-building, and aligning decarbonisation goals with broader socio-economic objectives to ensure these strategies contribute meaningfully to sustainable development.

1. Introduction: The goal of decarbonisation

The threat of global climate change has emerged as one of the most pressing challenges confronting humanity in the 21st century. The adverse impacts of rising temperatures, sea-level rise, extreme weather events, and ecological disruptions pose grave risks to human well-being, economic stability, and environmental sustainability (World Bank, 2014). While industrialised nations have historically been the primary contributors to global greenhouse gas (GHG) emissions, the trajectory of future emissions is anticipated to shift toward the developing world (Pigato et al., 2020). In response to this existential crisis, countries across all income levels have implemented various policies over the past thirty years, including setting ambitious targets to decarbonise their economies (World Bank, 2023). Accordingly, decarbonisation became central to efforts aimed at combating climate change and minimising global warming, aligning closely with the broader goals of sustainable development (Cernev and Fenner, 2020; Mahadevia et al., 2024).

Decarbonisation refers to the process of reducing carbon dioxide (CO_2) emissions released into the atmosphere, primarily through human activities such as burning fossil fuels for energy, industrial processes, and transportation (Babaniyi et al., 2024). The primary goal of decarbonisation is to achieve a low-carbon economy where the output of CO_2 emissions is significantly reduced, ideally to net-zero levels (Dixon et al., 2022). Achieving net zero means that any CO_2 emissions are balanced by an equivalent amount of CO_2 removal from the atmosphere, either through natural processes like afforestation or through technological solutions like carbon capture and storage (CCS) (Dixon et al., 2022; Lau et al., 2021). The timeline for many countries and organisations to reach net zero is typically set around the mid-century, following international agreements like the Paris Accord, which seeks to limit global temperature rise to below 2 degrees Celsius above pre-industrial levels (Sadai et al., 2022). Fig. 1 presents some components that showcase the many elements associated with decarbonisation and link them with some of the relevant UN Sustainable Development Goals (SDGs). The outer circles represent critical categories influencing decarbonisation strategies, derived from a synthesis of existing research and reports on sustainable development and climate action.

Switching from fossil fuels to renewable energy sources such as wind, solar, and hydroelectric power is one of the most significant steps (Rahman et al., 2022). Improving energy efficiency in buildings, transportation, and manufacturing processes also plays a crucial role in reducing overall energy demand (Economidou et al., 2020; Godil et al., 2021; Jahanger et al., 2023). Developing and adopting new technologies like electric vehicles, green hydrogen, and advanced battery storage systems are critical components of a decarbonised future (Waldron et al., 2022). The central goal of decarbonisation is to reduce carbon emissions, thereby mitigating the adverse effects of climate change and limiting the rise of global temperature in alignment with international agreements such as the Paris Agreement. This is an essential step in efforts to reduce the frequency of extreme events (Leal Filho et al., 2023).

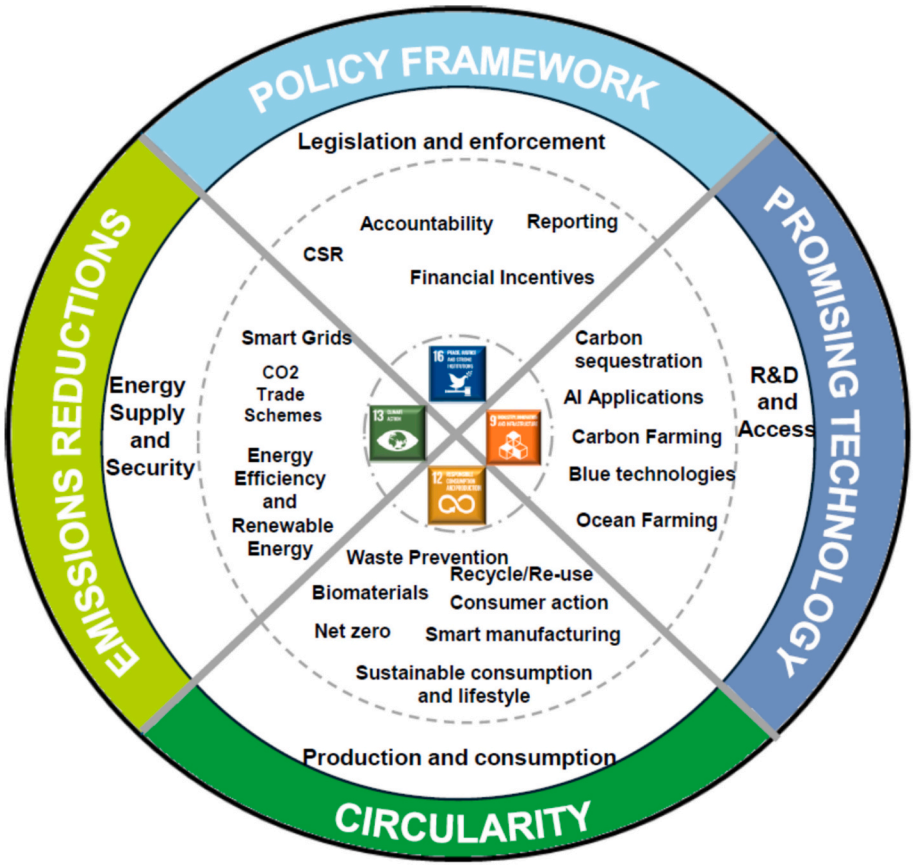

Fig. 1. Key factors shaping decarbonisation efforts (Source: author's elaboration).

Beyond its climate benefits, decarbonisation can also foster sustainable economic growth by creating new industries and job opportunities in green technologies (Hanna et al., 2024; Oyewo et al., 2020). It also seeks to improve public health by reducing air pollution associated with fossil fuel combustion (Penn et al., 2022). It also aims to ensure energy security by diversifying energy sources and reducing dependence on volatile fossil fuel markets (De Rosa et al., 2022; Holechek et al., 2022). By pursuing decarbonisation, societies aim not only to mitigate the adverse effects of climate change but also to create a sustainable, resilient, and equitable future for all (Abram et al., 2020, 2022).

However, substantial disparities exist between developing nations' pronounced decarbonisation objectives and the myriad structural challenges that hinder their practical implementation, often rendering such commitments "empty promises". These challenges encompass insufficient fiscal resources, deficient technological infrastructure, and the competing exigencies of economic development and social welfare imperatives (Das and Ghosh, 2023; Yan et al., 2023). In many cases, these structural barriers undermine the feasibility of achieving the ambitious decarbonisation targets set by developing countries, highlighting the critical need for comprehensive support, international collaboration, and capacity-building efforts to transform these "empty promises" into tangible actions.

A comprehensive understanding of the critical requirements for successful decarbonisation in developing countries is imperative to capitalise on these opportunities and overcome the multi-faceted challenges. This research paper aims to contribute to this understanding by conducting an extensive review of existing literature, reports, and case studies, complemented by an in-depth examination of decarbonisation initiatives and experiences across various industrialised and developing nations. Firstly, the paper will explore decarbonisation efforts through the lens of seven industrialised countries and regions: the United States, the European Union (EU27), Germany, Italy, France, Finland, and Australia. These case studies will provide insights into the strategies, policies, and best practices employed by nations at the forefront of decarbonisation efforts, highlighting successes, challenges, and lessons learned. Further, the inclusion of both the EU27 and individual member states allows for an analysis of decarbonisation strategies at both regional and national scales, highlighting collective EU efforts as well as unique national approaches within the same policy context.

Secondly, the paper will examine the decarbonisation trajectories of six key developing countries: China, Brazil, South Africa, India, Mexico, and Kenya. These countries were selected based on their geographical diversity, varying economic development levels, and roles as key contributors or emerging leaders in global decarbonisation efforts, ensuring a representative analysis of the Global South. These countries represent diverse geographical regions and development stages, with varying natural resource availability, industrial bases, and socio-economic challenges. This allows for a comprehensive analysis of how developing nations approach decarbonisation within their unique constraints and opportunities. This comparative analysis will illuminate the distinct challenges faced by developing economies in their transition to low-carbon pathways.

This comprehensive research paper provides a novel and timely addition to the discourse on climate change mitigation in developing countries. Although numerous studies have investigated the technical aspects of decarbonisation strategies and projected emission reduction pathways, this paper adopts a holistic and interdisciplinary approach. It goes beyond the narrow focus on technological solutions to explore the complex political, economic, social, and institutional factors that influence the successful implementation of decarbonisation efforts in the Global South.

This paper is structured into three main sections. Section 2 outlines the study methodology. Section 3 presents the findings, and Section 4 summarises this study's implications in the conclusion.

2. Methods

In order to provide a comprehensive overview of trends related to decarbonisation, this paper deployed an extensive review of existing research, reports, and case studies on decarbonisation trends. The aim was to document the current situation and identify gaps in current knowledge. Accordingly, the paper is based on a comprehensive review of scientific literature, policy documents, and technical reports published between 2015 and 2024. The choice of 2015 as our starting point aligns with the adoption of the Paris Agreement, a pivotal moment in global climate action that fundamentally reshaped national approaches to decarbonisation. We searched major academic databases, including Web of Science, Scopus, and Google Scholar, using combinations of key search terms: 'decarbonisation' OR 'decarbonisation' AND '[country name]' AND ('policy' OR 'strategy' OR 'implementation'). Additional searches included terms specific to each country's energy transition initiatives. We limited our search to English-language publications. We supplemented these academic sources with grey literature, including government policy documents, international organisation reports (UNEP, World Bank, IEA), and national climate action plans. By doing so, the authors could identify and analyse themes and patterns, drawing insights on decarbonisation efforts and impacts. The work was complemented by the use of a set of case studies aimed at showcasing practical efforts being made by seven industrialised countries and regions (USA, EU27, Germany, Italy, France, Finland and Australia) and six developing countries (China, Brazil, South Africa, India, Mexico, and Kenya) as shown in Fig. 2, which serves the purpose of illustrating current trends.

The selection of these countries as case studies for decarbonisation was based on three main factors:

1. Diverse economic and energy profiles: the chosen countries represent a broad spectrum of economic development and energy consumption patterns. This diversity allows for examining decarbonisation strategies across different contexts, making the findings more universally applicable. For instance, gathering information from a highly industrialised nation such as Germany and a developing country such as Brazil, with growing renewable energy initiatives can provide insights into varied approaches and challenges.
2. Policy and commitment to decarbonisation: These selected countries have shown strong political will and commitment to decarbonisation through policies, international agreements, and national targets. Their engagement in initiatives such as the Paris Agreement and their ambitious national plans for reducing carbon emissions make them exemplary cases for studying the effectiveness of different decarbonisation strategies. Describing their policy frameworks and implementation can offer valuable lessons for other nations.
3. Innovative technological and financial mechanisms: Some selected countries are at the forefront of developing and deploying innovative technologies and financial mechanisms to support decarbonisation. This includes advancements in renewable energy technologies, smart grids, carbon capture and storage (CCS), and green finance instruments. Describing these innovations provides insights into how technological and financial solutions can be scaled and adapted in different regions to achieve decarbonisation goals.

These factors collectively ensure that the case studies provide a comprehensive understanding of the multi-faceted approaches to decarbonisation and the potential pathways for other countries to follow suit. The results obtained are described in the next section.

3. Results and discussion: Current status of decarbonisation

The literature analysis has revealed that the transition toward decarbonisation and a low-carbon economy presents distinct challenges for developed and developing nations. In advanced economies such as

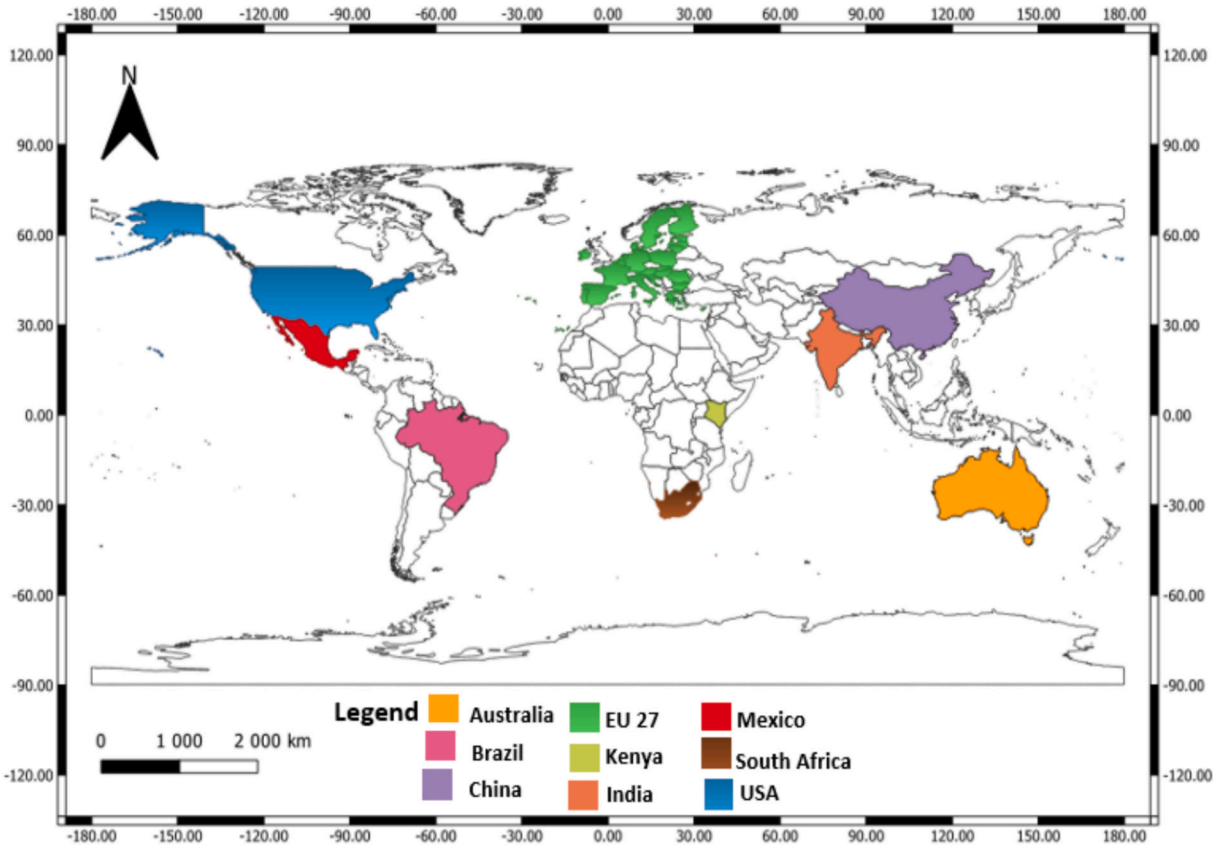

Fig. 2. Geographic scope of the study
(Source: author's elaboration).

Germany, ample financial resources, technological prowess, and established infrastructures enable the extensive uptake of renewable energy sources and the enactment of carbon mitigation measures. As the largest economy in Europe and the primary contributor to carbon emissions, Germany has set the ambitious goal of achieving greenhouse gas neutrality by 2045. Germany has also demonstrated notable advancements in this realm, setting ambitious goals to retire coal-fired power plants and emphasising the expansion of its renewable energy sector, particularly in wind and solar energy (Husarek et al., 2021; Keles and Yilmaz, 2020; Sgarciu et al., 2023). However, Germany's temporary return to coal during the 2022–2023 winter energy crisis raised concerns about its decarbonisation targets and the durability of its climate policies. This move underscored the importance of accelerating renewable energy investments to enhance energy security (Wiertz et al., 2023).

In contrast, a developing country like Brazil faces more significant challenges due to its rapidly growing energy demands and limited financial capacity to deploy clean technologies. As the 11th largest economy globally and with a population exceeding 200 million, Brazil has committed itself to an ambitious target of reducing its greenhouse gas emissions by half by the year 2030. However, its decarbonisation efforts are further complicated by the need to balance environmental sustainability with providing affordable energy access to its sizeable population, many of whom still lack reliable electricity. Indeed, Brazil's climate strategy is deeply tied to land use and deforestation policies. Historical reliance on hydroelectric power has enabled significant progress in renewable energy, but political shifts have undermined consistent enforcement of anti-deforestation efforts. Further, Brazil's advancements in biodiesel production have contributed to reducing emissions in the transportation sector, yet deforestation remains a significant barrier, undermining its overall emissions reduction targets (Hebeda et al., 2023; Köberle et al., 2020; da Silva et al., 2022). Thus, while both nations acknowledge the urgency of climate action, the relative ease or difficulty of executing decarbonisation strategies can vary substantially between developed and developing countries (Hebeda et al., 2023; Köberle et al., 2020).

In fact, decarbonisation efforts in developing nations are beset by several challenges, notably financial constraints, technological deficits, and the imperative for economic development. Firstly, financial limitations (Emodi et al., 2022) and lack of infrastructure (Di Silvestre et al., 2018) hinder substantial investments in requisite infrastructure and innovative solutions. Like other technological innovations, low-carbon technologies require substantial upfront capital investments in research and development, adaptation to local contexts, and large-scale deployment (Pigato et al., 2020). Further, many competing economic and social priorities, such as healthcare, education, and poverty alleviation, put immense pressure on public funds (Hadfield and Cook, 2019). Indeed, developing countries often face the dual challenge of driving economic growth through industrialisation and infrastructure development while meeting urgent social welfare needs, such as reducing poverty and expanding access to education and healthcare. These priorities can sometimes compete with decarbonisation efforts, as resources are diverted to immediate socio-economic challenges. Accordingly, policymakers must balance mitigating environmental impacts and fostering economic growth, job creation, and poverty alleviation. This precarious position makes it difficult to allocate sufficient funds toward decarbonisation initiatives. Additionally, access to affordable financing and investment capital for renewable energy projects may be limited, hindering the scaling up of renewable energy deployment in developing countries and, more so, the high upfront cost needed (Warren, 2020).

Secondly, the lack of access to cutting-edge clean energy technologies and insufficient technological capacity perpetuate reliance on

Table 1
Overview of decarbonization efforts in various developed and developing countries and regions.

Case study country	Nature of the effort	Main challenges	Source
USA	- Despite significant regional and partisan divisions, the USA has implemented landmark legislation like the Inflation Reduction Act 2022, representing a major federal-level shift toward decarbonisation. This is complemented by state-level initiatives, showcasing the complex multi-level governance landscape shaping U.S. climate action. - In 2021, The USA has re-joined the Paris Agreement and set a target to reduce greenhouse gas emissions by 50–52 % below 2005 levels by 2030. However, on Jan 20, 2025, the new Trump administration withdrew from the Paris Agreement. - The Inflation Reduction Act 2022 provides $369 billion in climate incentives and tax credits for clean energy projects and technologies. - Efforts have been sector-specific and driven at the state/local level, with significant regional variations. - Carbon capture and storage (CCS) and hydrogen are important tools.	- The lack of cohesive nationwide policies and partisan divisions pose hurdles for accelerated, economy-wide decarbonisation efforts.	(Bang, 2021; Bayulgen, 2020)
EU 27	- The EU is a global leader in climate policy, driven by the European Green Deal targeting net-zero emissions by 2050. Legally binding laws and funding mechanisms, like the Innovation Fund, support its goals. However, balancing diverse member states' energy needs remains challenging despite progress in phasing out coal and advancing cross-border energy infrastructure. - The EU has set legally binding targets to reduce greenhouse gas emissions by at least 55 % by 2030 compared to 1990 and achieve net-zero emissions by 2050. - The European Green Deal, approved in 2020, is the EU's strategy to transition to a sustainable economy, aiming to decarbonise all sectors while enhancing competitiveness. - Wind, solar, and bioenergy, among other renewable sources, rapidly expand to achieve a 32 % share in final energy consumption by 2030. - Another central focus area is improving energy efficiency. - The European Commission has proposed phasing out internal combustion engine cars by 2035. - Funding mechanisms like the Innovation Fund support low-carbon technologies and industrial decarbonisation projects. - Individual EU member states have also set national energy and climate plans.	- Ensuring a just transition for sectors/regions dependent on fossil fuels. - Mobilising investments and strengthening cross-border energy infrastructure.	(European Commission, 2018, 2019; Giannakis and Zittis, 2021; Lagioia et al., 2023)
Germany	- Germany has long been a pioneer in renewable energy, with its *Energiewende* (energy transition) policy leading to significant investments in wind and solar power. - The country's ambitious goals to achieve greenhouse gas neutrality by 2045 and reduce emissions by 65 % compared to 1990 levels by 2030 under its Climate Action Plan (Klimaschutzgesetz, reflect its leadership. - Energy efficiency measures across industries, buildings, and transportation are the major focus. - Germany will gradually phase out coal to generate electricity by 2038. - Renewable energy sources are being rapidly expanded, with a target of 80 % share in electricity by 2030.	- High costs, impacts on industries/jobs, upgrading energy infrastructure, and integrating renewable energy sources.	(Husarek et al., 2021; Keles and Yilmaz, 2020; Sgarciu et al., 2023)
Italy	- Italy's decarbonisation journey has been shaped by its dependence on natural gas and EU climate commitments. - Italy has set a target to reduce greenhouse gas emissions by 55 % by 2030 compared to 1990 levels and achieve net-zero emissions by 2050. - The National Integrated Energy and Climate Plan outlines strategies across sectors like increasing renewable energy sources, improving energy efficiency, sustainable mobility, and promoting circular economy principles. - Phasing out coal-fired power plants and decarbonising the electricity sector is a priority. - Industrial decarbonisation focuses on energy-intensive sectors.	- Italy still relies heavily on natural gas and faces infrastructure upgrades to accelerate its decarbonisation in line with EU climate commitments.	(Frilingou et al., 2023; Pastore et al., 2022; Vellini et al., 2020)
France	- France's low-carbon electricity grid, dominated by nuclear energy, has long provided a foundation for its climate policy. The government's focus on increasing renewable capacity while maintaining nuclear reliance showcases its dual strategy. - France has set a target to achieve carbon neutrality by 2050 as part of the Paris Agreement and the European Green Deal goals. - Nuclear power accounts for around 70 % of France's electricity generation, providing a relatively low-carbon baseload supply.	- Phasing out remaining fossil fuels, ensuring a just transition for affected sectors and workers, and managing intermittency from increased renewable energy.	(International Energy Agency, 2021; Mathy et al., 2015)

(*continued on next page*)

Table 1 (*continued*)

Case study country	Nature of the effort	Main challenges	Source
	- The country aims to install over 100 GW of solar and 34 GW of onshore wind capacity by 2050. - Energy efficiency measures target the building sector through renovation programs and stricter construction standards.		
Finland	- Finland's decarbonisation strategy is among the most ambitious, aiming for carbon neutrality by 2035. The country seeks to become the world's first fossil fuel-free welfare society, leveraging its leadership in biomass gasification and sustainable forestry practices to drive innovation. - In the energy sector, Finland aims to phase out coal by 2029 and increase the share of renewable energy sources to over 50 % by 2030. - Finland has pioneered technologies like biomass gasification and sustainable forestry practices. - Finland is exploring emerging technologies like hydrogen, Power-to-X, and Carbon Capture and Storage (CCS) for hard-to-abate sectors.	- Overreliance on forest biomass - Decarbonising energy-intensive industries remains a major technological and economic challenge. - High energy consumption. - Integrating variable renewable energy.	(Groundstroem, 2023; Pilpola et al., 2019; Sillman et al., 2023)
Australia	- Australia has indicated its intent to attain a net zero emissions target by 2050 in alignment with its sustainable development goals. - However, the country has not planned or determined to eliminate generation entirely from fossil fuel. It continues to be one of the world's main exporters of coal and gas to other countries. - Carbon sequestration augmented by carbon capture technologies is considered a potential solution to mitigate carbon emissions, but its overall efficacy as a grand solution is not yet entirely convincing. - Among renewable energies, solar, wind and hydro energies are considered significant potential ones to reduce emissions from its current energy mix as such adoption on a large scale is subject to supportive policies as well as plans for grid integration and expansion in various regions of the country.	- Fossil fuels remain a hegemony attached to the country's economy. - Renewable energies are options subject to complementary policies. - Carbon sequestration and related technologies to offset emissions from fossil fuel utilisation require further examination of its viability.	(Elavarasan et al., 2024; Heesh, 2021; Lucas, 2022; Wright et al., 2021)
China	- China is the world's second-largest economy in East Asia, characterised as a developing economy, China has pledged to achieve carbon neutrality by 2060 under the Paris Agreement. - Such a decarbonisation attempt is crucial in alignment with the country's emphasized sustainable development initiatives, which have measurable implications for global climate change given the evidence that the world has been experiencing more severe climate crises than before. - China has scaled its utilisation of renewable energy in its energy mix in electric power generation to support its carbon neutralisation target. It is expected to reach its carbon emission peak in 2030. - Policy uncertainties could affect scaling up the adoption of renewable energy, and coal is likely to remain a significant fuel source for power generation to ensure the stability of its power grid and support the escalating demand from ongoing economic activities. Clean coal technologies are deployed to mitigate carbon emissions from such facilities.	- Continued reliance on coal despite efforts to scale up the use of renewable energy. - Economic development still considered a priority. - Policy uncertainties in balancing between economic and sustainable development.	(Lin and Liu, 2024; Pata, 2024; Zhang et al., 2022)
Brazil	- Brazil's climate strategy is heavily tied to land use, with deforestation being a central challenge. The country's abundant renewable energy resources, such as hydropower and biofuels, position it as a leader in the global south. - Brazil's advancements in biodiesel production have contributed to reducing emissions in the transportation sector, yet deforestation remains a significant barrier, undermining its overall emissions reduction targets. - Brazil committed to reducing its GHG emissions by 50 % by 2030. - The agriculture, forests, and land use sector forms the core of Brazil's Nationally Determined Contributions (NDCs) to the Paris Agreement (PA). - Brazil has also pledged to end illegal deforestation, while energy targets aim for increased renewable energy shares and improved efficiency by 2030. - Brazil intends to prioritise decarbonisation efforts in sectors that pose significant challenges for emissions reduction, such as its steel, cement, aluminium, and aviation industries.	- Deforestation and land use change - Dependence on fossil fuels - Expansion of agribusiness - Renewable energy supply reliability and affordability - Lack of infrastructure	(Hebeda et al., 2023; Köberle et al., 2020; da Silva et al., 2022)
South Africa	- South Africa's decarbonisation is heavily constrained by its reliance on coal, which accounts for over 80 % of its electricity. While the government has initiated renewable energy programs, transitioning coal-dependent communities and managing the economic impacts remain significant challenges.	- High reliance on coal accounts for over 80 % of its electricity generation. - Funding constraints ensuring a just transition for coal communities	(Msimango et al., 2023; Tyler and Hochstetler, 2021)

(*continued on next page*)

Table 1 (*continued*)

Case study country	Nature of the effort	Main challenges	Source
	- The government has set a target to reduce greenhouse gas emissions by at least 28 % by 2030. - South Africa is pursuing renewable energy sources like solar, wind, and concentrating solar power (CSP) to diversify its energy mix and reduce reliance on coal. - In the transportation sector, efforts include promoting biofuel blending and adopting electric vehicles. - Restoring ecosystems and better land management practices in agriculture and forestry are also part of the mitigation strategy.	- Managing the impacts of decarbonisation on energy-intensive industries.	
India	- India faces the dual challenge of meeting growing energy demand while decarbonising its economy. Its ambitious renewable energy targets have made it a leader in solar and wind power, yet reliance on coal and economic constraints hinder progress. - India ranks the third-largest emitter worldwide despite its low per-capita emissions, which stand at 1.8 tons of CO_2 (versus the United States at 14.7 and China at 7.6). - In 2021, at COP26, India announced its ambition to become a net-zero emitter by 2070. - India has established ambitious goals to derive 50 % of its installed power generation capacity from non-fossil fuel-based energy resources. - India is currently ranking fifth globally in installed solar power capacity and fourth in wind power capacity, with its combined renewable energy capacity surpassing 100 gigawatts.	- Rapid energy demand growth. - Reliance on coal - Financing constraints. - Energy access - Agriculture and land use. - Public awareness and behaviour change.	(McKinsey, 2022; Shankar et al., 2022)
Mexico	- Mexico's energy transition has been shaped by its heavy reliance on oil and gas, which remain central to its economy. While the country has made strides in expanding renewable energy and energy efficiency programs, political shifts and an ageing energy infrastructure limit its progress. - Mexico aims to generate 35 % of its electricity from clean energy sources by 2024 and 50 % by 2050. - Mexico is investing heavily in expanding its renewable energy capacity, particularly wind and solar power. - Mexico has programs to improve energy efficiency across sectors like housing, transportation, and industry to reduce emissions. - The government provides subsidies and tax incentives to promote private investment in clean energy projects.	- High reliance on fossil fuels, especially oil and gas, which are critical to its economy. - Deforestation and land-use change. - Ageing grid infrastructure. - Regional disparities.	(Buira et al., 2021; Elizondo et al., 2017; Veysey et al., 2016)
Kenya	- Kenya has positioned itself as a renewable energy leader in Africa, with over 70 % of its electricity already derived from renewables, such as geothermal and hydropower. However, infrastructural limitations and financing constraints hinder the scaling of clean energy technologies. - Kenya has set a target to achieve 100 % renewable energy for its overall electricity supply by 2030. - The country is already a regional leader in renewable energy, with around 73 % of its electricity coming from renewable sources as of 2020. - Kenya aims to increase ethanol and biodiesel blending with gasoline and diesel in the transportation sector to reduce emissions. - Kenya is working to restore its forest cover through initiatives like banning logging and promoting agroforestry to increase carbon sinks.	- Challenges remain regarding financing, technological capabilities, and infrastructural constraints to accelerate decarbonisation across all sectors.	(Kehbila et al., 2021; Ogeya et al., 2021; Wambui et al., 2022)

carbon-intensive sources (Babayomi et al., 2022). Indeed, since a substantial proportion of patented inventions about clean energy solutions originate from advanced industrialised nations such as the European Union member states, Japan, the United States, as well as China, a significant technology gap exists wherein developing countries are mainly dependent on developed economies for the transfer of cutting-edge innovations (Babayomi et al., 2022).

Thirdly, for power generation, most developing countries still rely on old, inefficient infrastructure prone to high GHG emissions (Kabeyi and Olanrewaju, 2022), and no new investments are being made into sustainable green grids. Transitioning away from fossil fuels requires significant policy reforms, investment, and restructuring of energy systems, which is still challenging as sometimes countries are reluctant due to the reasons above. Fossil fuels remain high contributors to air pollutants such as carbon dioxide, nitrogen oxide, and other GHGs (Matandirotya and Burger, 2023).

The case studies have also revealed some interesting trends. Firstly, it can be seen that while certain countries have achieved notable progress in curtailing their carbon emissions, others grapple with fundamental challenges that impede the implementation of effective decarbonisation strategies. Also, the interaction between the economy, energy systems, and environment is different under different decarbonisation scenarios. Furthermore, while countries like Kenya and South Africa prioritise renewable energy expansion to improve energy security, others, such as Brazil and Mexico, face significant challenges in addressing deforestation and land-use change. These unique contexts highlight the diverse pathways and barriers to decarbonisation in the Global South. Table 1 provides an overview of some of the sampled developing and industrialised countries' efforts to achieve decarbonisation.

It can be seen that decarbonisation involves multiple strategies and technologies, a trend also outlined in the literature (Nurdiawati and Urban, 2021). There are five main lessons learned from the case studies

on decarbonisation.

Firstly, policy and regulatory frameworks are essential for catalysing and sustaining decarbonisation efforts. Mitigating climate change has evolved beyond mere rhetorical commitments and high-level pledges. Tangible progress now hinges on the formulation and execution of transformative policies that catalyse concrete action across all sectors and segments of society (World Bank, 2023). Effective climate policies necessitate consistent, predictable, and long-term policy signals that provide clarity and certainty to investors, businesses, and consumers. Frameworks prone to frequent changes or lack a long-term vision tend to create uncertainty, deterring investment in low-carbon technologies. The substantial investments and entrenched interests in existing fossil fuel supply chains and carbon-intensive industries both economic incentives and political pressure to keep the high-carbon status quo (Pigato et al., 2020). For example, the United States' repeated shifts in climate policy—including rejoining and later withdrawing from the Paris Agreement—have created policy instability, undermining long-term investments (Table 1). In contrast, stable and well-designed policies, bolstered by robust enforcement mechanisms, instil confidence among stakeholders, encourage the adoption of clean technologies, and support the behavioural changes necessary for a successful transition to low-carbon economies. The right policies can make investments in cleaner industrial processes more profitable and significantly expedite emissions reductions. Effective policies can also disseminate innovations through international supply chains, benefiting companies in countries that lack robust policies of their own (Rissman et al., 2020). For instance, Germany's *Energiewende* policy and its legally binding climate commitments have demonstrated how long-term policy stability fosters investment in renewable energy (Table 1).

Secondly, well-designed incentive structures and support mechanisms are pivotal for driving the widespread adoption of clean technologies and catalysing innovation in the low-carbon sector. Successful decarbonisation strategies often encompass a judicious blend of regulatory instruments and financial incentives. On the regulatory front, policies like obligatory objectives, strict emissions regulations, and carbon pricing structures give businesses and consumers strong financial incentives to switch to sustainable alternatives. Financial incentives, such as grant programs, tax credits, and targeted subsidies, support these regulatory initiatives by helping to lower the upfront costs of clean energy and developing technologies. This method, adequately calibrated and adapted to national circumstances, acts as a potent catalyst, punishing carbon-intensive processes while rewarding and encouraging the development, implementation, and growth of low-emission technology and business models (Pigato et al., 2020). For example, the EU's Innovation Fund provides substantial financial support for industrial decarbonisation projects, ensuring that firms can transition toward low-carbon production methods (Table 1).

The third critical factor is the transfer of low-carbon technologies from industrialised countries to the developing world. Leveraging and scaling up the deployment of currently available low-carbon technologies (LCTs) across four pivotal sectors—energy, industry, transportation, and construction—holds immense potential for reducing global emissions by almost two-thirds (Pigato et al., 2020). Successful technology transfer in the context of low-carbon transitions extends far beyond the mere physical acquisition of hardware components like solar panels or wind turbines. For effective adoption and sustained impact, the transfer process must also encompass the dissemination of technical knowledge, expertise, and capabilities necessary to comprehend, operate, and maintain these advanced technologies. This capacity-building dimension is crucial for enabling local communities and industries to fully harness the potential of imported innovations and adapt them to context-specific needs (Cirera and Maloney, 2017; Lema and Lema, 2012). China's large-scale expansion of renewable energy and battery storage illustrates how policy-backed technology transfer can accelerate low-carbon transitions in developing economies. Likewise, Kenya's leadership in geothermal energy reflects how targeted investments in technology can enhance a country's renewable energy capacity, even in resource-constrained settings (Table 1).

Fourthly, adopting inclusive and participatory approaches throughout the policy-making and implementation phases of decarbonisation initiatives is essential. A fundamental transformation is unlikely to happen without a high level of stakeholder engagement in the policy development process (Dorian et al., 2006). Strategies formulated through processes that actively engage diverse stakeholders, encompassing industries, local communities, civil society organisations, and environmental advocacy groups, tend to yield more comprehensive and widely accepted decarbonisation roadmaps. For example, Brazil's decarbonisation strategy heavily depends on land use policies, but conflicting interests between agribusiness and environmental conservation have created challenges in achieving deforestation reduction goals (Table 1). Participatory approaches generate a feeling of ownership and buy-in among stakeholders by addressing problems from all parts of society, embracing various viewpoints, and encouraging open communication. This reduces the likelihood of opposition or reaction and strengthens the final policy's resilience, context-sensitivity, and legitimacy. Ultimately, these inclusive governance models raise the chances of effective implementation by coordinating decarbonisation activities with the requirements, goals, and circumstances of the many stakeholders affected by the shift (Linton et al., 2020).

Fifthly, monetising social impacts is key to decarbonisation efforts for both developing and industrialised countries. Monetising social impacts is an increasingly relevant approach to evaluating and justifying policies, especially for interventions focusing on decarbonisation, climate change mitigation, and sustainable development (Yao et al., 2020). By assigning monetary value to social benefits or costs, this framework bridges the gap between economic analysis and social outcomes therefore providing a foundation for comprehensive decision-making (Diaz-Sarachaga, 2021). For most developing countries, there is often a lack of capital to transition to clean energy; however, through monetising benefits such as improved air quality, reduced health expenditures, and job creation in the renewable sector, governments can justify subsidies and attract international financing. Monetising social impacts remains a powerful tool for demonstrating the value of decarbonisation as well as sustainable development initiatives (Arendt et al., 2020). Translating social and environmental benefits into monetary terms bridges the gap between economic decision-making and social outcomes (Yao et al., 2020). For instance, India has emphasized the co-benefits of decarbonisation in job creation and public health to justify its ambitious renewable energy targets despite financial constraints (Table 1). However, the process must be approached carefully, with attention to data quality, equity, and methodological rigor. When done effectively, monetisation can unlock funding, guide policy, and ensure social benefits are central to development strategies. Monetising social impacts is a transformative tool that connects economic analysis with social and environmental priorities (Thi et al., 2016). By quantifying benefits such as improved health, reduced inequality, and enhanced climate resilience, monetisation enables better-informed decision-making and appropriate resource allocation (Ghorbani Pashakolaie et al., 2023). At the same time, challenges such as the unavailability of data limitations and equity considerations remain, and the utilisation of monetised social impacts into policy frameworks worldwide, including the global south.

A key lesson emerging from this analysis is the value of addressing decarbonisation strategies at both regional and national scales, as illustrated through the inclusion of the EU27 and some member states. Although the EU27 operates under common climate policies like the European Green Deal, member states like France and Germany often implement these frameworks differently due to varying energy profiles, economic conditions, and domestic political considerations. For instance, Germany's reliance on coal contrasts with France's nuclear-dominated energy mix, necessitating distinct approaches to achieve EU-wide decarbonisation targets. Accordingly, the regional framework

provided by the EU27 highlights the benefits of collective action, shared resources, and coordinated policies, which align member states under common objectives. However, the national-level analysis reveals the importance of tailoring strategies to account for each country's unique challenges, priorities, and resource capacities (European Commission, 2020; Jordan and Moore, 2023). This multi-scale approach underscores the necessity of balancing regional coordination with localised implementation to effectively address the diverse socio-economic and institutional contexts in which decarbonisation occurs. These findings suggest that successful decarbonisation efforts require robust regional frameworks complemented by adaptive, country-specific strategies to ensure both alignment with overarching goals and responsiveness to local needs. This lesson has broader implications for other regions seeking to harmonise collaborative efforts with individual nation-state initiatives.

Further, social acceptance is a critical element in implementing decarbonisation measures. Its added value for decarbonisation strategies in developing countries lies in enhanced community engagement and cooperation. When local populations support these initiatives, implementation becomes smoother and more effective. Social acceptance fosters trust, encourages participation, and aligns projects with community needs, leading to better resource allocation and sustainability. For instance, South Africa's dependence on coal has created significant resistance to decarbonisation policies among affected communities, underscoring the need for inclusive transition strategies (Table 1). Similarly, in Brazil, balancing decarbonisation with agribusiness interests has been a challenge, as deforestation linked to agricultural expansion directly conflicts with the country's emissions reduction goals. Efforts to enforce environmental policies have faced pushback from industry stakeholders, underscoring the importance of social and economic alignment in climate strategies (Table 1). Furthermore, it helps mitigate resistance, ensuring long-term commitment to climate goals and creating a shared vision for a greener future that benefits everyone (Milani et al., 2024; Neves et al., 2022).

Moreover, it is essential to emphasize that while case studies from industrialised nations offer valuable insights, their direct applicability to developing economies is often constrained by significant differences in institutional capacity, financial resources, and socio-economic priorities. Decarbonisation strategies developed in the Global North cannot simply be transplanted into the Global South without thoughtful adaptation. The diverse socio-economic systems, governance structures, and limited resources in the Global South require tailored strategies suitable for local needs and capabilities. Recent studies highlight this issue, displaying the need to keep global consumption within planetary limitations (Tian et al., 2024b) and the unequal consequences of rising energy costs on vulnerable populations, like the elderly and low-income groups (Tian et al., 2024a). The findings underscore the need for adapted and equitable climate policies for developing countries—strategies stressing scalable, affordable solutions, use of international cooperation, and progressively strengthening institutional capacities.

4. Conclusion: The way ahead

Drawing upon an extensive review of literature, reports, and case studies from industrialised and developing countries, this research has elucidated the multi-faceted requirements for successfully implementing decarbonisation strategies in the Global South. The findings underscore that there are now some clear signs of engagement toward decarbonisation, but these are not even. Some countries are quite active, but others are lagging behind. The case studies of industrialised nations, such as the United States, the European Union, Germany, Italy, France, and Finland, have shed light on the innovative policies, technologies, and best practices employed by countries at the forefront of decarbonisation efforts. These experiences offer valuable lessons for developing economies, highlighting the potential pitfalls, challenges, and opportunities inherent in the low-carbon transition.

Countries aiming to decarbonise their economies can systematise efforts through comprehensive and multi-faceted strategies. Firstly, they should establish clear, long-term goals aligned with international agreements like the Paris Agreement. These goals need to be legally binding to ensure accountability. Secondly, countries must develop detailed roadmaps that outline sector-specific targets, timelines, and policies. These roadmaps should be adaptable to incorporate technological advancements and changing economic circumstances.

Another critical step is the creation of robust regulatory frameworks that incentivise low-carbon technologies and penalise high-carbon emissions. This can include carbon pricing mechanisms such as carbon taxes or cap-and-trade systems. Governments must further promote research and development in clean energy technologies, offering grants and tax incentives to stimulate innovation in renewable energy, energy storage, and energy efficiency. Public investment in infrastructure is another key step in attempts to decarbonise economies. This involves upgrading national grids to accommodate renewable energy sources, expanding public transportation systems, and retrofitting buildings for energy efficiency. Strategic investment in smart grids, electric vehicle charging networks (especially in industrialised countries with the infrastructure to support electric vehicles), and hydrogen production facilities may also support the transition to a low-carbon economy.

Moreover, countries should foster public-private partnerships to leverage private-sector investment. Additionally, green finance mechanisms, like green bonds and sustainability-linked loans, should be promoted to attract investment from institutional investors and international development banks. Education and workforce training programmes also are necessary to ensure that the labour force is equipped with the skills needed for new green jobs. Social policies should also be implemented to support communities and industries adversely affected by the transition, ensuring a just and inclusive transition.

The need to tackle global climate change via coordinated decarbonisation initiatives cannot be overstated. Rising temperatures, sea-level rise, severe weather events, and ecological changes threaten human well-being, economic stability, and environmental sustainability. While the need for decarbonisation is widely recognised, the approaches and implementation obstacles differ significantly across industrialised and developing countries. Significant investment is required, potentially amounting to trillions of dollars globally, to support decarbonisation efforts fully. This investment is not merely a cost but an opportunity to stimulate economic growth, create jobs, and enhance energy security. By taking a systematic and well-coordinated approach, countries can effectively decarbonise their economies while fostering sustainable development.

Further, the social acceptance of decarbonisation strategies in developing countries is important for successful implementation. Engaging national governments and local communities in decision-making fosters trust and ensures that initiatives align with their needs. Education and awareness campaigns can help demystify carbon reduction efforts, highlighting benefits such as improved air quality, job creation, and energy security. Additionally, policymakers should consider cultural values and socio-economic contexts to promote inclusive strategies. By prioritising community involvement and transparency, developing countries can enhance social support, leading to more effective and sustainable decarbonisation efforts that address both environmental goals and local development priorities (Sovacool et al., 2021).

The task of reconciling decarbonisation initiatives with pressing social and economic priorities is especially difficult in developing countries. As previously stated, limited financial resources frequently force governments to choose between investing in renewable energy and meeting immediate social needs. Ensuring that decarbonisation measures do not jeopardize social acceptance is critical to their long-term viability. Policies must be crafted to match climate goals with socio-economic growth in order to gain widespread public support and

ensure long-term implementation.

Furthermore, to ensure the successful implementation of decarbonisation strategies in developing economies, it is important to adapt lessons and solutions from industrialised nations to local contexts. This requires leveraging international support, such as climate finance initiatives and cooperation programs, to address financial and technical resource gaps. Partnerships can help fund renewable energy projects, provide advanced technologies, and build local expertise through training programs. Developing regionally appropriate regulatory frameworks is equally essential. These frameworks should align with local priorities, focusing on scalable solutions, such as small-scale renewable energy systems or sustainable agriculture practices, while fostering economic resilience. Additionally, education and community-driven approaches are essential for social acceptance and participation. Public awareness campaigns, inclusive policy-making, and capacity-building programs can empower communities and ensure alignment with societal goals.

Adapting these lessons ensures decarbonisation efforts are feasible, equitable, and sustainable, addressing the unique challenges of developing economies while contributing to global climate goals.

Another important requirement for successful decarbonisation in developing countries is the need for a holistic, integrated approach that addresses the intersections between energy, water, and food systems, often conceptualised as the Water–Energy–Food (WEF) nexus. Sustainable development in the Global South cannot be achieved through isolated efforts in a single sector; instead, it requires a systemic understanding of how energy production affects water availability, how water use impacts food security, and how agricultural practices influence energy demand (Dupar and Oates, 2012; Hoff, 2011; White et al., 2018). By incorporating the WEF nexus into decarbonisation strategies, policymakers can ensure that efforts to reduce emissions are not only practical but also equitable, addressing the broader needs of communities and enhancing resilience against climate-related challenges.

Finally, it is equally important to recognise that the decarbonisation landscape is rapidly evolving, and new challenges, opportunities, and best practices will likely emerge as nations embark on this transformative journey. Continuous monitoring, evaluation, and adaptation of strategies will be necessary to ensure their relevance and effectiveness over time.

CRediT authorship contribution statement

Walter Leal Filho: Writing – review & editing, Writing – original draft, Validation, Methodology, Conceptualization. **Tarek Ben Hassen:** Writing – review & editing, Writing – original draft, Conceptualization. **Newton Matandirotya:** Writing – review & editing, Writing – original draft, Conceptualization. **Artie Ng:** Writing – original draft, Conceptualization.

Declaration of competing interest

The authors declare no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Acknowledgments

This paper is part of the “100 papers to accelerate climate change mitigation and adaptation” initiative led by the International Climate Change Information and Research Programme (ICCIRP).

Data availability

No data was used for the research described in the article.

References

Abram, S., Atkins, E., Dietzel, A., Hammond, M., Jenkins, K., Kiamba, L., Kirshner, J., Kreienkamp, J., Pegram, T., Vining, B., 2020. Just Transition: Pathways to Socially Inclusive Decarbonisation. https://www.ucl.ac.uk/public-policy/justtransition-pathways-socially-inclusive-decarbonisation.

Abram, S., Atkins, E., Dietzel, A., Jenkins, K., Kiamba, L., Kirshner, J., Kreienkamp, J., Parkhill, K., Pegram, T., Santos Ayllón, L.M., 2022. Just transition: A whole-systems approach to decarbonisation. Clim. Pol. 22 (8), 1033–1049. https://doi.org/10.1080/14693062.2022.2108365.

Arendt, R., Bachmann, T.M., Motoshita, M., Bach, V., Finkbeiner, M., 2020. Comparison of different monetization methods in LCA: A review. Sustainability (Switzerland) 12 (24), 1–39. https://doi.org/10.3390/su122410493.

Babaniyi, B.R., Adebomi, J.I., Olowoyeye, B.R., Daramola, O.E., Bisi-Omotosho, A., Areo, I.F., 2024. Decarbonization and the future fuels. In: Microbial Biotechnology for Bioenergy. Elsevier, pp. 81–96. https://doi.org/10.1016/B978-0-443-14112-6.00005-5.

Babayomi, O.O., Dahoro, D.A., Zhang, Z., 2022. Affordable clean energy transition in developing countries: Pathways and technologies. IScience 25 (5), 104178. https://doi.org/10.1016/j.isci.2022.104178.

Bang, G., 2021. The United States: conditions for accelerating decarbonisation in a politically divided country. Int. Environ. Agreem.: Politics Law Econ. 21 (1), 43–58. https://doi.org/10.1007/s10784-021-09530-x.

Bayulgen, O., 2020. Localizing the energy transition: town-level political and socio-economic drivers of clean energy in the United States. Energy Res. Soc. Sci. 62, 101376. https://doi.org/10.1016/j.erss.2019.101376.

Buira, D., Tovilla, J., Farbes, J., Jones, R., Haley, B., Gastelum, D., 2021. A whole-economy deep Decarbonization pathway for Mexico. Energ. Strat. Rev. 33, 100578. https://doi.org/10.1016/j.esr.2020.100578.

Cernev, T., Fenner, R., 2020. The importance of achieving foundational sustainable development goals in reducing global risk. Futures 115, 102492. https://doi.org/10.1016/j.futures.2019.102492.

Cirera, X., Maloney, W.F., 2017. The Innovation Paradox: Developing-Country Capabilities and the Unrealized Promise of Technological Catch-Up. World Bank, Washington, DC. https://doi.org/10.1596/978-1-4648-1160-9.

Silva, T.B., da, Baptista, P., Santos Silva, C.A., Santos, L., 2022. Assessment of decarbonization alternatives for passenger transportation in Rio de Janeiro, Brazil. Transp. Res. Part D: Transp. Environ. 103 (November 2021), 103161. https://doi.org/10.1016/j.trd.2021.103161.

Das, A., Ghosh, A., 2023. Vision net zero: A review of decarbonisation strategies to minimise climate risks of developing countries. Environ. Dev. Sustain. https://doi.org/10.1007/s10668-023-03318-6.

De Rosa, M., Gainsford, K., Pallonetto, F., Finn, D.P., 2022. Diversification, concentration and renewability of the energy supply in the European Union. Energy 253, 124097. https://doi.org/10.1016/j.energy.2022.124097.

Di Silvestre, M.L., Favuzza, S., Riva Sanseverino, E., Zizzo, G., 2018. How Decarbonization, digitalization and decentralization are changing key power infrastructures. Renew. Sust. Energ. Rev. 93 (May), 483–498. https://doi.org/10.1016/j.rser.2018.05.068.

Diaz-Sarachaga, J.M., 2021. Monetizing impacts of Spanish companies toward the sustainable development goals. Corp. Soc. Responsib. Environ. Manag. 28 (4), 1313–1323. https://doi.org/10.1002/csr.2149.

Dixon, J., Bell, K., Brush, S., 2022. Which way to net zero? A comparative analysis of seven UK 2050 decarbonisation pathways. Renewable and Sustainable Energy Transition 2, 100016. https://doi.org/10.1016/j.rset.2021.100016.

Dorian, J.P., Franssen, H.T., Simbeck, D.R., 2006. Global challenges in energy. Energy Policy 34 (15), 1984–1991. https://doi.org/10.1016/j.enpol.2005.03.010.

Dupar, M., Oates, N., 2012. Getting to grips with the water-energy-food “nexus.”. https://cdkn.org/story/getting-to-grips-with-the-water-energy-food-nexus.

Economidou, M., Todeschi, V., Bertoldi, P., D’Agostino, D., Zangheri, P., Castellazzi, L., 2020. Review of 50 years of EU energy efficiency policies for buildings. Energ. Buildings 225, 110322. https://doi.org/10.1016/j.enbuild.2020.110322.

Elavarasan, R.M., Nadarajah, M., Shafiullah, G.M., 2024. Multi-criteria decision analysis of clean energy technologies for envisioning sustainable development goal 7 in Australia: Is solar energy a game-changer? Energy Convers. Manag. 321, 119007. https://doi.org/10.1016/j.enconman.2024.119007.

Elizondo, A., Pérez-Cirera, V., Strapasson, A., Fernández, J.C., Cruz-Cano, D., 2017. Mexico’s low carbon futures: An integrated assessment for energy planning and climate change mitigation by 2050. Futures 93, 14–26. https://doi.org/10.1016/j.futures.2017.08.003.

Emodi, N.V., Wade, B., Rekker, S., Greig, C., 2022. A systematic review of barriers to greenfield investment in decarbonisation solutions. Renew. Sust. Energ. Rev. 165 (February), 112586. https://doi.org/10.1016/j.rser.2022.112586.

European Commission, 2018. A clean planet for all a European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A52018DC0773.

European Commission, 2019. The European green Deal. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640%3AFIN.

European Commission, 2020. Stepping up Europe’s 2030 climate ambition - investing in a climate-neutral future for the benefit of our people. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52020DC0562.

Frilingou, N., Xexakis, G., Koasidis, K., Nikas, A., Campagnolo, L., Delpiazzo, E., Chiodi, A., Gargiulo, M., McWilliams, B., Koutsellis, T., Doukas, H., 2023. Navigating through an energy crisis: challenges and progress towards electricity decarbonisation, reliability, and affordability in Italy. Energy Res. Soc. Sci. 96, 102934. https://doi.org/10.1016/j.erss.2022.102934.

Ghorbani Pashakolaie, V., Heydari, K., Almena, A., 2023. Monetization of policy costs and sustainability benefits associated with renewable energy in fossil fuel-rich countries (FFRCs). Environmental and Sustainability Indicators 19, 100271. https://doi.org/10.1016/j.indic.2023.100271.

Giannakis, E., Zittis, G., 2021. Assessing the economic structure, climate change and Decarbonisation in Europe. Earth Syst. Environ. 5 (3), 621–633. https://doi.org/10.1007/s41748-021-00232-7.

Godil, D.I., Yu, Z., Sharif, A., Usman, R., Khan, S.A.R., 2021. Investigate the role of technology innovation and renewable energy in reducing transport sector <scp> CO $_2$ </scp> emission in China: A path toward sustainable development. Sustain. Dev. 29 (4), 694–707. https://doi.org/10.1002/sd.2167.

Groundstroem, F., 2023. Cross-border impacts of climate change affect the energy transition: Insights from the Finnish energy sector. Clim. Chang. 176 (11), 146. https://doi.org/10.1007/s10584-023-03619-9.

Hadfield, P., Cook, N., 2019. Financing the low-Carbon City: Can local government leverage public finance to facilitate equitable Decarbonisation? Urban Policy Res. 37 (1), 13–29. https://doi.org/10.1080/08111146.2017.1421532.

Hanna, R., Heptonstall, P., Gross, R., 2024. Job creation in a low carbon transition to renewables and energy efficiency: a review of international evidence. Sustain. Sci. 19 (1), 125–150. https://doi.org/10.1007/s11625-023-01440-y.

Hebeda, O., Guimarães, B.S., Cretton-Souza, G., La Rovere, E.L., Pereira, A.O., 2023. Pathways for deep decarbonization of the Brazilian iron and steel industry. J. Clean. Prod. 401, 136675. https://doi.org/10.1016/j.jclepro.2023.136675.

Heesh, N., 2021. Low carbon policy and market mechanisms to enable carbon capture and storage and decarbonisation in Australia. International Journal of Greenhouse Gas Control 105, 103236. https://doi.org/10.1016/j.ijggc.2020.103236.

Hoff, H., 2011. Understanding the nexus. In: *Background Paper for the Bonn 2011* Conference: The Water, Energy and Food Security Nexus. https://www.sei.org/mediamanager/documents/Publications/SEI-Paper-Hoff-UnderstandingTheNexus-2011.pdf.

Holechek, J.L., Geli, H.M.E., Sawalhah, M.N., Valdez, R., 2022. A global assessment: Can renewable energy replace fossil fuels by 2050? Sustainability 14 (8), 4792. https://doi.org/10.3390/su14084792.

Husarek, D., Schmugge, J., Niessen, S., 2021. Hydrogen supply chain scenarios for the decarbonisation of a German multi-modal energy system. Int. J. Hydrog. Energy 46 (76), 38008–38025. https://doi.org/10.1016/j.ijhydene.2021.09.041.

International Energy Agency, 2021. France energy policy review.

Jahanger, A., Ozturk, I., Chukwuma Onwe, J., Joseph, T.E., Razib Hossain, M., 2023. Do technology and renewable energy contribute to energy efficiency and carbon neutrality? Evidence from top ten manufacturing countries. Sustain Energy Technol Assess 56, 103084. https://doi.org/10.1016/j.seta.2023.103084.

Jordan, A.J., Moore, B., 2023. The durability–flexibility dialectic: the evolution of decarbonisation policies in the European Union. J. Eur. Publ. Policy 30 (3), 425–444. https://doi.org/10.1080/13501763.2022.2042721.

Kabeyi, M.J.B., Olanrewaju, O.A., 2022. Sustainable energy transition for renewable and low carbon grid electricity generation and supply. Frontiers in Energy Research 9 (March), 1–45. https://doi.org/10.3389/fenrg.2021.743114.

Kehbila, A.G., Masumbuko, R.K., Ogeya, M., Osano, P., 2021. Assessing transition pathways to low-carbon electricity generation in Kenya: A hybrid approach using backcasting, socio-technical scenarios and energy system modelling. Renewable and Sustainable Energy Transition 1, 100004. https://doi.org/10.1016/j.rset.2021.100004.

Keles, D., Yilmaz, H.Ü., 2020. Decarbonisation through coal phase-out in Germany and Europe — impact on emissions, electricity prices and power production. Energy Policy 141, 111472. https://doi.org/10.1016/j.enpol.2020.111472.

Köberle, A.C., Rochedo, P.R.R., Lucena, A.F.P., Szklo, A., Schaeffer, R., 2020. Brazil's emission trajectories in a well-below 2 °C world: The role of disruptive technologies versus land-based mitigation in an already low-emission energy system. Clim. Chang. 162 (4), 1823–1842. https://doi.org/10.1007/s10584-020-02856-6.

Lagioia, G., Spinelli, M.P., Amicarelli, V., 2023. Blue and green hydrogen energy to meet European Union decarbonisation objectives. An overview of perspectives and the current state of affairs. Int. J. Hydrog. Energy 48 (4), 1304–1322. https://doi.org/10.1016/j.ijhydene.2022.10.044.

Lau, H.C., Ramakrishna, S., Zhang, K., Radhamani, A.V., 2021. The role of carbon capture and storage in the energy transition. Energy Fuel 35 (9), 7364–7386. https://doi.org/10.1021/acs.energyfuels.1c00032.

Leal Filho, W., Tuladhar, L., Li, C., Balogun, A.-L.B., Kovaleva, M., Abubakar, I.R., Azadi, H., Donkor, F.K.K., 2023. Climate change and extremes: implications on city livability and associated health risks across the globe. International Journal of Climate Change Strategies and Management 15 (1), 1–19. https://doi.org/10.1108/IJCCSM-07-2021-0078.

Lema, R., Lema, A., 2012. Technology transfer? The rise of China and India in green technology sectors. Innov. Dev. 2 (1), 23–44. https://doi.org/10.1080/2157930X.2012.667206.

Lin, B., Liu, Z., 2024. Optimal coal power phase-out pathway considering high renewable energy proportion: A provincial example. Energy Policy 188, 114071. https://doi.org/10.1016/j.enpol.2024.114071.

Linton, S., Clarke, A., Tozer, L., 2020. Strategies and governance for implementing deep Decarbonization plans at the local level. Sustainability 13 (1), 154. https://doi.org/10.3390/su13010154.

Lucas, A., 2022. Fossil networks and dirty power: The politics of decarbonisation in Australia. In: Tindall, D., Stoddart, M.C.J., Dunlap, R.E. (Eds.), Handbook of Anti-Environmentalism. Edward Elgar Publishing. https://doi.org/10.4337/9781839100222.00020.

Mahadevia, D., Lathia, S., Mukhopadhyay, C., 2024. SDG-enabled decarbonisation transport pathways for mid-sized Indian cities. Global Social Challenges Journal 1–10. https://doi.org/10.1332/27523349Y2024D000000005.

Matandirotya, N.R., Burger, R., 2023. An assessment of NO2 atmospheric air pollution over three cities in South Africa during 2020 COVID-19 pandemic. Air Qual. Atmos. Health 16 (2), 263–276. https://doi.org/10.1007/s11869-022-01271-3.

Mathy, S., Criqui, P., Hourcade, J.C., 2015. Pathways to Deep Decarbonization in France.

McKinsey, 2022. Decarbonising India: Charting a pathway for sustainable growth. https://www.mckinsey.com/capabilities/sustainability/our-insights/decarbonising-india-charting-a-pathway-for-sustainable-growth.

Milani, A., Dessi, F., Bonaiuto, M., 2024. A meta-analysis on the drivers and barriers to the social acceptance of renewable and sustainable energy technologies. Energy Res. Soc. Sci. 114, 103624. https://doi.org/10.1016/J.ERSS.2024.103624.

Msimango, N., Orffer, C., Inglesi-Lotz, R., 2023. South Africa's energy policy: prioritizing competition and climate change for decarbonisation. Energy Policy 183, 113815. https://doi.org/10.1016/j.enpol.2023.113815.

Neves, C., Oliveira, T., Santini, F., 2022. Sustainable technologies adoption research: A weight and meta-analysis. Renew. Sust. Energ. Rev. 165, 112627. https://doi.org/10.1016/J.RSER.2022.112627.

Nurdiawati, A., Urban, F., 2021. Towards deep Decarbonisation of energy-intensive industries: A review of current status. Technologies and Policies. Energies 14 (9), 2408. https://doi.org/10.3390/en14092408.

Ogeya, M.C., Osano, P., Kingiri, A., Okemwa, J.M., 2021. Challenges and opportunities for the expansion of renewable electrification in Kenya. In: Building Innovation Capabilities for Sustainable Industrialisation. Routledge, pp. 46–70. https://doi.org/10.4324/9781003054665-3.

Oyewo, A.S., Aghahosseini, A., Ram, M., Breyer, C., 2020. Transition towards decarbonised power systems and its socio-economic impacts in West Africa. Renew. Energy 154, 1092–1112. https://doi.org/10.1016/j.renene.2020.03.085.

Pastore, L.M., Lo Basso, G., Cristiani, L., de Santoli, L., 2022. Rising targets to 55% GHG emissions reduction – the smart energy systems approach for improving the Italian energy strategy. Energy 259, 125049. https://doi.org/10.1016/j.energy.2022.125049.

Pata, U.K., 2024. Decarbonization efforts under the energy and climate policy uncertainties: a comparison between the USA and China. Clean Techn. Environ. Policy. https://doi.org/10.1007/s10098-024-02992-y.

Penn, A.S., Bartington, S.E., Moller, S.J., Hamilton, I., Levine, J.G., Hatcher, K., Gilbert, N., 2022. Adopting a whole systems approach to transport Decarbonisation, air quality and health: an online participatory systems mapping case study in the UK. Atmosphere 13 (3), 492. https://doi.org/10.3390/atmos13030492.

Pigato, M., Black, S., Dussaux, D., Mao, Z., McKenna, M., Rafaty, R., Touboul, S., 2020. Technology transfer and innovation for low-carbon development. The World Bank. https://doi.org/10.1596/978-1-4648-1500-3.

Pilpola, S., Arabzadeh, V., Mikkola, J., Lund, P., 2019. Analyzing national and local pathways to carbon-neutrality from technology, emissions, and resilience perspectives—case of Finland. Energies 12 (5), 949. https://doi.org/10.3390/en12050949.

Rahman, A., Farrok, O., Haque, M.M., 2022. Environmental impact of renewable energy source based electrical power plants: Solar, wind, hydroelectric, biomass, geothermal, tidal, ocean, and osmotic. Renew. Sust. Energ. Rev. 161, 112279. https://doi.org/10.1016/j.rser.2022.112279.

Rissman, J., Bataille, C., Masanet, E., Aden, N., Morrow, W.R., Zhou, N., Elliott, N., Dell, R., Heeren, N., Huckestein, B., Cresko, J., Miller, S.A., Roy, J., Fennell, P., Cremmins, B., Koch Blank, T., Hone, D., Williams, E.D., de la Rue du Can, S., Helseth, J., 2020. Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070. Appl. Energy 266, 114848. https://doi.org/10.1016/j.apenergy.2020.114848.

Sadai, S., Spector, R.A., DeConto, R., Gomez, N., 2022. The Paris agreement and climate justice: Inequitable impacts of sea level rise associated with temperature targets. *Earth's*. Future 10 (12). https://doi.org/10.1029/2022EF002940.

Sgarciu, S., Scholz, D., Müsgens, F., 2023. How CO2 prices accelerate decarbonisation – the case of coal-fired generation in Germany. Energy Policy 173, 113375. https://doi.org/10.1016/j.enpol.2022.113375.

Shankar, A., Saxena, A.K., Idnani, T., 2022. Roadmap to India's 2030 Decarbonization target. https://www.energy-transitions.org/publications/roadmap-to-indias-2030-decarbonization-target/#download-form.

Sillman, J., Hynynen, K., Dyukov, I., Ahonen, T., Jalas, M., 2023. Emission reduction targets and electrification of the Finnish energy system with low-carbon power-to-X technologies: Potentials, barriers, and innovations – a Delphi survey. Technol. Forecast. Soc. Chang. 193, 122587. https://doi.org/10.1016/j.techfore.2023.122587.

Sovacool, B.K., Turnheim, B., Hook, A., Brock, A., Martiskainen, M., 2021. Dispossessed by decarbonisation: Reducing vulnerability, injustice, and inequality in the lived experience of low-carbon pathways. World Dev. 137, 105116. https://doi.org/10.1016/j.worlddev.2020.105116.

Thi, T.L.N., Laratte, B., Guillaume, B., Hua, A., 2016. Quantifying environmental externalities with a view to internalizing them in the price of products, using different monetization models. Resour. Conserv. Recycl. 109, 13–23. https://doi.org/10.1016/j.resconrec.2016.01.018.

Tian, P., Feng, K., Sun, L., Hubacek, K., Malerba, D., Zhong, H., Zheng, H., Li, D., Zhang, N., Li, J., 2024a. Higher total energy costs strain the elderly, especially low-income, across 31 developed countries. Proc. Natl. Acad. Sci. 121 (12). https://doi.org/10.1073/pnas.2306771121.

Tian, P., Zhong, H., Chen, X., Feng, K., Sun, L., Zhang, N., Shao, X., Liu, Y., Hubacek, K., 2024b. Keeping the global consumption within the planetary boundaries. Nature 635 (8039), 625–630. https://doi.org/10.1038/s41586-024-08154-w.

Tyler, E., Hochstetler, K., 2021. Institutionalising decarbonisation in South Africa: navigating climate mitigation and socio-economic transformation. Environmental Politics 30 (sup1), 184–205. https://doi.org/10.1080/09644016.2021.1947635.

Vellini, M., Bellocchi, S., Gambini, M., Manno, M., Stilo, T., 2020. Impact and costs of proposed scenarios for power sector decarbonisation: An Italian case study. J. Clean. Prod. 274, 123667. https://doi.org/10.1016/j.jclepro.2020.123667.

Veysey, J., Octaviano, C., Calvin, K., Martinez, S.H., Kitous, A., McFarland, J., van der Zwaan, B., 2016. Pathways to Mexico's climate change mitigation targets: A multi-model analysis. Energy Econ. 56, 587–599. https://doi.org/10.1016/j.eneco.2015.04.011.

Waldron, J., Rodrigues, L., Gillott, M., Naylor, S., Shipman, R., 2022. The role of electric vehicle charging Technologies in the Decarbonisation of the energy grid. Energies 15 (7), 2447. https://doi.org/10.3390/en15072447.

Wambui, V., Njoka, F., Muguthu, J., Ndwali, P., 2022. Scenario analysis of electricity pathways in Kenya using low emissions analysis platform and the next energy modeling system for optimization. Renew. Sust. Energ. Rev. 168, 112871. https://doi.org/10.1016/j.rser.2022.112871.

Warren, P., 2020. Blind spots in climate finance for innovation. Adv. Clim. Chang. Res. 11 (1), 60–64. https://doi.org/10.1016/j.accre.2020.05.001.

White, D.J., Hubacek, K., Feng, K., Sun, L., Meng, B., 2018. The water-energy-food Nexus in East Asia: a tele-connected value chain analysis using inter-regional input-output analysis. Appl. Energy 210, 550–567. https://doi.org/10.1016/j.apenergy.2017.05.159.

Wiertz, T., Kuhn, L., Mattissek, A., 2023. A turn to geopolitics: Shifts in the German energy transition discourse in light of Russia's war against Ukraine. Energy Res. Soc. Sci. 98, 103036. https://doi.org/10.1016/j.erss.2023.103036.

World Bank, 2014. Turn down the Heat : Confronting the New Climate Normal. World Bank, Washington, DC. https://doi.org/10.1596/978-1-4648-0437-3.

World Bank, 2023. Reality Check: Lessons from 25 Policies Advancing a Low-Carbon Future.

Wright, C., Nyberg, D., Bowden, V., 2021. Beyond the discourse of denial: The reproduction of fossil fuel hegemony in Australia. Energy Res. Soc. Sci. 77, 102094. https://doi.org/10.1016/j.erss.2021.102094.

Yan, C., Murshed, M., Ozturk, I., Siddik, A.B., Ghardallou, W., Khudoykulov, K., 2023. Decarbonization blueprints for developing countries: The role of energy productivity, renewable energy, and financial development in environmental improvement. Resources Policy 83, 103674. https://doi.org/10.1016/j.resourpol.2023.103674.

Yao, F., Liu, G., Ji, Y., Tong, W., Du, X., Li, K., Shrestha, A., Martek, I., 2020. Evaluating the environmental impact of construction within the industrialized building process: A monetization and building information modelling approach. Int. J. Environ. Res. Public Health 17 (22), 1–22. https://doi.org/10.3390/ijerph17228396.

Zhang, T., Zhang, S., Qu, J., 2022. The impact of China's carbon neutrality target on its energy consumption structure by 2050. Energy Sources B: Econ. Plan. Policy 17 (1). https://doi.org/10.1080/15567249.2022.2088896.