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THE CARBON EXIT: INTERNATIONAL IMPACTS OF DECARBONIZATION STRATEGIES

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PREFACE

In an era defined by accelerating climate crises and the urgent pursuit of sustainable futures, the global community faces a critical juncture: how to effectively transition away from carbon-intensive systems without compromising economic stability, social equity, and technological innovation. This volume, The Carbon Exit: International Impacts of Decarbonization Strategies, emerges as a timely and necessary intervention into that discourse.

The transition to low-carbon energy systems is not merely a technical challenge—it is a profound political, economic, and social transformation that requires coordinated action across borders, sectors, and disciplines. The contributions in this book examine the multidimensional consequences of decarbonization, exploring how scientific advancements, financial mechanisms, governance structures, and ethical imperatives must align to ensure a just and inclusive energy future.

By drawing from a diverse range of methodological approaches and regional perspectives, this work provides an integrative understanding of the evolving dynamics in global carbon governance. It reflects the growing recognition that decarbonization strategies must be informed not only by environmental science, but also by the complex realities of international political economy, development disparities, and socio-technological systems.

This book would not have been possible without the dedication and intellectual rigor of the contributing scholars, whose research advances both academic inquiry and policy relevance. Their collective work demonstrates that achieving net-zero emissions is not an isolated goal, but one deeply embedded in broader aspirations for justice, resilience, and planetary well-being.

I extend my heartfelt gratitude to all authors, reviewers, and partners who contributed to the realization of this volume. May their insights inspire meaningful dialogue and action across the global academic and policy-making communities.

Prof. Germán Martínez Prats
Editorin Chief
New York, July 2025

CHAPTER 1

BIOLOGICAL AND CHEMICAL PATHWAYS IN CARBON MARKETS: ADVANCING INTERNATIONAL ENERGY SUSTAINABILITY AND POLICY

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INTRODUCTION

Context and Urgency

The global climate crisis has reached an unprecedented level of urgency as scientific evidence continues to accumulate that global average temperatures are rising faster than anticipated. Current trends suggest a high probability of global warming exceeding the tipping points needed to prevent the most catastrophic climate impacts. Record temperatures in recent years show an accelerating warming trend. This warming trend is not a statistical aberration but signals a fundamental shift in Earth's climate system. Most countries, especially vulnerable ones, are already experiencing severe climate-related disasters in the form of unprecedented heat waves, floods, and droughts that threaten livelihoods, food security, and water resources. The interconnectedness of these impacts underscores the systemic nature of the crisis, where environmental degradation fuels social and economic instability.

Water scarcity is emerging as one of the most pressing impacts of climate change, particularly in regions facing rapid urbanization and population growth. Agriculture, which consumes the bulk of global freshwater resources, faces increasing competition for water, exacerbating food insecurity and energy production problems. Such resource pressures can exacerbate domestic conflicts and instability, particularly in countries with fragile social institutions. Furthermore, climate-induced displacement is likely to worsen, with estimates that by mid-century, hundreds of millions of people will become permanent climate migrants. Such mass migration will place additional pressure on cities and international borders, heighten geopolitical tensions, and complicate global governance. The scale and complexity of these traps underscore the urgency of comprehensive mitigation and adaptation mechanisms.

Despite repeated emissions reductions, current international pledges fall far short of what is needed to keep global warming within safe limits. Projections suggest that average global temperatures will rise significantly, triggering mutually reinforcing feedback processes that push the climate system toward a less stable and less habitable state. The shortfall in meeting climate goals is compounded by geopolitical setbacks. Withdrawals from international agreements by major emitters hinder collective action and weaken global climate governance. Such political forces slow the transition to a low-carbon economy and reduce the effectiveness of market-based mechanisms that seek to drive emissions reductions. Reforming the global energy system is paramount here. Fossil fuel dependency remains entrenched, and energy infrastructure is increasingly vulnerable to climate impacts. Transitioning to renewables and energy efficiency is essential but not sufficient. New technologies with the potential to directly capture and use carbon dioxide from the atmosphere are essential to achieving net-zero emissions and stabilizing the climate.

Carbon markets are gaining popularity as a flexible and cost-effective tool for delivering emissions reductions across sectors and internationally. By pricing carbon, markets encourage investment in sustainable practices and clean technologies. However, the integrity of carbon markets depends on the environmental integrity of the underlying emissions reductions and the integrity and robustness of measurement, reporting, and verification systems. Scientific research is needed to improve the efficiency of carbon markets. Biological processes, such as photosynthetic carbon fixation and microbial carbon assimilation, provide natural pathways for capturing atmospheric CO_2. However, chemical processes enable the conversion of CO_2 into valuable fuels and chemicals, which offer economic incentives to utilize carbon. Together, these biological and chemical processes expand the range of mitigation options for carbon markets.

However, there are significant difficulties in scaling up these technologies. Technical limitations, prohibitive costs, and regulatory uncertainty are barriers to widespread implementation. Furthermore, ensuring that carbon credits from these pathways represent real and incremental emissions savings requires rigorous standards and transparent governance. Equity issues are also central to discussions around carbon markets and the energy transition. Developing countries typically face barriers to modern technology and finance and may be locked out of future carbon markets. Addressing these asymmetries is key to creating inclusive climate solutions and advancing sustainable development goals. The political economy of the energy transition is complex, involving competing interests, power asymmetries, and social equity issues. Ambitious climate action requires not only technological transformation but also institutional transformation and participatory governance that can manage trade-offs and distribute benefits equitably.

Aim and Scope

This chapter explores the critical role of biological and chemical innovations in shaping carbon markets in the broader context of sustainability and international energy policy. It adopts an interdisciplinary approach that bridges advances in natural science with the complexities of political economy, aiming to inform effective strategies for climate mitigation.

The scientific focus covers key biological carbon fixation pathways, such as photosynthesis and microbial CO_2 assimilation, alongside chemical processes such as enzymatic CO_2 hydration and catalytic conversion to valuable products. These pathways offer promising solutions for scaling up carbon capture, utilization and storage, expanding the range of options available for carbon markets. A comprehensive assessment of the technical and economic feasibility of these innovations is provided, considering factors such as scalability, energy efficiency, life cycle emissions and potential environmental co-benefits. Real-world case studies and demonstration projects are used to illustrate their practical applications and challenges. Policy and governance aspects are examined with an eye toward integrating these emerging technologies into existing carbon market frameworks. This includes developing robust verification standards, regulatory mechanisms and safeguards to ensure the credibility and longevity of carbon credits generated through biological and chemical pathways.

Finally, this work emphasizes the importance of equity and international cooperation, highlighting the need for technology transfer and capacity building to enable developing countries to fully participate in carbon markets. The ultimate goal is to promote sustainable, inclusive and effective carbon market solutions that accelerate the global transition to low-carbon energy systems.

1. CARBON MARKETS IN THE INTERNATIONAL POLITICAL ECONOMY

1.1 Overview of Carbon Markets

For the past fifteen years, carbon markets have become a cornerstone of global climate policy, designed to reduce greenhouse gas emissions through economic incentives. These markets set a price on carbon emissions, encouraging companies and countries to lower their carbon footprints by trading emission allowances or credits. Carbon markets come in two main forms: compliance markets, such as emissions trading schemes (ETS), which are regulated by governments, and voluntary carbon markets (VCMs), where private actors engage in offsetting emissions outside of regulatory requirements. Both types have grown rapidly, reflecting a global shift toward market-based approaches to climate mitigation.

At the international level, carbon markets facilitate cooperation by allowing entities to trade emission reductions across borders. This flexibility allows emissions to be cut where they are most cost-effective, potentially lowering the overall cost of meeting climate targets. Article 6 of the Paris Agreement formalizes this cooperation, providing a framework for international carbon trading while emphasizing the need for transparency, environmental integrity, and avoidance of double counting. These provisions aim to build trust and encourage broader participation in carbon markets around the world.

Developing countries in the global south are increasingly embracing carbon markets as part of their climate strategies. Countries such as China, Mexico, Indonesia, India, and Brazil have launched or expanded national ETS platforms, signaling a shift toward market-based mitigation policies. Regional initiatives such as the African Carbon Market Initiative (ACMI) further illustrate efforts to leverage carbon finance for sustainable development and climate resilience. These developments demonstrate the growing importance of carbon markets beyond traditional Western economies.

However, carbon markets operate in complex political and economic contexts. National governments consider their participation based on strategic interests, including economic competitiveness, energy security, and social equity. While carbon markets are often lauded for their efficiency, some countries may prefer alternative mechanisms such as carbon taxes or direct regulation depending on domestic priorities and political considerations. This diversity of approaches reflects the broader challenge of aligning global climate goals with national interests.

Effective governance remains a critical challenge for carbon markets. Past experiences with market volatility, weak oversight, and fraudulent credits have highlighted the need for strong regulatory frameworks and institutional capacity. Robust measurement, reporting, and verification (MRV) systems are essential to ensure that carbon credits represent real, additional, and permanent emission reductions. Without these safeguards, market credibility and investor confidence could be eroded.

In many regions, particularly in developing countries, there is growing awareness of the social and environmental implications of carbon markets. Concerns about the commodification of natural resources, equitable sharing of benefits, and the inclusion of marginalized communities are increasingly shaping market design and governance. Recent international negotiations have sought to address these concerns by strengthening rules on host country authorization, increasing transparency, and linking carbon market activities to sustainable development goals.

The evolving nature of carbon markets and their integration into the international political economy provide a basis for a more in-depth examination of their design, challenges, and impacts. The following sections explore these dimensions in more detail, focusing on how biological and chemical innovations intersect with market mechanisms to advance international energy sustainability.

1.2 Political Economy Considerations

The design and functioning of carbon markets are heavily influenced by global power dynamics and economic interests. Major emitting countries and economic powers often shape the rules and structures of international carbon trading to align with their strategic priorities. This influence extends to how carbon markets are integrated with trade policies and energy systems, reflecting broader geopolitical considerations. For example, countries with advanced technological capabilities and financial resources tend to advocate market mechanisms that promote innovation and cost-effectiveness while maintaining their economic competitiveness in global markets.

Trade relationships and levels of economic development also play important roles in shaping the architecture of carbon markets. Carbon pricing and trading schemes must carefully address the risk of carbon leakage, where emissions are diverted to countries with less stringent regulations. This challenge often results in the adoption of border carbon adjustments and related trade measures, which can create friction among trading partners. Developing countries face the difficult task of balancing their economic growth ambitions with the need to participate in global carbon markets without being disproportionately burdened by carbon-related costs on their exports.

Addressing equity and access is fundamental to the political economy of carbon markets. Many developing countries lack the institutional capacity, technological infrastructure, and financial resources needed to fully participate in carbon trading schemes. This gap risks excluding them from global climate finance opportunities and limiting their influence in shaping market rules. To foster inclusive participation, targeted policy measures—such as capacity building, technology transfer, and financial assistance—are essential to empower developing countries and ensure they can engage effectively and equitably.

In addition, the distribution of benefits and burdens both within and across countries raises critical questions about climate justice. Carbon markets must be structured to avoid reinforcing existing inequalities and to advance sustainable development goals. This involves protecting vulnerable populations from negative economic impacts and ensuring that revenues generated from carbon trading support social and environmental priorities. International frameworks increasingly emphasize inclusive governance and transparent mechanisms for equitable benefit sharing to address these issues.

Navigating the complex political economy landscape requires carbon market designs that accommodate a variety of national circumstances and development trajectories. Combining flexible market mechanisms with strong international cooperation can help reconcile the often competing goals of economic growth, climate ambition, and social justice.

Addressing these considerations effectively is key to building carbon markets that are not only efficient in reducing emissions but are also perceived as legitimate and fair by all stakeholders.

1.3 Regulatory Frameworks And Verification Challenges.

Carbon markets operate in a complex and evolving regulatory landscape that spans multiple jurisdictions and levels of governance. Regulatory frameworks are critical to defining the rules of participation, ensuring environmental integrity, and fostering market confidence. These frameworks vary widely, from national emissions trading schemes and voluntary carbon market standards to international agreements such as those set out in Article 6 of the Paris Agreement. The patchwork nature of these regulations reflects different national priorities, capacities, and stages of market development.

Compliant carbon markets, such as emissions trading schemes (ETS), are typically governed by legally binding regulations that set limits on emissions and establish mechanisms for trading allocations. Examples include the EU ETS, the UK ETS, and national schemes in countries such as China and Brazil. These frameworks define the scope of regulated entities, the emissions covered, and penalties for non-compliance. Voluntary carbon markets, on the other hand, are often governed by standards developed by independent organizations, such as Gold Standard or Verra, which certify carbon credits based on project-level criteria.

A critical component of the regulatory framework is the establishment of a robust Monitoring, Reporting, and Verification (MRV) system. MRV ensures that carbon credits represent real, additional, and permanent emission reductions. However, designing an effective MRV framework poses significant challenges, especially as carbon markets expand to include new biological and chemical carbon capture technologies. These technologies require specific methodologies to accurately measure carbon sequestration and conversion, and to verify their environmental benefits over time.

International efforts to harmonize carbon market regulation have gained momentum, especially following the COP29 agreement that emphasized transparency, standardization, and avoidance of double counting. The development of international carbon market standards aims to provide consistent guidance for credit issuance, accounting, and cross-border transfers. Despite this progress, differences in national regulations and verification protocols continue to create barriers to market integration and can undermine trust among participants.

Financial regulators are increasingly involved in overseeing carbon markets to address risks associated with market manipulation, price volatility, and transparency. For example, the European Securities and Markets Authority (ESMA) has recommended enhanced reporting requirements and transaction tracking for carbon derivatives to improve market oversight. Similarly, global bodies such as IOSCO are working to develop an assurance framework for sustainability disclosures to strengthen the credibility of voluntary carbon markets.

As carbon markets evolve, regulatory frameworks must adapt to emerging challenges and innovations. This includes integrating new technologies, addressing equity and access issues, and ensuring that regulation supports environmental objectives and market stability. Building a comprehensive, transparent and flexible regulatory ecosystem is critical to unlocking the full potential of carbon markets in driving global emissions reductions.

2. BIOLOGICAL PATHWAYS FOR CARBON CAPTURE AND UTILIZATION

2.1 Natural Carbon Fixation Mechanisms

Carbon fixation is a fundamental biological process by which inorganic carbon dioxide (CO_2) is converted into organic compounds, forming the basis of the carbon cycle of life. Among the various pathways, the Calvin-Benson-Bassham (CBB) cycle stands out as the most widespread and well-characterized mechanism. This cycle operates in plants, algae, and many photosynthetic bacteria, where the enzyme ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco) catalyzes the fixation of CO_2 into stable organic forms. The CBB cycle is central to photosynthesis, enabling the synthesis of sugars that drive metabolism and cell growth.

In plants and algae, the CBB cycle occurs in the chloroplast stroma, where atmospheric CO_2 is first incorporated into ribulose-1,5-bisphosphate

(RuBP), yielding two molecules of 3-phosphoglycerate. These molecules are then converted through a series of enzymatic reactions to glyceraldehyde-3-phosphate, a key intermediate for carbohydrate synthesis. This cycle regenerates RuBP, allowing the process to continue. The efficiency of the CBB cycle is influenced by environmental factors such as light intensity, temperature, and CO_2 concentration, which affect the carboxylation activity of Rubisco.

Marine algae, which contribute significantly to global carbon fixation, rely primarily on the CBB cycle but have developed additional mechanisms to cope with low CO_2 availability in seawater. For example, many species have CO_2 concentrating mechanisms (CCMs) that increase the local CO_2 concentration around Rubisco. These CCMs often involve the enzymatic conversion of bicarbonate (HCO_3^-) to CO_2 by carbonic anhydrase, which increases the efficiency of carbon fixation under limiting conditions. Such adaptations are essential for maintaining high rates of photosynthesis in aquatic environments where CO_2 diffusion is slower than in air.

Beyond the classical CBB cycle, some algae and cyanobacteria use alternative carbon fixation pathways to optimize carbon assimilation under varying environmental conditions. One such pathway is the reductive acetyl-CoA pathway, found primarily in anaerobic bacteria and certain archaea. This pathway fixes CO_2 by reducing it to acetyl-CoA, a versatile metabolic intermediate that enters a variety of biosynthetic pathways. The reductive acetyl-CoA pathway is energy efficient and can operate in oxygen-limited environments, making it important for the carbon cycle in many ecosystems.
Another important alternative is the 3-hydroxypropionate cycle, found in some bacteria and archaea. This pathway fixes CO_2 through a series of enzymatic steps that convert it to 3-hydroxypropionate and ultimately to glyoxylate and pyruvate, which are precursors for biomass synthesis. The 3-hydroxypropionate cycle is unique in its enzymatic composition and energy requirements, offering a distinct route for autotrophic growth in certain microbial taxa.

Recent research has revealed that certain marine macroalgae, such as Ulva prolifera, utilize a combination of the CBB cycle and a C4-like pathway to enhance carbon fixation. The C4 pathway, more commonly associated with land plants, involves the initial fixation of CO_2 to a four-carbon compound, which is then decarboxylated to release CO_2 near Rubisco, thereby increasing its efficiency. In Ulva prolifera, this multifaceted carbon acquisition strategy allows the alga to thrive in environments with fluctuating CO_2 levels and high light intensities, contributing to rapid biomass accumulation.

Eukaryotic algae have evolved sophisticated CCMs that actively transport inorganic carbon species into the chloroplast. For example, bicarbonate transporters and carbonic anhydrases work together to increase the CO_2 concentration around Rubisco, overcoming the enzyme's relatively low affinity for CO_2. These CCMs vary among species and are tightly regulated in response to environmental cues such as light and carbon availability, underscoring the dynamic nature of biological carbon fixation.

The diversity of carbon fixation pathways across organisms reflects evolutionary adaptation to different ecological niches.

While the CBB cycle remains dominant in most photosynthetic organisms, the existence of alternative microbial pathways expands the biological toolkit for carbon assimilation. Understanding these mechanisms provides valuable insights for biotechnological efforts aimed at improving carbon capture efficiency in food crops and bioenergy systems.

Advances in synthetic biology and systems biology are now enabling the transfer and optimization of these natural carbon fixation pathways to non-native hosts. For example, genes encoding microbial CCM components or alternative fixation pathways are being introduced into food crops to enhance photosynthetic performance and increase crop yields. Such innovations hold promise for addressing challenges.

2.2 Bio-CCUS Technologies

Bioenergy with Carbon Capture and Storage (BECCS) is a leading bio-CCUS technology that combines renewable energy generation from biomass with the capture and permanent storage of carbon dioxide emissions. Biomass, such as agricultural residues, forestry wastes, or specialty energy crops, absorbs CO_2 from the atmosphere during growth. When this biomass is used to generate energy, the CO_2 released is captured before it enters the atmosphere and stored underground or in long-lasting products. This process is emissions-negative, actively removing carbon from the atmosphere while providing renewable energy, making BECCS an important tool for climate mitigation.

BECCS' advantages include its scalability and cost-effectiveness relative to other carbon capture technologies. The technology can be integrated into existing energy infrastructure, such as power plants and industrial facilities, allowing for a smoother transition from fossil fuels to low-carbon alternatives. Projects such as the Drax Power Station in the UK demonstrate the practical application of BECCS by converting a coal-fired power station to biomass with carbon capture, illustrating the potential for significant emissions reductions while maintaining energy production.

In addition to BECCS, advances in synthetic biology have enabled the engineering of microorganisms to enhance their natural ability to capture and convert CO_2. Genetically modified bacteria, algae, and cyanobacteria can be optimized to increase carbon fixation rates and produce valuable biochemicals or biofuels directly from CO_2. These engineered microbes provide a promising platform for scalable and versatile biological carbon capture, offering a pathway to integrating carbon removal with sustainable materials and fuel production.

Systems biology and bioinformatics are critical tools in optimizing these biological carbon capture technologies. By analyzing the complex metabolic networks of microorganisms, researchers identify key enzymes and pathways that can be enhanced or modified to improve CO_2 uptake and conversion efficiency. Computational modeling guides the design of engineered strains and microbial consortia, accelerating the development of robust bio-CCUS systems capable of operating under industrial conditions.

Despite its promise, bio-CCUS technologies face challenges such as ensuring a sustainable biomass supply for BECCS, managing land use impacts, and overcoming regulatory and economic barriers. Engineered microorganisms require thorough evaluation for environmental safety and scalability. Continued innovation, supported by interdisciplinary research and supportive policy frameworks, is essential to unlocking the full potential of bio-CCUS as a cornerstone of global carbon management and energy sustainability.

3.3 Case Studies

Real-world applications and demonstration projects are essential to demonstrate the practical feasibility of bio-CCUS technology. A prominent example is the Ince BECCS Project in the UK, which captures CO_2 from biomass gasification. The project highlights the potential of a modular plant design that can be scaled up incrementally, reducing initial costs and operational risks. The Ince Project also highlights the importance of comprehensive risk management and cost estimation to ensure successful implementation and investor confidence.

Another notable case is the BECCS pilot at Drax Power Station, also in the UK, which integrates carbon capture technology with a biomass-fired power plant. The pilot has provided valuable data on capture efficiency, operational challenges, and integration of the carbon capture system with existing energy infrastructure. The Drax project illustrates the technical feasibility of large-scale BECCS and the complexities involved in retrofitting conventional power plants for carbon capture and storage.

In the US, government-backed initiatives have accelerated the development of BECCS pilot projects that aim to achieve multi-megaton carbon capture capacity by 2030. These projects are testing a range of biomass feedstocks, capture technologies, and storage solutions. The U.S. experience underscores the critical role of public funding and policy support in overcoming economic and technical barriers, while encouraging innovation and private sector engagement.

Performance metrics from these projects typically focus on CO_2 capture rates, energy efficiency, life-cycle emissions, and economic costs. For example, capture rates at pilot plants often exceed 85%, but energy penalties and operational costs remain challenges to overcome. Life-cycle assessments help ensure that biomass sourcing and processing do not offset the climate benefits of carbon capture. These metrics provide important benchmarks for evaluating the scalability and sustainability of bio-CCUS technologies.

Scalability remains a key consideration for bio-CCUS deployment. Successful pilot projects demonstrate that modular design, integration with existing infrastructure, and flexible use of feedstocks can enhance scalability. However, challenges such as sustainable biomass supply, competing land uses, and regulatory complexities must be carefully managed. Lessons learned from the case studies inform best practices and guide policy frameworks to support broader adoption of bio-CCUS as a critical component of global carbon management strategies.

3. CHEMICAL PATHWAYS FOR CO_2 CONVERSION AND SEQUESTRATION

3.1 Chemical CO_2 Conversion Processes

The enzymatic hydration of CO_2 is primarily catalyzed by carbonic anhydrase (CA), an enzyme that accelerates the reversible conversion of CO_2 to bicarbonate (HCO_3^-). This reaction is fundamental in biological carbon transport and pH regulation. Industrial applications of CA focus on improving the efficiency of CO_2 capture in aqueous media, where the high enzyme turnover rate (up to 10^6 reactions per second) significantly reduces the energy requirement compared to conventional chemical sequestration methods. However, challenges such as enzyme stability under industrial conditions, potential inhibition by contaminants, and cost-effective immobilization remain. Recent advances in protein engineering and nanomaterial support have improved enzyme robustness and recyclability, enabling scalable implementation for carbon capture and utilization (CCU) processes.

The catalytic conversion of CO_2 to fuels and value-added chemicals is an important pathway for converting captured carbon into economically viable products. Metal catalysts, including copper, palladium, ruthenium, and others, facilitate hydrogenation and reduction reactions that convert CO_2 to methanol, urea, formic acid, hydrocarbons, and other chemicals. The synthesis of methanol from CO_2 and hydrogen is one of the most mature technologies, offering a renewable fuel and chemical feedstock that could replace fossil fuels. The reaction typically requires high temperatures (200–300°C) and pressures (50–100 bar), but ongoing research is focused on developing catalysts that operate under milder conditions with higher selectivity and durability. The production of urea from CO_2 and ammonia is a well-established industrial process, widely used in fertilizer manufacturing, demonstrating the commercial viability of chemical CO_2 conversion.

Electrochemical CO_2 reduction has emerged as a promising approach that uses renewable electricity to convert CO_2 to fuels and chemicals at ambient conditions. This method offers advantages in scalability, energy efficiency, and integration with intermittent renewable energy sources. Catalysts such as nanostructured copper, silver, and ionic liquid-modified electrodes have demonstrated high activity and selectivity for products including carbon monoxide, formic acid, ethanol, and ethylene. Challenges include improving catalyst stability, reducing overpotentials, and enhancing product selectivity. Advances in electrode design, electrolyte composition, and reactor engineering are accelerating the commercialization pathway for electrochemical CO_2 conversion.

Photocatalytic CO_2 conversion is another emerging technique that harnesses solar energy to drive the CO_2 reduction reaction. Photocatalysts, typically semiconductors such as TiO_2 or modified metal oxides, absorb light and generate electron-hole pairs that facilitate the reduction of CO_2 to fuels such as methane or methanol. While photocatalysis offers a sustainable and potentially low-cost route, current limitations include low product selectivity, limited quantum efficiency, and catalyst deactivation.

Research efforts are focused on developing novel photocatalysts, cocatalysts, and reactor designs to enhance light absorption, charge separation, and catalytic activity.

Chemo-enzymatic approaches combine high enzyme selectivity with chemical catalysis to achieve efficient CO_2 conversion under mild conditions. For example, CO_2 can be enzymatically converted to formate or methanol using formate dehydrogenase or carbon monoxide dehydrogenase, followed by chemical upgrading to higher value products. These hybrid systems leverage the advantages of both biological and chemical catalysis, enabling stereoselective synthesis and reducing energy input. Industrial applications include CO_2 capture from power plants coupled with chemo-enzymatic conversion to bulk chemicals, which is a promising pathway for sustainable carbon utilization.

3.2 Analytical and Computational Chemistry Approaches

Analytical chemistry plays a critical role in monitoring CO_2 conversion processes, ensuring accurate quantification of reactants, intermediates, and products. Techniques such as gas chromatography (GC), mass spectrometry (MS), nuclear magnetic resonance (NMR), and infrared (IR) spectroscopy provide detailed molecular-level information about reaction pathways and product distributions. Isotope labeling with ^13C or ^14C tracers allows precise tracking of carbon atoms, confirming CO_2 incorporation into target molecules and detecting unwanted emissions. These analytical tools are essential for validating carbon capture claims, supporting regulatory compliance, and supporting carbon credit certification.

Computational chemistry and molecular modeling complement experimental efforts by elucidating reaction mechanisms and guiding catalyst design. Density functional theory (DFT) and molecular dynamics simulations reveal the active sites, energy barriers, and intermediate species involved in CO_2 conversion reactions. These insights enable the rational design of catalysts with enhanced activity, selectivity, and stability. Process simulations model reactor performance and scale-up scenarios, optimizing parameters such as temperature, pressure, and reactant ratios to maximize efficiency and minimize costs. Integrating computational prediction with experimental validation accelerates technology development and reduces trial-and-error experiments.

Machine learning and data-driven approaches are increasingly being applied to analyze large datasets from experiments and simulations, identify patterns, and predict catalyst performance. These tools facilitate high-throughput screening of catalyst materials and reaction conditions, accelerating the discovery of new catalysts for CO_2 conversion. Combined with advances in automation and robotics, computational chemistry is changing the landscape of catalyst development for sustainable carbon utilization.

3.3 Integration with Carbon Markets

Integrating chemical CO_2 conversion pathways into carbon markets requires a robust framework for measuring, reporting, and verifying emissions reductions. Unlike geological storage, chemical conversion often results in carbon being embedded in products with variable lifetimes, making it difficult to assess permanence. For example, methanol used as a fuel releases CO_2 upon combustion, while carbon embedded in durable plastics can remain sequestered for decades or longer. Therefore, carbon accounting must take into account the product life cycle, usage patterns, and end-of-life emissions to accurately measure net carbon removals.

Measurement, reporting, and verification (MRV) systems face challenges in tracking carbon flows through complex chemical transformations and supply chains. Transparent and standardized MRV protocols are essential to prevent double counting and ensure credibility. Emerging methodologies leverage experience from biological carbon markets and industry standards, adapting them to the unique characteristics of chemical CCUs. Independent third-party verification and blockchain-based registries are being explored to enhance traceability and trust.

Economic considerations are critical to the successful integration of chemical CCUs into carbon markets. Capital and operating costs, feedstock availability, and market demand for CO_2-derived products influence project feasibility. Policy mechanisms such as carbon pricing, tax incentives, and subsidies can bridge the cost gap and stimulate investment. Public-private partnerships and innovation funding accelerate technology maturity and adoption, supporting the scaling of chemical CCUs in carbon markets.

Alignment of carbon market frameworks with international climate agreements, such as Article 6 of the Paris Agreement, is essential to harmonize accounting standards and facilitate cross-border carbon trading. Clear guidelines on additionality, sustainability, and environmental integrity will enable chemical CCU projects to contribute effectively to global emissions reduction targets.

4. SYNERGIES AND INTEGRATION: BIOLOGICAL AND CHEMICAL PATHWAYS IN CARBON MARKETS

4.1 Hybrid Approaches

Hybrid carbon capture and utilization systems combine biological and chemical processes to harness the strengths of both. Biological pathways, including algal photosynthesis and microbial fermentation, offer high selectivity and operate under mild conditions but often have slower kinetics and limited product ranges. Chemical catalysis provides fast conversions and a broad product range but typically requires harsher conditions and higher energy inputs. Combining these approaches in an integrated biorefinery or CCUS facility increases overall carbon conversion efficiency and product diversity.

For example, an algae-based biorefinery captures CO_2 biologically, producing biomass rich in lipids, carbohydrates, and proteins. This biomass can then be chemically processed through catalytic upgrading to biofuels, bioplastics, or specialty chemicals. Engineered microbial consortia can produce platform chemicals that serve as feedstocks for subsequent chemical synthesis. Such hybrid systems enhance carbon utilization, reduce waste, and diversify revenue streams, improving economic and environmental performance.

Hybrid CCUS systems also allow for flexible operation, adapting to fluctuating feedstock availability and energy inputs. The modular nature of the system facilitates gradual scaling and integration with existing industrial infrastructure. These features increase resilience and reduce investment risk, making the hybrid approach attractive for commercial deployments.

4.2 Role in Supporting Robust, Science-Based Carbon Accounting

Incorporating hybrid biological-chemical pathways into carbon markets requires a rigorous accounting framework to ensure that carbon credits represent real, additional, and permanent emissions reductions. Additionality requires that credits reflect reductions beyond business-as-usual scenarios. Permanence ensures that captured carbon is not prematurely re-emitted, while transparency requires clear documentation and verification of carbon flows through biological and chemical stages.

Developing methodologies that accurately capture the complexity of hybrid systems is challenging but essential to prevent double-counting and maintain market integrity. Advances in monitoring technology, data analytics, and blockchain-based registries offer promising tools to improve traceability and accountability. Science-based carbon accounting frameworks that integrate life cycle assessment (LCA) and dynamic modeling are essential for evaluating the net climate impacts of hybrid CCUS projects.

Supporting diverse and complementary carbon capture technologies strengthens the resilience and robustness of carbon markets. Hybrid approaches enable solutions tailored to regional resource availability and industry contexts, fostering innovation and accelerating the global transition to a low-carbon economy. Coordinated efforts among researchers, industry, regulators, and market participants are essential to realizing the full potential of integrated biological and chemical carbon pathways.

5. POLICY, REGULATION, AND INTERNATIONAL COLLABORATION

5.1 Techno-Economic Feasibility

The technical-economic feasibility of biological and chemical Carbon Capture, Utilization, and Storage (CCUS) technologies is a critical determinant of their large-scale deployment. Cost-benefit analyses show that while current CCUS technologies face high capital and operating costs, particularly for the capture and compression stages, there is significant potential for cost reduction through technological advances, economies of scale, and learning on the job. For example, carbon capture costs vary widely depending on the concentration of the CO_2 source, ranging from as little as USD 15–25 per ton for concentrated streams (e.g., ethanol production) to over USD 100 per ton for dilute sources such as power plants. Life cycle assessments further highlight the environmental benefits of CCUS, with net carbon reductions dependent on sustainable biomass sources and energy inputs.

Despite these promising benefits, several barriers hinder commercialization and scale-up. These include high initial capital investment, the need for extensive infrastructure such as CO_2 transport pipelines and storage sites, and uncertainties surrounding long-term permanent storage. Furthermore, integration challenges with existing industrial processes and energy systems can increase operational costs and complexity. Policy uncertainty and limited market incentives also constrain private sector investment. However, experience from the renewables sector shows that with a supportive policy framework, cost reductions similar to those seen in solar and wind can be achieved for CCUS.

Public funding and policy incentives, such as tax credits, grants, and carbon pricing, play a critical role in bridging the cost gap and reducing investment risk. For example, the US Section 45Q tax credit has significantly boosted CCUS project development by providing financial benefits for captured and stored CO_2. Regional hubs that combine multiple emitters and share infrastructure can further reduce costs and improve project feasibility. Overall, techno-economic feasibility is improving, but continued policy support and innovation are essential to accelerate deployment.

5.2 Regulatory and Verification Needs

A robust regulatory framework and verification system are essential to ensure the credibility and environmental integrity of emerging carbon market mechanisms involving CCUS. Monitoring, Reporting and Verification (MRV) standards should be tailored to the specific characteristics of biological and chemical carbon capture pathways. This includes accurate quantification of CO_2 captured, transformed or stored, accounting for potential leakage, and verification of sequestration permanence. Transparent and consistent MRV protocols help prevent double counting and build trust among market participants and regulators.

International cooperation is essential to align MRV policy frameworks and standards across jurisdictions. Article 6 of the Paris Agreement provides a foundation for cross-border carbon trading but requires further elaboration to address the complexities of CCUS projects, particularly those involving hybrid biological-chemical pathways. Collaborative efforts can facilitate the development of common methodologies, data-sharing platforms, and common verification mechanisms, reducing transaction costs and enabling scalable carbon markets. Multilateral institutions and international organizations have an important role to play in coordinating these efforts and providing technical assistance to developing countries.

In addition, the regulatory framework must address the safety, environmental, and social issues associated with CCUS deployment, including site selection, long-term monitoring, and community engagement. Clear rules and accountability mechanisms for remediation in the event of leaks are essential to ensure public trust.

The regulatory environment must also incentivize innovation while maintaining stringent standards to safeguard climate outcomes.

5.3 Equitable Access and Capacity Building

Equitable access to CCUS technologies and carbon markets remains a significant challenge, particularly for developing countries that face gaps in financial resources, technical expertise, and institutional capacity. Without deliberate efforts to address these gaps, there is a risk that the benefits of CCUS and carbon finance deployment will be distributed unequally, exacerbating existing inequalities. Developing countries often lack the infrastructure for large-scale CCUS projects and face barriers to accessing international climate finance.

Capacity building is therefore critical to enable meaningful participation by developing countries in CCUS and carbon market initiatives. This includes knowledge transfer, training programs, and technical assistance to develop local expertise in project design, MRV, and regulatory compliance. International partnerships and technology transfer agreements can facilitate access to advanced CCUS technologies and best practices. Financial mechanisms such as concessional loans, grants, and blended financing can help address capital constraints.

Furthermore, inclusive policy design should ensure that CCUS projects contribute to sustainable development goals, including job creation, poverty alleviation, and environmental protection. Involving local communities in project planning and benefit sharing enhances social acceptance and equity. Promoting regional collaboration and hub models can also enable shared infrastructure and knowledge, reducing costs and boosting collective capacity.

6. FUTURE DIRECTIONS AND RECOMMENDATIONS

6.1 Scaling Innovation

Accelerating research, development, and deployment (RD&D) of biological and chemical CCUS technologies is critical to meeting global climate targets. Strategies to scale innovation include increasing funding for early-stage research, supporting pilot and demonstration projects, and encouraging technology transfer between academia, industry, and government.

Public investment can reduce the risks associated with new technologies, enabling private sector engagement and commercialization. Additionally, creating innovation hubs and testbeds facilitates collaboration, knowledge sharing, and rapid technology iteration under real-world conditions.

Public-private partnerships (PPPs) are particularly effective in bridging the gap between research and market deployment. By combining public funding with private sector expertise and capital, PPPs can accelerate technology maturation and scale-up. Cross-sector collaborations between energy, agriculture, manufacturing, and waste management can also unlock synergies, such as using industrial by-products as feedstock for CCUS or integrating CCUS with renewable energy systems. International cooperation and joint ventures further expand access to markets and resources, enabling global scaling of innovative CCUS solutions.

Policy frameworks that encourage innovation—such as carbon pricing, grants, and tax credits—are critical to stimulating investment and adoption. Streamlining regulatory approvals and providing clear pathways for technology certification reduce uncertainty and accelerate market entry. In addition, developing a skilled workforce through education and training programs supports the human capital needed for rapid technology deployment.

6.2 Aligning Science and Policy

Effective integration of scientific advances into carbon market design requires an adaptive, transparent, and evidence-based policy framework. Policymakers should engage scientists and technologists early in the regulatory process to understand emerging opportunities and challenges. This dialogue ensures that market rules accommodate innovation while preserving environmental integrity. For example, MRV standards should evolve to capture the complexity of hybrid biological-chemical CCUS systems and emerging technologies such as bioelectrochemical synthesis.

Interdisciplinary dialogue involving scientists, economists, legal experts, and stakeholders from industry and civil society enhances policy relevance and legitimacy. Stakeholder engagement fosters trust, identifies practical barriers, and aligns incentives across sectors. Mechanisms such as advisory panels, public consultations, and collaborative platforms support ongoing knowledge exchange and co-creation of policy solutions. Policies should also encourage harmonization of standards and methodologies across jurisdictions to facilitate international carbon trading and cooperation. Aligning carbon accounting frameworks with global climate goals ensures consistency and comparability of emissions reductions. Furthermore, policies should address social and environmental safeguards, ensuring that CCUS implementation supports sustainable development and equitable outcomes.

6.3 Transformative Potential

Biological and chemical CCUS pathways have transformative potential to enable resilient, inclusive, and effective international energy sustainability policies. By diversifying the portfolio of carbon removal and utilization options, these technologies reduce reliance on any single approach, increasing the system's resilience to technological, economic, or geopolitical uncertainties. Their integration into carbon markets can drive large-scale emissions reductions while fostering innovation and economic growth.

Inclusive policies that prioritize equitable access and capacity development ensure that developing countries can fully participate in CCUS deployment and benefit from the associated economic opportunities. Supporting technology transfer, financing mechanisms, and local capacity development strengthens global climate action and promotes social equity. Furthermore, embedding CCUS within a broader sustainability framework aligns climate mitigation with biodiversity conservation, circular economy principles, and societal well-being.

The vision for future energy sustainability includes seamless integration of biological and chemical CCUS with renewable energy, energy efficiency, and demand-side management. This holistic approach accelerates the transition to a low-carbon economy, stabilizes global temperatures, and safeguards ecosystems. Realizing this vision requires sustained commitment, interdisciplinary collaboration, and innovative governance models that can adapt to evolving scientific and societal needs.

CONCLUSION

Biological and chemical pathways for carbon capture, utilization, and storage represent transformative tools in the global effort to mitigate climate change and transition toward sustainable energy systems. These pathways harness the power of natural processes and innovative technologies to convert atmospheric CO_2 into valuable products or securely sequester it, thereby reducing net greenhouse gas emissions. The complementary strengths of biological mechanisms—such as the Calvin-Benson-Bassham cycle and microbial CO_2 assimilation—and chemical processes—including enzymatic hydration and catalytic conversion—expand the portfolio of viable carbon management solutions. Together, they enhance the efficiency, scalability, and versatility of carbon capture technologies, making them indispensable components of future carbon markets.

The integration of these scientific advances into international carbon markets depends on robust measurement, reporting, and verification systems that ensure transparency, environmental integrity, and market credibility. Equally important is the establishment of equitable frameworks that enable developing countries to access technology, finance, and capacity building, thereby fostering inclusive participation in global climate action. Addressing techno-economic barriers and regulatory challenges requires coordinated policy efforts that align innovation incentives with environmental goals.

Interdisciplinary collaboration among scientists, policymakers, industry leaders, and civil society is critical to bridging the gap between scientific discovery and practical implementation. Such collaboration fosters the development of adaptive policies that can respond to evolving technologies and market dynamics, while ensuring social and environmental safeguards. Moreover, international cooperation and harmonization of standards will facilitate cross-border carbon trading and accelerate the deployment of CCUS technologies worldwide.

Ultimately, the transformative potential of biological and chemical carbon pathways lies not only in their technical capabilities but also in their ability to support resilient, inclusive, and effective energy sustainability policies. By embracing these innovations within integrated policy and market frameworks, the global community can accelerate the transition to a low-carbon economy, safeguard ecosystems, and promote sustainable development for current and future generations.

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CHAPTER 2

DECARBONIZATION AND DEVELOPMENT DILEMMAS: THE POLITICAL ECONOMY OF ENERGY TRANSITIONS IN AFRICA

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INTRODUCTION

Africa faces the dual challenge of pursuing economic development while meeting global decarbonization goals. Its energy transition must be context-specific, just, and responsive to local socio-economic priorities. This chapter explores Africa's transition pathways from a political economy perspective, focusing on the interplay between structural barriers, governance dynamics, and external influences.

The unfolding climate crisis is now universally recognized as one of the most pressing challenges of the 21st century. The Intergovernmental Panel on Climate Change (IPCC, Working Group III, 2022) underscores that limiting global warming to 1.5°C above pre-industrial levels necessitates a rapid and profound transformation of global energy systems, entailing deep cuts in fossil fuel use, large-scale deployment of renewables, and significant improvements in energy efficiency.

Since the adoption of the Paris Agreement in 2015, there has been a surge in national commitments to net-zero emissions, accompanied by increased investments in clean energy technologies (Ritchie et al., 2023). According to the International Energy Agency (IEA, 2021), the energy sector alone is responsible for about 73% of global greenhouse gas emissions, making it both the primary contributor to climate change and a key sector for mitigation efforts.

However, despite advances and falling renewable costs, the global transition remains uneven. Many developing countries face structural barriers that limit their ability to move quickly away from fossil fuels, raising questions about the equity and feasibility of global decarbonization pathways (Newell & Paterson, 2010).

Table 1.1 shows the share of global greenhouse gas (GHG) emissions by sector, indicating that electricity and heat production alone generate nearly a third of total emissions, followed by transport, industry, and land use change. This underscores why transforming the energy sector is central to any credible decarbonization pathway.

Table Error! No text of specified style in document.**.1:** Share of global greenhouse gas emissions by sector

Source: Data adapted from IEA (2021) and Our World in Data (2020).

Sector	**Share of Total Emissions (%)**
Energy (Electricity & Heat)	31%
Transportation	16%
Industry	12%
Other Energy	14%
Agriculture, Forestry & Land Use	18%
Waste & Others	9%

While this sectoral breakdown shows the global picture, it is important to consider Africa's distinct position within this context. Figure 1.1 illustrates the historically low per capita CO_2 emissions in Africa compared to the global average, underscoring the continent's marginal contribution to climate change despite facing disproportionate climate-related impacts. This disparity points to the need for fair and context-sensitive approaches to global emission reduction targets.

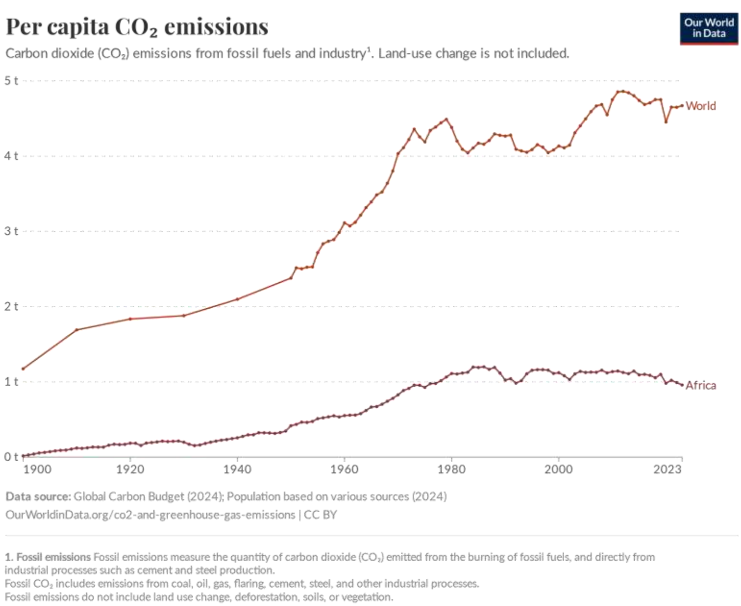


Figure Error! No text of specified style in document.**.1:** Per capita CO_2 emissions: Africa vs. World (1900–2023)

Source: Our World in Data, 2024; Global Carbon Budget (Ritchie et al., 2023)

The persistent gap between Africa's per capita emissions and the world average highlights a core dilemma: while African nations face increasing pressure to decarbonize in line with global climate targets, their historical and current contribution to climate change remains minimal. This underscores the importance of applying principles of climate justice and differentiated responsibilities when designing global mitigation pathways.

Given this tension, this chapter addresses the following key questions:

- How can African countries pursue decarbonization while safeguarding their socio-economic development goals?
- What governance frameworks and international dynamics shape this balance?
- How can principles of energy justice and equitable transitions be integrated into national energy strategies?

The overarching objective is to contribute to a nuanced understanding of Africa's energy transition within the broader field of International Political Economy, highlighting how global imperatives intersect with local realities.

In this global context, Africa occupies a paradoxical position. Despite contributing only about 4% of total global carbon emissions, the continent bears a disproportionate burden of climate impacts, including droughts, floods, and food insecurity (IPCC, Working Group III, 2022). At the same time, energy poverty remains pervasive: approximately 600 million Africans still live without access to electricity, and nearly 900 million rely on traditional biomass for cooking (World Bank, 2021; IRENA, 2021).

Consequently, African governments face a complex policy dilemma. On the one hand, they must expand energy infrastructure to fuel industrialization and lift millions out of poverty; on the other, they are under increasing international pressure to align their development pathways with global climate targets (Obeng-Odoom, 2014). This dual imperative creates unique trade-offs that are rarely addressed adequately in dominant global climate discourses.

This study employs a critical political economy approach, which situates energy transitions within broader power relations, historical dependencies, and global governance structures (Bridge et al., 2018). Empirical insights are drawn from a review of scholarly literature, policy reports from key institutions (e.g., IEA, IRENA, UNFCCC), and illustrative country case studies focusing on Morocco, South Africa, Kenya, and Nigeria.

The chapter unfolds in six main parts:

(1). Theoretical and conceptual frameworks underpinning energy transitions and decarbonization;
(2). Key dilemmas and trade-offs facing African states;
(3). Country case studies showcasing diverse pathways and challenges;
(4). The influence of international actors and financial mechanisms;
(5). Policy implications and recommendations for an inclusive, context-sensitive transition;
(6). Conclusion highlighting future directions and research gaps.

The Intergovernmental Panel on Climate Change (IPCC) warns that limiting global warming to 1.5°C requires rapid, far-reaching transitions in energy systems (IPCC, Working Group III, 2022). Post-Paris Agreement ambitions have intensified investment in renewable energy, energy efficiency, and low-carbon technologies (Ritchie et al., 2023). The energy sector alone contributes over 70% of global greenhouse gas emissions (IEA, 2021).

1. THEORETICAL AND ANALYTICAL FRAMEWORKS

Understanding the political economy of Africa's energy transitions requires a solid grounding in interdisciplinary conceptual frameworks. This section introduces five interconnected lenses that frame our analysis: the concept of energy transition, decarbonization in international political economy, development debates in Africa, energy justice, and critical political economy of energy.

1.1 Energy Transition As A Socio-Technical Process

The term energy transition refers to the structural shift from carbon-intensive energy systems—predominantly fossil fuels—to renewable and low-carbon energy sources such as solar, wind, and hydropower. This transformation is not merely technological but also institutional, economic, social and cultural (Geels et al., 2017). The scope and scale of this transition vary across countries depending on resource endowments, infrastructure, and policy environments.

For African countries, the energy transition presents both a challenge and an opportunity. On one hand, they must leapfrog carbon-intensive development paths; on the other, they can harness abundant renewable resources to close energy access gaps and stimulate green jobs (IRENA & AfDB, 2022).

However, the transition must also consider reliability, affordability, and energy security—elements often neglected in global policy debates dominated by industrialized economies. The diagram bellow illustrates the sequential phases from fossil fuel dependence to a diversified low-carbon mix. (Adapted from IRENA, 2021).

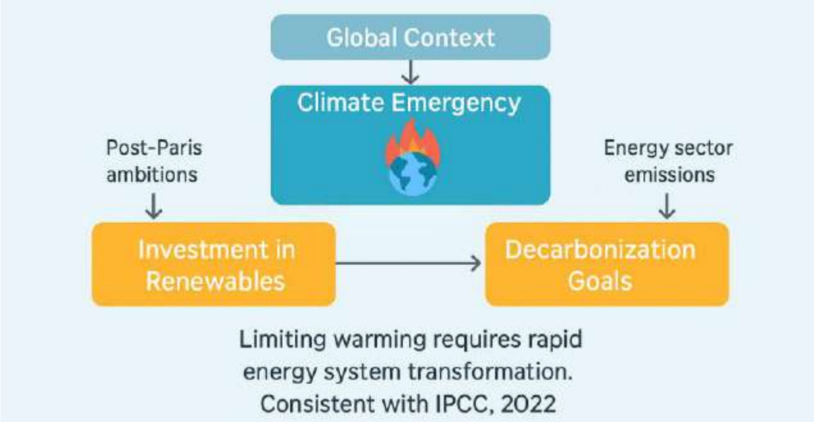


***Figure** Error! No text of specified style in document.**.2:** Phases of a typical energy transition*

(Source:** Adapted from IRENA, 2021**)

1.2 Decarbonization And Global Asymmetries

Decarbonization—reducing carbon emissions from economic activity—is a deeply political process embedded in the global political economy. (Newell & Paterson, 2010) argue that decarbonization is shaped by power asymmetries between countries, particularly in how climate finance, technology transfer, and policy advice are distributed. Many African states depend on international aid or concessional loans to fund climate initiatives. These often come with conditionalities that influence national priorities, favoring donor-driven strategies over locally designed solutions (McCauley et al., 2013).

Moreover, debates around decarbonization frequently overlook the historical responsibility of high-emitting nations, placing undue mitigation expectations on countries with negligible contributions to global emissions. This tension raises critical issues of fairness, sovereignty, and geopolitical agency.

Key global actors shaping decarbonization finance are:

- Green Climate Fund (**GCF**)
- World Bank Climate Investment Funds
- Global Environment Facility (**GEF**)
- Bilateral donors (**GIZ**, **AFD**, **USAID**)

1.3 Developmental States and Structural Constraints

African development remains a contested terrain, influenced by both internal dynamics and external pressures. Postcolonial development debates highlight tensions between endogenous growth and dependency on global markets (Amin & PEARCE, 1976). Despite decades of growth-focused strategies, many African states continue to face persistent poverty, unemployment, and low industrial diversification.

Energy transitions that neglect these developmental realities risk exacerbating inequalities. For instance, abrupt shifts away from fossil fuels could undermine sectors like mining, transportation, or manufacturing, which are crucial for job creation and public revenues.

Table Error! No text of specified style in document.**.2:** Contrasting development priorities in African energy transitions

Source: Author’s elaboration based on IEA & UNDP data

Priority	**Global North**	**Sub-Saharan Africa**
Emissions reduction	Central goal	Secondary to access
Innovation focus	Hydrogen, nuclear, smart grids	Mini-grids, biomass
Energy demand	Saturated, decarbonizing	Rapidly growing
Finance access	Abundant private flows	Reliant on donors

1.4 Energy Justice and Differentiated Development

Energy justice seeks to address the inequities in how energy systems operate—who benefits, who bears the costs, and who has agency in decision-making **(Sovacool & Dworkin, 2015)**. In the African context, this implies recognizing the historical legacies of underinvestment in rural areas, as well as disparities in access based on geography, gender, and class.

Three core dimensions of energy justice are particularly relevant in the African energy transition:

- ***Distributive justice***: Fair allocation of energy services and burdens.
- ***Procedural justice***: Inclusive decision-making processes that allow marginalized voices to influence outcomes.
- ***Recognition justice***: Acknowledging and valuing local knowledge systems and historically excluded communities.

A just transition in Africa must go beyond emissions targets to address these multiple layers of inequality. It requires rethinking not only how energy is produced and consumed, but also how transition pathways are designed, financed, and governed.

Recent academic literature underscores the importance of situating energy justice within broader structural and historical contexts. For instance, Baker, Burton, and Newell (2022) emphasize that in the Global South, justice frameworks must incorporate redistributive mechanisms, historical accountability, and socioeconomic restructuring. Their work argues that:

"Just transitions in the Global South must engage not only with carbon metrics, but with development justice, labour rights, and democratic ownership of energy systems" (Baker, Burton, & Newell, 2022, p. 796).

Similarly, Heffron & McCauley, 2017 propose that a truly just transition includes three intersecting forms of justice—procedural, distributive, and recognition—which are essential for ensuring social legitimacy and political sustainability of decarbonization pathways.

In this sense, achieving energy justice in Africa also entails confronting systemic patterns of exclusion, including those embedded in international finance, donor-driven energy projects, and technocratic top-down planning (Newell & Mulvaney, 2013).

Many studies emphasize the importance of situating energy justice within broader structural and historical contexts. For example, (Olmos Giupponi, 2023) argue that in the Global South, justice frameworks must incorporate redistributive mechanisms, historical accountability, and socioeconomic restructuring. Their work highlights how transitions that ignore these deeper dimensions risk reproducing existing inequalities under a green label.

1.5 Critical Political Economy Of Energy: An Analytical Lens

Finally, this chapter adopts a critical political economy perspective to unpack the systemic forces shaping Africa's energy transitions. As Bridge et al., 2018 argue, energy systems are not neutral infrastructures but are deeply embedded in political and economic relations of power, including state-corporate dynamics, international governance, and financial regimes.

This lens clarifies why African pathways differ from Western narratives. It draws attention to how transitions may reproduce old dependencies—such as reliance on imported technologies or donor funding—under a green label. It also encourages scholars and policymakers to question who drives transitions, who benefits, and whose visions of development are prioritized.

2. KEY DILEMMAS OF DECARBONIZATION IN AFRICA

As shown in Figure 3.1, global renewable electricity capacity is projected to increase by 60 % by 2026, reaching ~305 GW annually and creating pressure on African countries to maintain competitiveness.

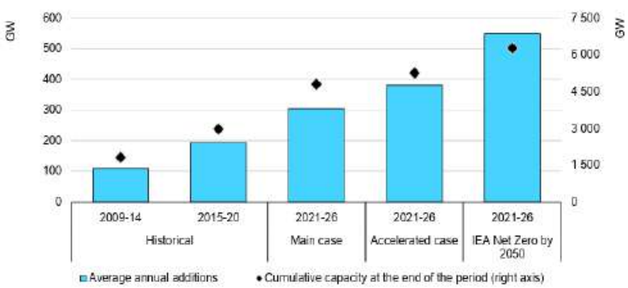
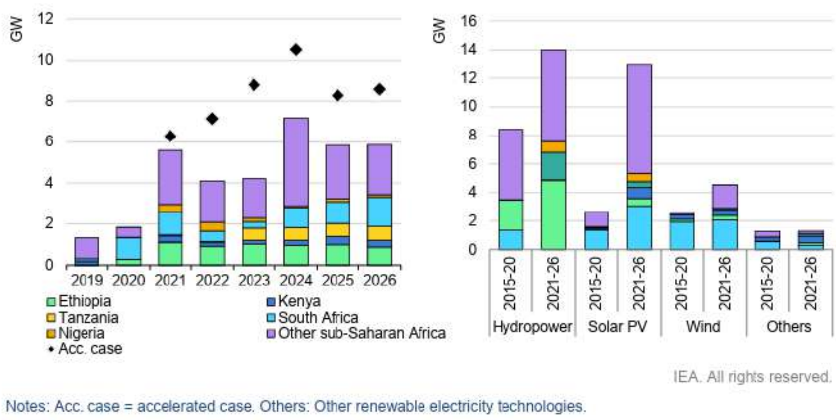


Figure Error! No text of specified style in document.**.3:** Global Annual Renewable Electricity Additions, 2021–2026.

Source: IEA (2021). Renewables 2021: Analysis and forecast to 2026, p. 22. https://www.iea.org/reports/renewables-2021

2.1 Universal Energy Access Vs. Emission Reduction

One of the most pressing dilemmas for African countries is the trade-off between expanding universal energy access and meeting global emission reduction targets. Sub-Saharan Africa is home to over 600 million people without electricity, and more than 900 million people still rely on traditional biomass for cooking (IEA, 2022). Access to modern energy is a development imperative, yet doing so often entails expanding fossil fuel use, at least in the short and medium term, due to cost, reliability, and infrastructure constraints (Bazilian et al., 2012).



In many countries, natural gas is promoted as a transitional fuel. Nigeria and Mozambique for example, are leveraging their abundant gas reserves to accelerate electrification while avoiding coal dependence. Yet critics argue that locking in fossil fuel infrastructure risks carbon lock-in and stranded assets (Newell & Paterson, 2010).

Figure 3.2 illustrates the disparities in renewable energy deployment across Sub-Saharan Africa countries, where progress remains uneven.

Figure Error! No text of specified style in document.**.4:** Sub-Saharan Africa renewable additions by country, 2019-2026 (left) and additions by technology and country, 2015-2026 (right)

Source: IEA (2021). Renewables 2021: Analysis and forecast to 2026, p. 79. https://www.iea.org/reports/renewables-2021

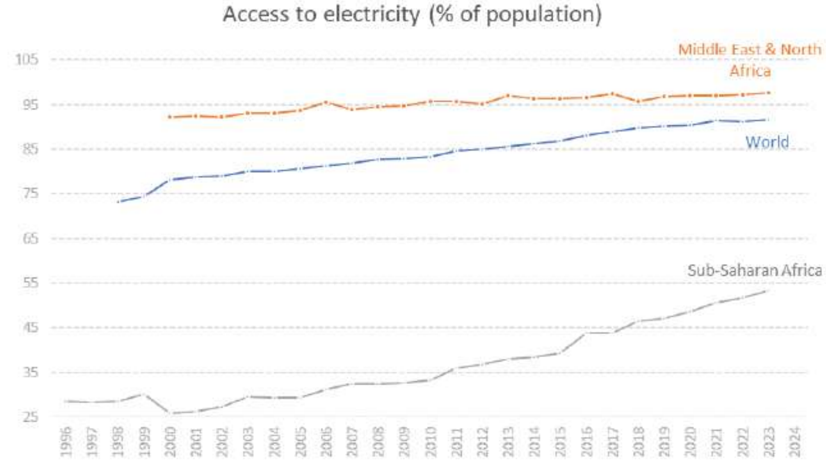


Figure Error! No text of specified style in document..**5:** Comparative access to electricity for Sub-Saharan Africa, Middle East & North Africa, and World (1996–2024).

Source: World Bank Open Data (2025); author's calculation based on World Development Indicators (Indicator: EG.ELC.ACCS.ZS)

2.2 Industrialization, Infrastructure, And Fossil Dependence

Africa's industrialization is tightly bound to affordable energy. Heavy industries, mining, and cement production rely largely on coal and oil. For example, South Africa generates more than 70% of its electricity from coal, underpinning sectors like steel and mining (Baker et al., 2014). Rapidly phasing out these fuels risks undermining job creation and economic competitiveness (Obeng-Odoom, 2014). Moreover, renewables alone may not yet provide the stable baseload power required for certain industrial processes due to variability and storage limits (Geels et al., 2017). Hence, a nuanced approach balancing decarbonization with gradual industrial upgrading is critical. Figure 3.3 illustrates the projected global acceleration of solar PV and wind power deployment between 2020 and 2026. The "accelerated case" reflects what could be achieved with stronger policy support While these projections highlight what is technically and economically feasible worldwide, most African countries remain far behind these levels due to infrastructure and financing constraints.

2.3 Budget Constraints And Climate Finance Dependence

Implementing clean energy solutions and resilient infrastructure requires enormous upfront capital, which many African economies struggle to mobilize internally due to limited fiscal space and high debt levels. Consequently, countries increasingly depend on international climate finance and development aid, primarily from the World Bank, the African Development Bank, and the Green Climate Fund (Nakhooda & Marigold Norman, 2014). Funding institutions provide essential funding, over 50% of these funds come in the form of loans, raising debt sustainability concerns. However, accessing these funds is often conditional upon regulatory reforms, privatization measures, or strict compliance with donor-driven indicators that may not align fully with local socio-economic realities (Bumpus & Liverman, 2008a). This raises questions about sovereignty and policy space.

2.4 Policy Fragmentation and Governance Challenges

A recurring problem is the fragmentation between national ministries and agencies responsible for energy, climate, and development. Disconnected planning results in overlapping projects, inefficient resource use, and missed synergies (Karekezi, 2003). For example, off-grid renewable initiatives and grid-extension projects may compete for funding without a coherent national electrification roadmap. Weak institutional capacity and limited technical expertise further hinder integrated planning and monitoring, particularly in rural areas.

2.5 Marginalization Risks in Global Climate Governance

Although Africa bears the brunt of climate change impacts, its representation in global governance institutions remains limited. Major climate finance mechanisms, carbon market rules, and global emission targets are often shaped by richer economies, risking the marginalization of African priorities (Okereke & Coventry, 2016).

For example, the design of global carbon offset markets may privilege cost efficiency over local environmental justice, with minimal benefit for communities (Lohmann, 2009).

3. AFRICAN CASE STUDIES: DIVERSE PATHWAYS

This section highlights how diverse African countries navigate the complex intersection of energy transition, economic development, and social realities. By many African countries, it illustrates varying national strategies, policy instruments, and socio-economic constraints.

3.1 Morocco: State-Led Green Strategy

Morocco is widely recognized as a leader in Africa's renewable energy rollout. Since adopting its National Energy Strategy in 2009, the country aims to reach 52% of installed electricity capacity from renewables by 2030, combining solar, wind, and hydro, supported by clear policies, foreign investment, and international climate finance (IEA, 2023; MASEN, 2022). The Noor Ouarzazate Solar Complex, one of the world's largest CSP plants, exemplifies successful public-private partnerships backed by institutions like the World Bank and AfDB (IEA, 2021). However, challenges persist in imported technology dependence, grid integration of intermittent renewables, and ensuring equitable benefit distribution, particularly in rural zones that remain critical (Hafner et al., 2018).

Figure 4.1 illustrates how solar PV dominates renewable growth in the MENA region, reinforcing Morocco's alignment with broader regional dynamics via auctions and supportive regulation.

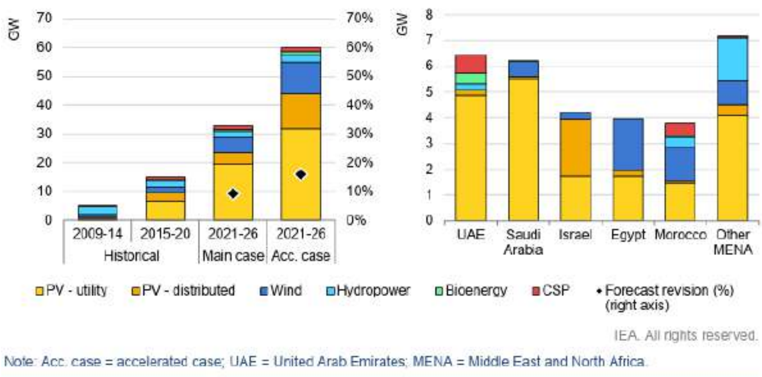


Figure Error! No text of specified style in document.**.6:** MENA Renewable Capacity Growth by Technology, 2009-2026 (left) and by country, 2021-2026 (right)

Source: IEA (2021), p. 82.

3.2 South Africa: Coal Legacy And Social Tensions

South Africa remains the largest emitter in Africa, heavily reliant on coal for over 70% of electricity generation (Baker et al., 2014). Coal is deeply embedded in the socio-economic fabric: it provides employment for over 80,000 people and supports mining-dependent communities.

The government's Integrated Resource Plan (IRP) envisions a gradual coal phase-out, while increasing renewables and gas. However, the energy transition sparks contentious debates on just transition, job losses, and energy security amid Eskom's chronic financial and operational crises (Burton et al., 2018). Community resistance and labor union concerns slow policy reforms, highlighting the social justice dimensions of decarbonization.

Figure 4.2 contrasts South Africa's persistent coal reliance with the global shift toward solar and wind dominance by 2026.

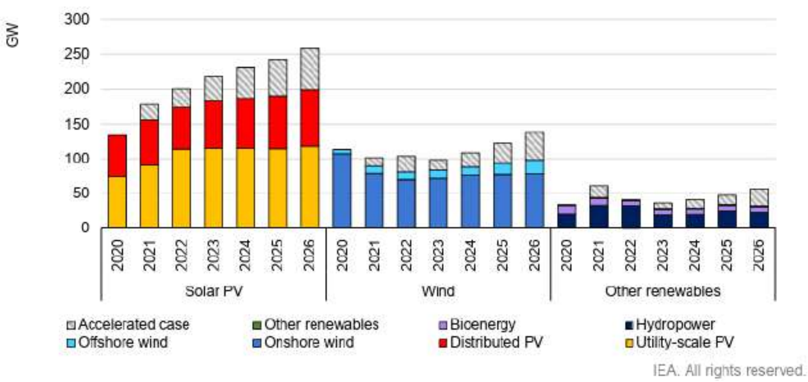


Figure Error! No text of specified style in document.**.7:** Annual Renewable Capacity Additions (solar PV, wind and other renewables), main and accelerated cases in Sub-Saharan Africa, 2020-2026.

Source*:* IEA (2021). Renewables 2021: Analysis and forecast to 2026, p. 27

3.3 Kenya: Renewables And Regional Disparities

Kenya is a leader in geothermal energy — it ranks among the world's top ten geothermal producers, with about 47% of its electricity from geothermal and wind (IRENA & AfDB, 2022). Projects like the Lake Turkana Wind Power Project, Africa's largest wind farm, show the potential of renewables in boosting national capacity.

However, despite impressive national figures, disparities persist: rural regions and marginalized communities often face unreliable access, highlighting the challenge of energy equity in the transition. Governance issues and land rights disputes have occasionally delayed large projects (Kiplagat et al., 2011).

3.4 Nigeria: Oil Dependency And Diversification Struggles

Nigeria exemplifies the fossil fuel dependency dilemma. The oil and gas sector contributes about 90% of export revenues and over 50% of government income (Nakhooda & Graaf, 2014). Despite substantial gas reserves and a growing population, Nigeria's energy infrastructure remains underdeveloped and unreliable.

Efforts to diversify the energy mix include the Renewable Energy Master Plan and policies to boost solar and gas-to-power projects. However, implementation lags due to governance issues, security risks, and vested interests in the oil sector. Decarbonization is viewed with skepticism if it threatens fiscal stability.

Table Error! No text of specified style in document.**.3:** Comparative summary of four case studies.

Source: Author's elaboration based on cited literature

Country	Key Strength	Key Challenge	Policy Highlight
Morocco	State leadership and climate finance	Technology dependence	National Energy Strategy
South Africa	Coal exit vision	Social justice, job losses	Integrated Resource Plan
Kenya	Geothermal and wind leadership	Regional inequalities	Feed-in Tariff Policy
Nigeria	Huge gas and oil reserves	Governance, conflict	Renewable Energy Master Plan

4. INTERNATIONAL FINANCIAL INSTITUTIONS AND CLIMATE FINANCE

International financial institutions (IFIs) such as the World Bank, the African Development Bank (AfDB), and the Green Climate Fund (GCF) play a pivotal role in enabling and shaping Africa's energy transitions. these institutions collectively channel over USD 30 billion per year into African climate and energy projects.

They provide concessional loans, grants, and technical assistance that many African countries rely on due to domestic budget constraints. However, more than 50% of these flows are loans rather than grants, creating future debt burdens. the conditionalities attached to this financing often influence national policy choices and priorities, raising concerns about policy sovereignty (Nakhooda & Graaf, 2014).

Table Error! No text of specified style in document.**.4:** Climate finance commitments by key international financial institutions in *africa*

Source: Climate Policy Initiative (2022). Africa Climate Finance Landscape

IFI	**Total Climate Finance to Africa (latest year)**	**Grant share (%)**	**Main Focus Areas**
World Bank	$17.5 billion	35%	Clean Energy, Resilience
AfDB	$12.0 billion	30%	Renewable Infrastructure, Adaptation
Green Climate Fund	$5.3 billion	100% (mainly grants)	Clean Tech, Capacity Building

Table Error! No text of specified style in document.**.5:** Example comparison of climate finance disbursement by IFIs in Sub-Saharan Africa (2010–2020)

Sources: World Bank Climate Finance Reports, AfDB Climate Change and Green Growth Reports.

Institution	**Total climate funding (USD Billion)**	**Main Target Sectors**
World Bank	$17.5	Energy, Resilience
AfDB	$12.0	Renewable Energy, Water
GCF	$5.3	Clean Tech, Adaptation

4.1 Bilateral Agencies and Conditionalities

Beyond multilateral banks, bilateral donors such as Germany's GIZ, France's AFD, and USAID are instrumental in co-financing renewable energy and infrastructure projects. Their interventions often come with governance conditions such as institutional reforms, regulatory harmonization, or liberalization of energy markets (Bumpus & Liverman, 2008b). For example, the AFD co-financed Morocco's Noor Solar Complex with EUR 300 million in concessional loans (AFD, 2021) While these can strengthen governance, they may also reflect donor priorities over local needs.

Table Error! No text of specified style in document.**.6:** Examples of bilateral donor programs and their conditionalities in african countries

Source: AFD Project Reports; USAID Power Africa

Agency	Example Program	Type of Conditionality	Beneficiary Country
GIZ	Energy Governance Support	Regulatory reform	Kenya
AFD	Noor Solar Project	Public debt ceiling compliance	Morocco
USAID	Power Africa	Liberalization of energy markets	Nigeria

4.2 Carbon Markets and ESG Standards

Carbon trading schemes and Environmental, Social, and Governance (ESG) standards are increasingly integrated into African energy projects. Mechanisms like the Clean Development Mechanism (CDM) have attracted investment but also raised criticism for failing to deliver equitable benefits (Lohmann, 2009). Similarly, ESG criteria set by global investors can be misaligned with local socio-economic realities.

Table 5.4 presents an overview of the number of Clean Development Mechanism (CDM) projects in Kenya, South Africa, and Nigeria, highlighting their estimated annual CO_2 emission reductions and main focus sectors.

Table Error! No text of specified style in document.**.7**: egistered CDM Projects and Estimated Emission Reductions in Selected African Countries
***Source**:* UNEP DTU CDM Pipeline

Country	**Registered CDM projects**	**Estimated annual emission reductions ($MtCO_2e$)**	**Key sectors**
Kenya	25	2.1	Geothermal, Landfill Gas
South Africa	53	14.2	Industrial Gas, Renewables
Nigeria	32	4.0	Oil & Gas Flaring

4.3 Global Forums: COP, IRENA, IEA

Global forums such as the UNFCCC Conference of the Parties (COP) and the International Energy Agency (IEA) set norms and targets that shape national roadmaps. However, limited African representation and negotiation power can lead to frameworks that inadequately address the continent's unique development needs and influence agenda-setting, which can perpetuate North-South power asymmetries (Okereke & Coventry, 2016).

4.4 Local Ownership Vs External Policy Influence

Finally, striking a balance between external influence and local ownership remains critical. While global finance and expertise are vital, transitions that do not integrate local contexts risk social resistance and inefficiency. to avoid externally driven transitions, countries like Rwanda and Ethiopia are experimenting with locally designed off-grid solar programs and mini-grids, mobilizing community cooperatives and local SMEs. This hybrid approach fosters ownership and resilience (Newell & Mulvaney, 2013).
Table 5.5 illustrates how locally-driven energy initiatives in Rwanda, Ethiopia, and Senegal have contributed to rural electrification, community resilience, and inclusive job creation.

Table Error! No text of specified style in document.**.8:** examples of local ownership initiatives and outcomes in selected African countries

Sources: Climate Policy Initiative. Africa Climate Finance Landscape, AFD - Noor Solar Complex, USAID Power Africa - Official Page, UNEP DTU CDM Pipeline - CDM Statistics,UNFCCC COP27 - COP27 Summary

Country	Example of Local Ownership	Outcome
Rwanda	Off-Grid Solar Cooperatives	20% rural electrification increase
Ethiopia	Community Mini-Grids	Improved village resilience
Senegal	Local Solar Entrepreneurs	Job creation for youth and women

5. TOWARDS A JUST AND CONTEXTUALIZED ENERGY TRANSITION

5.1 Principles for A Just Transition

A just energy transition goes beyond simply replacing fossil fuels with renewable energy. It prioritizes equity, social inclusion, and fair compensation for communities that bear the brunt of structural changes (Heffron & McCauley, 2017). This implies anticipating and mitigating job losses in carbon-intensive sectors through reskilling, creating alternative livelihoods, and guaranteeing social protection.

A notable example is South Africa's Just Energy Transition Partnership (JETP), launched at COP26, which aims to mobilize $8.5 billion to support a fair coal phase-out while ensuring no worker is left behind (JETP SA, 2021). Table 6.1 outlines the core dimensions of energy justice, emphasizing the importance of fair processes, equitable outcomes, and the recognition of diverse stakeholder interests within energy transitions (Heffron & McCauley, 2017).

Table Error! No text of specified style in document.**.9:** Core dimensions of energy justice

Source: Adapted from Heffron & McCauley, 2017

Justice Dimension	What it Means	Example
Procedural	Inclusive decision processes	Multi-stakeholder energy forums
Distributional	Equitable benefit/cost sharing	Community benefit-sharing in wind farms

Recognition	Acknowledge diverse groups	Indigenous land rights in energy siting

5.2 Integrating Transition in Endogenous Development

Africa's transition must be embedded in endogenous development strategies that build domestic capacities, foster local industries, and stimulate innovation (Obeng-Odoom, 2014). For example, Morocco's green energy push has spurred local manufacturing of solar panels and wind turbine parts, creating jobs and reducing import dependency (IEA, 2021).

Table 6.2 highlights selected examples of local content policies that strengthen domestic job creation and build capacity within renewable energy supply chains.

***Table** Error! No text of specified style in document.**.10:** Local content examples*

Source: Author's compilation based on IEA (2021) and national policy documents

Country	**Policy**	**Local Impact**
Morocco	Local manufacturing quotas for renewables	15,000+ jobs in solar/wind
Kenya	Community-owned mini-grids	Local operators manage assets
South Africa	Renewable Energy Independent Power Producer Procurement Programme (REIPPPP)	Local employment quotas

5.3 Coherent Policies and Inclusive Planning

Effective transition governance demands coherence across sectors—energy, environment, industry, and social welfare must align (Karekezi, 2003). Fragmented policies risk inefficiency and social backlash.

Best Practices:

- Develop National Energy and Climate Plans (NECPs) that integrate SDGs.
- Use participatory planning tools (e.g., stakeholder mapping).
- Monitor and evaluate policy impacts with clear KPIs.

Case Insight: Rwanda's Integrated Energy Master Plan coordinates grid expansion, off-grid electrification, and climate goals, reducing duplication and ensuring rural inclusion (Rwanda Energy Group, 2020).

5.4 Role of Local Knowledge and Civil Society

Community knowledge and grassroots organizations play a pivotal role in designing contextually relevant solutions. Local actors can inform site choices, resource use, and conflict resolution, enhancing project legitimacy (Newell & Mulvaney, 2013).

Practical Examples:

- In Kenya, community conservancies co-manage wind projects.
- In Ghana, women's cooperatives run biomass cookstove initiatives.
- NGOs facilitate energy literacy to build local ownership.

5.6 Regional Cooperation and South-South Solidarity

Given Africa's fragmented energy markets, regional integration can pool resources and strengthen bargaining power in global forums (IEA, 2022). Power pools such as the Southern African Power Pool (SAPP) and West African Power Pool (WAPP) are key examples.

At the same time, South-South cooperation—sharing know-how and technology with peers like India or Brazil—can help tailor solutions to similar socio-economic contexts. Table 6.3 summarizes key regional energy cooperation initiatives in Africa, which aim to improve cross-border energy trade and enhance energy security.

Table Error! No text of specified style in document.**.11:** Selected african regional energy initiatives

Source: Compiled from IEA (2022) and regional power pool reports

Initiative	Members	Goal	Status
SAPP	12 countries	Regional electricity trading	Operational
WAPP	14 countries	Grid interconnection	Expanding
EAPP	11 countries	Cross-border hydro and geothermal	Under development

CONCLUSION

This chapter demonstrates that decarbonization and development in Africa are inseparable and must be approached holistically. Aligning global imperatives with local contexts requires inclusive governance, fair financing, and knowledge co-production. Future research should further examine context-specific policy mixes and the role of African agency.

This chapter has explored the complex interlinkages between decarbonization imperatives and Africa's socio-economic development needs, situating the African experience within the broader debates of the political economy of energy transitions. It demonstrates that for African countries, decarbonization cannot be treated as an isolated technological fix, but must be embedded in a holistic strategy that addresses energy poverty, industrialization goals, and socio-economic inequalities.

By drawing on critical political economy perspectives (Bridge et al., 2018; Newell & Paterson, 2010) and context-specific case studies from Morocco, South Africa, Kenya, and Nigeria, this work highlights how power asymmetries, global finance flows, and governance arrangements shape national pathways, often reproducing historical dependencies and development dilemmas.

Importantly, the chapter underscores the need for a just transition approach — one that prioritizes procedural, distributional, and recognition justice (Akrofi et al., 2024; Heffron & McCauley, 2017). In doing so, it contributes to re-framing Africa's energy transition not merely as a technical challenge, but as a deeply political and social process, requiring inclusive decision-making, local empowerment, and regional solidarity.

The comparative analysis shows that while countries like Morocco have made significant strides through state-led green strategies supported by international donors, others like Nigeria continue to grapple with entrenched fossil fuel dependencies and weak diversification efforts. South Africa's coal legacy further illustrates the profound social justice tensions that can emerge if transitions are not managed equitably.

Therefore, for Africa, balancing universal energy access with emission reduction targets demands innovative governance arrangements, robust institutions, and context-sensitive climate finance mechanisms that respect national ownership and development sovereignty (Amin & PEARCE, 1976; Obeng-Odoom, 2014).

Looking ahead, future research should:

- Deepen understanding of hybrid policy mixes that reconcile growth, decarbonization, and equity.
- Examine local innovations, community-driven models, and informal energy solutions that often escape mainstream policy attention.
- Investigate how Africa can strengthen its negotiating power in global climate governance, ensuring that international norms and finance flows genuinely support transformative, endogenous development.

Policymakers, donors, and civil society must collaborate to design transition pathways that are resilient, inclusive, and adaptive, recognizing the continent's heterogeneity and the vital role of African agency in shaping its energy future.

Ultimately, achieving a just and contextualized energy transition in Africa is not only essential for meeting climate goals but also a catalyst for broader sustainable development and social transformation. As this chapter has argued, only by addressing the intricate dynamics of politics, power, and participation can Africa's transition pathways avoid reproducing old inequalities and instead pave the way for a more equitable, prosperous, and low-carbon future.

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CHAPTER 3

INDIA'S DECARBONISATION PATHWAY: DOMESTIC PROGRESS, GLOBAL STAKES AND STRUCTURAL CHALLENGES

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INTRODUCTION

Across India's dynamic socio-economic landscape, the transition to a low-carbon future is gradually unfolding—not just in policy circles, but also in the routines and choices of everyday life. Electric vehicles are increasingly visible on congested city streets, especially in the form of two-wheelers and e-rickshaws that serve millions in urban and semi-urban areas. Rooftop solar panels gleam atop residential buildings, rural homes, railway stations, government and private offices, signaling a push toward renewable energy. Households in both urban and semi-urban areas are now more likely to engage in waste segregation practices, aligning with growing awareness of circular economy principles and emission reduction. The increasing adoption of energy-efficient appliances, expansion of public transport systems such as metro rail networks, and the use of cleaner cooking fuels like LPG under schemes such as the Pradhan Mantri Ujjwala Yojana collectively reflect a gradual, yet impactful, societal shift. These developments are visible markers of India's decarbonisation efforts—clear manifestations of a national agenda that is becoming deeply embedded in public consciousness and daily life practices.

Decarbonisation, defined as the systematic reduction of carbon dioxide emissions across sectors—especially energy, transport, and industry—is central to the global fight against climate change. For a country like India, where economic development remains a pressing imperative, the pursuit of decarbonisation demands a nuanced balance between sustainability and inclusivity. India has long championed a model of development rooted in the principles of justice, equity, and environmental stewardship. Anchored in a civilizational ethos that emphasizes harmony between humanity and nature, the country has consistently sought to align growth with ecological responsibility. Its proactive stance on climate change mitigation—seen in both policy frameworks and on-the-ground transitions—stands as a powerful testament to this enduring commitment.

As the world's most populous nation and the fifth-largest economy, India is poised to play a pivotal role in global climate solutions. Despite contributing only around 4% to historical cumulative greenhouse gas emissions, India has pledged ambitious action under its Nationally Determined Contributions (NDCs). At COP26 in Glasgow, it committed to achieving net-zero emissions by 2070, sourcing 50% of its electricity from renewable sources by 2030 and reducing the emissions intensity of its GDP by 45% from 2005 levels. These targets are supported by comprehensive policy instruments such as the National Action Plan on Climate Change (NAPCC), the National Electric Mobility Mission Plan, and a growing focus on green hydrogen as a future energy vector. Nonetheless, India’s decarbonisation journey is not without formidable challenges. Structural constraints—ranging from the predominance of coal in the energy mix, an expansive informal sector, technological gaps, to limited financial and institutional capacity—pose significant obstacles. Disparities in infrastructure, regulatory fragmentation, and social vulnerabilities further complicate the transition to a green economy. Achieving a just and equitable decarbonisation process, especially in a diverse and densely populated country, necessitates systemic reforms, long-term vision, and inclusive policymaking.

Compared to several other Asian economies, India’s progress is commendable, especially in its ability to mainstream sustainability within the fabric of developmental planning. The country has embedded environmental considerations across policy frameworks, from urban planning and infrastructure development to energy transition and rural livelihood programs. Its efforts hold both national and global significance: domestically, they promise improved air quality, energy security, and employment generation in green sectors; globally, India’s role as a responsible climate actor and advocate for the Global South enhances its moral and strategic leverage.

This chapter explores India’s decarbonisation pathway through the lens of domestic progress, structural challenges, and global stakes. It argues that while the country’s efforts are ambitious and increasingly visible, their long-term success will depend on the extent to which they can overcome internal constraints and foster a resilient, inclusive, and low-carbon future.

1. INTRODUCTION TO DECARBONISATION

Decarbonisation refers to the systematic reduction of **carbon dioxide (CO_2)** emissions **intensity** in all economic/human activities, particularly the combustion of fossil fuels such as coal, oil, and natural gas. The ultimate aim is to transition toward a low-carbon economy, primarily powered by renewable energy sources like wind, solar, and hydroelectric power, supported by sustainable technologies and resource-efficient practices (IEA, 2023).

According to a McKinsey report, **83% of global CO_2 emissions** stem from energy consumption. Annually, over **34 billion tonnes of CO_2** are released into the atmosphere, making emission reduction an imperative step toward climate stabilisation (McKinsey & Company, 2022).

Decarbonisation is not a singular action, but a long-term, systemic transformation of how energy is produced, goods are manufactured, people and resources are transported, and economies are structured. It lies at the heart of global climate mitigation and resilience strategies.

1.1 Evolution of the Global Decarbonisation Agenda

The concept of decarbonisation has evolved gradually, gaining prominence through scientific discovery, environmental diplomacy, and increasing public concern about climate risks.

1.1.1 Key Milestones in Decarbonisation Policy

The following timeline outlines significant events that have propelled decarbonisation onto the international stage:

- **1988** – Establishment of the Intergovernmental Panel on Climate Change (IPCC)
- **1997** – Adoption of the Kyoto Protocol, setting binding emission targets for developed nations
- **2015** – Paris Agreement commits countries to limit global temperature rise to below 2°C
- **2018** – IPCC Special Report warns of dire consequences of exceeding 1.5°C warming
- **2021** – UNEP Emissions Gap Report highlights urgent need for action
- **2023–2024** – Record-breaking global emissions underscore the shrinking carbon budget

1.2 Key Shifts Required for Achieving Decarbonisation

The path to achieving decarbonisation requires a comprehensive transformation across all major sectors of the economy. Foremost is the transition to renewable energy sources, such as solar and wind, alongside improvements in energy efficiency to decarbonise the power sector.

Heavy industries like steel, cement, and chemicals, which rely on high-temperature processes, must adopt clean technologies including green hydrogen, electrification, and carbon capture, though these require significant scaling and investment. The transport sector needs a shift to electric vehicles supported by robust charging infrastructure and renewable energy, while aviation and shipping must adopt sustainable fuels and efficiency upgrades. In the building sector, reducing emissions involves enhancing insulation, retrofitting, and replacing fossil fuel-based heating systems with low-carbon alternatives. Equally important is transforming land use through regenerative agriculture, afforestation, and restoration of ecosystems to turn natural landscapes into carbon sinks. Finally, a circular economy approach—focusing on reuse, recycling, and sustainable product design—can significantly reduce material consumption and emissions. Together, these shifts demand not only technological innovation but also strong policy support, financial investment, and coordinated public-private action.

1.2.1 Enablers of The Decarbonisation Transition

While technological innovation is critical, the success of decarbonisation also hinges on a combination of policy coherence, market mechanisms, institutional frameworks, and societal engagement. The following enablers are essential:

- Strong and consistent climate policy frameworks
- Public investment in research, infrastructure, and clean energy
- Private sector leadership and innovation
- Transparency and accountability in climate governance
- Inclusive and equitable transition strategies for vulnerable populations

1.2.2 India's Decarbonisation Pathway: Balancing Climate Responsibility with Developmental Ambitions

India's diverse geography—from high mountains and vast deserts to long coastlines and dense forests—makes it particularly vulnerable to the impacts of climate change. Its heavy reliance on monsoons for agriculture, the large agrarian workforce, extensive coastal population, and stressed water systems intensify these risks. Building climate resilience and developing robust adaptation strategies are therefore essential to protect economic progress and safeguard livelihoods and ecosystems.

However, India’s climate strategy extends beyond national necessity. As international climate rules evolve, India is positioning itself as both a climate-vulnerable nation and a constructive player in global climate action. With a population exceeding 1.4 billion and a significant share of global emissions, India faces the complex task of balancing rapid development with emission reductions. Growing energy needs, poor air quality, rising climate risks, and the goal of energy self-reliance have all driven the country to pursue a low-carbon transition. Rather than seeing these challenges as limitations, India increasingly views climate action as an opportunity for innovation, competitiveness, and inclusive growth.

Despite its scale, India’s historical contribution to global greenhouse gas emissions remains relatively low compared to its population share. This contrast reinforces the need for climate equity and positions India as a leader among developing nations committed to sustainable development. Its strong push for renewable energy and clean technology signals a deliberate effort to align economic ambitions with environmental responsibility.

India’s decarbonisation strategy reflects a balance between national development priorities and international climate commitments. It includes an integrated framework that spans renewable energy, energy efficiency, clean transportation, afforestation, and emerging technologies. With a long-term goal of achieving net-zero emissions, India continues to strengthen its policy landscape, demonstrating that climate leadership can coexist with inclusive, high-growth development.

2. INDIA’S CLIMATE POLICY ARCHITECTURE: EVOLUTION AND MILESTONES

2.1 .1 Multilateral Foundations and India’s Constructive Role

India's engagement in global climate diplomacy has been rooted in equity, sustainable development, and differentiated responsibilities. The early international climate regime—shaped by the **United Nations Framework Convention on Climate Change (UNFCCC, 1992)** and the **Kyoto Protocol**

(1997)—assigned binding mitigation responsibilities primarily to industrialised nations. India, as a developing country with low historical emissions and high climate vulnerability, participated actively but was not subject to emission reduction obligations (UNFCCC, 1998).

2.1.2 Institutionalising Domestic Climate Action: The NAPCC

A major domestic shift occurred with the launch of the National Action Plan on Climate Change (NAPCC) in 2008. This pioneering initiative articulated India's voluntary leadership in climate mitigation and adaptation long before universal obligations under the Paris Agreement. It introduced **eight national missions**, integrating climate objectives into developmental priorities (Press Information Bureau [PIB], 2021).

By requiring the formulation of State Action Plans on Climate Change **(SAPCCs)**, the NAPCC helped mainstream climate resilience across India's federal governance system and diversified eco-geographies.

Table 1.
National Action Plan on Climate Change (NAPCC): Missions

S.No	Mission	Launched	Objective
1.	National Solar Mission	2010	Focus on solar technology penetration in the country both at a centralized and decentralized level. Establish India as a global leader in solar energy
2.	National Mission for Enhanced Energy Efficiency	2011	Focus on enhancing energy efficiency in energy intensive industries
3	National Mission on Sustainable Habitat	2010	Focus on Development of sustainable habitat standards that lead to robust development strategies while simultaneously addressing climate change related concerns
4.	National Water Mission	2011	Focus on increasing water use efficiency by 20%; to reduce wastage of water at all levels; promote wter conservation and preservation by all.

5.	National Mission for Sustaining the Himalayan Eco-system	2011	Focus on sustaining the Himalayan Ecosystem through various measures
6	National Mission for a Green India	2014	Focus on responding to climate change by a combination of adaptation and mitigation measures.
7.	National Mission for Sustainable Agriculture	2014	Focus on making agriculture more productive, sustainable, remunerative and climate resilient
8.	National Mission on Strategic Knowledge for Climate Change	2008 as part of NAPC C	Focus on building a vibrant and dynamic knowledge system to support national action for effective sustainable development.

Source: Press Information Bureau 2021

https://static.pib.gov.in/WriteReadData/specificdocs/documents/2021/dec/doc202112101.pdf

2.1.3 From Domestic Vision to Global Pledges: NDC and Beyond

The Paris Agreement (2015) marked a paradigm shift in climate governance by requiring all signatories to submit **Nationally Determined Contributions (NDCs)**. India's first NDC (2016) formalised its climate ambitions while remaining rooted in principles of equity and national circumstances. It is committed to:

- Reduce **emissions intensity of GDP by 33–35%** from 2005 levels by 2030.
- Achieve **40% non-fossil electricity capacity** by 2030.
- Create a **forest carbon sink** of **2.5–3 billion tCO_2 equivalent** through afforestation by 2030 (MoEFCC, 2016).
- Boost climate resilience in agriculture, water and health

These pledges aligned global cooperation with India's domestic priorities, signalling its transition from reactive participation to proactive climate leadership.

2.1.4 Enhanced NDC and Long-Term Strategy (2022)

India submitted an **updated NDC** in 2022 after the Conference of the Parties 26, (COP26), incorporating more ambitious goals and reflecting its growing leadership in climate action:

- Emissions intensity reduction target enhanced to 45% by 2030
- Non-fossil fuel share increased to 50% of total installed capacity by 2030
- Alignment with the Net Zero target by 2070, announced at COP26
- Focus on "Lifestyle for Environment (LiFE)" as a key behavioural dimension of mitigation (MoEFCC, 2022)

India also submitted its Long-Term Low Emissions Development Strategy (LT-LEDS) at COP27 in 2022, outlining pathways for decarbonisation in sectors like energy, transport, industry, and urban development.

2.2 Key Missions and Policy Frameworks Supporting Decarbonisation in India

India has launched multiple sector-specific missions to support its decarbonisation goals. The table below mentions key missions and policies that India.

Table 2: Sector-wise Decarbonisation Policies and Missions: A Glance

Sector	Key Missions/ Policies	Objective & Focus
Energy	Ujwal DISCOM Assurance Yojana (UDAY, 2015) National Electricity Plan (2018, 2023) Perform Achieve Trade (PAT) Scheme National Smart Grid Mission Green Energy Corridor	To improve the financial health and operational efficiency of state-owned power distribution companies (DISCOMs) in India. Comprehensive strategy for managing the country's energy resources, consumption, and production. Market-based mechanism to enhance industrial energy efficiency. Modernize power grids for renewable integration and demand-side management. Evacuate and integrate renewable power into the grid

Renewables	National Solar Mission (NSM, updated in 2015 under NAPCC) Wind-Solar Hybrid Policy (2018) PM KUSUM PM Surya Ghar-Muft Bijli Yojana National Green Hydrogen Mission	Promote solar capacity (goal revised to 280 GW by 2030. Optimize land and transmission for co-located solar-wind systems. Solarize agricultural pumps; reduce diesel use in agriculture. Increase the adoption of solar rooftop capacity and empower residential households to generate their own electricity. Reduce reliance on fossil fuels and establish India as a global leader in production, usage, and export of green hydrogen
Transport	FAME I & II (Faster Adoption and Manufacturing of Hybrid and EVs) National Electric Mobility Mission Plan (NEMMP) Scrappage Policy (2021)	Promote electric vehicles, hybrid tech, EV infrastructure Create ecosystem for e-mobility; target 30% EVs by 2030 Phase out polluting vehicles, promote fuel efficiency
Urban Planning	Smart Cities Mission National Mission on Sustainable Habitat (NAPCC sub-mission AMRUT 2.0 (Atal Mission for Rejuvenation and Urban Transformation)	Sustainable urban design, green buildings, e-mobility, smart transport Urban energy efficiency, mass transit, waste-to-energy, green construction Water & waste management, green space, clean energy infrastructure
Buildings	Energy Conservation Building Code (ECBC)	Set minimum energy efficiency standards for commercial and residential buildings

Industry	PAT scheme across sectors	Sector-specific targets for emissions intensity reduction (e.g. steel, cement, textiles)
Agriculture	National Mission for Sustainable Agriculture (NMSA) Soil Health Card Scheme PM-KUSUM	To promote sustainable agriculture practices, organic farming, climate resilience Reduce use of chemical based fertilisers and other products To reduce emission from diesel pumps
Forest & Land	National Afforestation Programme Green India Mission	Increase forest cover and carbon sinks Increasing Green cover and forest livelihoods
Waste Management	Swachh Bharat Mission (Urban + Rural) Waste to Energy Programme	Promote waste segregation, composting, biogas, reduce methane emissions from landfills. Promote biogas, RDF (refuse-derived fuel), and urban bioenergy
India led global mass movement for sustainable living	LiFE Movement	Encourage sustainable consumption and low-carbon living.

Source: Prepared by the author referring to various websites

3. INDIA’S ACHIEVEMENTS IN DECARBONISATION EFFORTS

The infographic below from the Press Information Bureau highlights India’s achievements with regard to its decarbonisation efforts.

Figure:1

Source:https://www.pib.gov.in/PressNoteDetails.aspx?id=154545&NoteId=154545&ModuleId=3

India has demonstrated notable progress in its decarbonisation journey, marked by strategic policy shifts, the rapid expansion of renewable energy capacity, and measurable reductions in greenhouse gas (GHG) emissions. Between 2015 and 2021, the country significantly enhanced its climate efforts through a multi-pronged approach involving robust policy instruments, strengthened institutional frameworks, and proactive international cooperation. One of the most significant short-term developments was the reduction in total GHG emissions during the COVID-19 pandemic.

As reported in the Government's Fourth Biennial Update Report (BUR-4) to the UNFCCC, India achieved a **7.93% decline in emissions in 2020 compared to 2019**, primarily due to the economic slowdown, reduced industrial activity, and lower fossil fuel consumption during lockdown periods (Ministry of Environment, Forest and Climate Change, (MoEFCC,2023).

India's decarbonisation efforts have gained substantial momentum in recent years, underpinned by transformative progress in renewable energy deployment, transport electrification, and emissions management. A defining achievement lies in the restructuring of the country's power generation portfolio. As of October 2024, India's total installed electricity generation capacity reached **452.69 GW**, of which **203.18 GW—over 46.3%—originates from renewable sources**, marking a strategic pivot toward low-carbon energy systems (Ministry of New and Renewable Energy [MNRE], 2024). This remarkable transformation is led by **solar power (92.12 GW)**, supported by **wind (47.72 GW)**, **large hydro (46.93 GW)**, **small hydro (5.07 GW)**, and **bioenergy (11.32 GW)**, effectively diversifying India's energy base while enhancing energy security and sustainability. The infographic below explains India's achievements in Renewabl energy sector.

Complementing these efforts, India has made substantial gains in improving the emissions intensity of its GDP, achieving a 33% reduction from 2005 levels by 2020, well on track to meet its NDC target of a 45% reduction by 2030 (MoEFCC, 2023). This achievement reflects advances in energy efficiency, a transition to cleaner fuels, and an expanding share of renewables in the energy mix.

In the transport sector, emissions grew from 105 $MtCO_2$ in 2000 to 325 $MtCO_2$ in 2019, yet per capita emissions remain the lowest in the G20 at just 0.25 tCO_2 (IEA, 2023). India has responded with a multi-modal green mobility strategy including rapid rail electrification, urban metro expansion, development of the Gati Shakti logistics platform, and robust support for electric vehicles (EVs) through the FAME I & II schemes. The allocation of $1.25 billion under FAME II has supported over 1.5 million EVs and the rollout of charging infrastructure. EV adoption is accelerating rapidly, with a 168% increase in sales in 2021 (NITI Aayog, 2022), indicating strong public and private sector alignment with low-carbon transport.

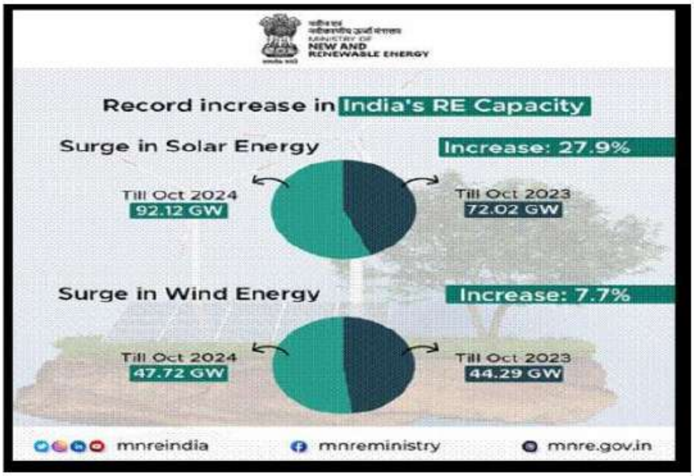

Figure: 2

Source: https://www.pib.gov.in/PressReleasePage.aspx?PRID=207303

India is also advancing nature-based solutions. Through its NDCs, the country aims to establish an additional carbon sink of 2.5 to 3 billion tonnes CO_2e by 2030 via afforestation and reforestation. The Green India Mission, a key initiative under the National Action Plan on Climate Change (NAPCC), targets increasing forest and tree cover by 5 million hectares and enhancing forest quality on another 5 million hectares. According to the India State of Forest Report (ISFR 2023), forest cover rose from 698,712 km² in 2013 to 715,343 km² in 2023 (Forest Survey of India, 2023), reinforcing India's nature-based climate mitigation approach.

Figure: 3

Source:https://www.pib.gov.in/PressNoteDetails.aspx?id=154545&NoteId=154545&ModuleId=3

India is also making progress in turning agricultural waste into clean energy. Every year, large amounts of crop residues like rice husk, wheat straw, and sugarcane waste—once commonly burned in open fields—are now being used to produce cleaner fuels and organic compost. Through national programmes, many new plants have been set up to process this waste into biofuel, helping to reduce air pollution in rural areas. These efforts not only improve environmental health but also create extra income for farmers and support the country's shift toward cleaner energy sources.

India's industrial sector—including steel, cement, aluminium, and chemicals—is making important efforts to reduce pollution and move toward cleaner production methods. For example, the steel industry is testing new ways to cut emissions by using cleaner energy and recycling heat from its processes. Similarly, the cement industry is using alternative materials and fuels to reduce its environmental impact. Although some clean technologies are still expensive and not widely used, the government is working to support their growth. With the right support, these efforts could significantly reduce industrial emissions in the coming years.

Collectively, these achievements reflect India's transformation into a proactive and responsible global climate leader. Anchored in a deep-rooted cultural ethos of environmental stewardship and driven by forward-looking policies, India is successfully harmonising rapid economic growth with the imperatives of low-carbon development.

This integrated approach not only advances domestic sustainability goals but also reinforces India's contribution to global climate action.

4. GLOBAL STAKES AND INDIA'S DECARBONISATION EFFORTS

As the world's third-largest greenhouse gas emitter and home to nearly 1.4 billion people, India's climate policy decisions have significant global implications. Its actions are pivotal in determining whether international efforts to limit global warming to 1.5°C or 2°C can succeed. Unlike many industrialised nations, India's emissions are primarily driven by developmental imperatives such as poverty reduction, infrastructure expansion, and energy access, rather than excessive consumption. This positions India uniquely in global climate discussions—balancing its right to develop with the responsibility to contribute meaningfully to global mitigation efforts.

The 2021 Glasgow COP26 summit and the 2023 G20 summit in Delhi reinforced India's growing leadership in climate diplomacy. Initiatives such as the **International Solar Alliance (ISA)**, the **Coalition for Disaster Resilient Infrastructure (CDRI)**, and the **Lifestyle for Environment (LiFE)** movement exemplify India's push to create a global low-carbon framework rooted in equity and sustainability (Ministry of External Affairs [MEA], 2023). Furthermore, India's NDCs under the Paris Agreement—updated in 2022—demonstrate enhanced ambition with commitments to reduce emissions intensity of GDP by 45% from 2005 levels and achieve 50% cumulative electric power installed capacity from non-fossil fuel sources by 2030 (UNFCCC, 2022).

India's success in low-cost solar energy deployment, electric vehicle promotion, and green hydrogen scaling could offer a model for other emerging economies. Its approach reinforces the global consensus that climate action can be integrated with poverty reduction and energy access—key pillars of the UN Sustainable Development Goals (SDGs).

India's focus on research, innovation, and building domestic capacities for low-carbon technologies can serve as a model for other developing countries. Accelerating technology development and its dissemination can enhance global resilience and facilitate a broader adoption of clean energy solutions.

For the world, India's decarbonisation efforts represent a vital test case for sustainable development that is equitable and scalable. If India can demonstrate that a populous, rapidly developing nation can grow while staying within climate limits, it provides a model for other Global South countries. Thus, the stakes are not only national or regional—they are decisively global.

5. STRUCTURAL CHALLENGES IN INDIA’S DECARBONISATION PATHWAY

ENERGY-INTENSIVE ECONOMIC GROWTH MODEL

India’s economic growth is heavily reliant on fossil fuels, especially coal, which continues to power the majority of its electricity needs. This dependence stems from the energy demands of core sectors like industry, transport, and manufacturing. While renewable energy is growing rapidly, its wider adoption is hindered by grid instability, limited storage, and intermittency.

Transitioning from coal presents complex economic and social challenges, particularly in regions where coal supports livelihoods and local economies. A balanced, phased approach is essential—one that ensures energy security, promotes clean technologies, and supports affected communities through a just transition.

Financing and Technological Gaps

Mobilising finance for green infrastructure and securing timely technology transfer remain two of the toughest hurdles on India’s decarbonisation path. Enormous capital outlays—running into many trillions of dollars—will be needed to build renewable power plants, modernise grids, expand electric-mobility networks, and green hard-to-abate industries. Yet affordable climate finance is still scarce, particularly for small and medium enterprises and rural energy projects that are essential to an inclusive transition. At the same time, next-generation solutions such as green hydrogen, carbon-capture systems, and smart grids remain costly and largely pre-commercial, constrained by limited domestic research capacity and scaled-up demonstration.

To unblock these bottlenecks, India will have to attract larger pools of concessional and blended finance, foster public–private investment platforms, and strengthen home-grown innovation ecosystems.

Strategic international partnerships, risk-sharing instruments, and clear, long-term policy signals can lower the cost of capital and accelerate the domestic uptake of advanced low-carbon technologies, ensuring that all sectors and regions share in the benefits of a green transformation.

Socioeconomic and Regional Inequities

Energy poverty, rural-urban disparities, and state-level variations in capacity and political will continue to complicate India's decarbonisation pathway. While states like Gujarat, Tamil Nadu, and Maharashtra are advancing rapidly in renewable energy deployment and green industrial policies, several others still rely heavily on coal. This reliance is not only due to local resource availability but also because coal mining and thermal power sectors remain major sources of employment and state revenues in certain regions. These regional imbalances create a fragmented national energy transition, where progress is uneven and influenced by local socio-economic factors.

To ensure that decarbonisation does not deepen existing inequalities, a just transition is essential. This involves more than shifting technologies; it requires protecting vulnerable communities through targeted interventions such as re-skilling coal-dependent workers, generating alternative livelihoods, and investing in sustainable rural infrastructure. Equally important is the need for participatory planning processes that involve local stakeholders in decision-making, ensuring that climate policies align with grassroots development priorities.

Institutional and Policy Gaps

Coordinating climate action across multiple sectors and levels of government remains a significant institutional challenge. In India, climate-related responsibilities are distributed among various ministries and regulatory bodies, which can result in overlapping mandates, delayed coordination, and inefficient implementation. As a result, the core objective remains unaccomplished. Additionally, many existing policies lack the coherence, enforcement strength, and ambition required to drive a transformative shift. Institutional limitations in capacity and technical expertise further hinder effective planning and execution.

These institutional hurdles are further compounded by the absence of a unified national climate governance framework that can align central and state-level priorities. While states have a critical role in implementing climate policies, particularly in energy, transport, and land use—the lack of consistent inter-agency coordination leads to fragmented action and duplication of efforts. Strengthening vertical and horizontal integration among government bodies, supported by clear mandates and shared accountability, is essential to streamline climate governance and ensure timely, effective implementation of India's decarbonisation strategies.

Long-term Planning and Uncertainty

India's commitment to achieving net-zero emissions by 2070 demands sustained action across multiple decades, involving complex and evolving interactions between technology, policy, economics, and behaviour. Long-term planning over such a horizon is inherently uncertain, as it must account for future developments that are difficult to predict—such as breakthrough innovations, global economic shifts, or climate-induced disruptions. Maintaining policy continuity and political will over successive administrations adds another layer of difficulty, especially in a democratic and federal system where priorities may vary over time.

Furthermore, the pace of technological change can either accelerate progress or create dependence on transitional solutions that may become obsolete. Market fluctuations, changing energy prices, and geopolitical factors also affect the feasibility and timing of key interventions like hydrogen infrastructure or carbon capture technologies. This uncertainty necessitates flexible, adaptive policy frameworks that can respond to emerging challenges without derailing long-term goals. Strategic foresight, robust data systems, and regular course corrections will be essential to ensure India remains on a resilient and credible decarbonisation pathway.

Trade-offs Between Development and Decarbonization

India’s development priorities—such as reducing poverty, expanding energy access, and accelerating industrial growth—are closely tied to carbon-intensive sectors, making deep decarbonisation particularly challenging.

Coal continues to play a vital role in providing affordable electricity, especially in economically weaker regions, which complicates a rapid shift to cleaner alternatives. Moreover, aggressive climate policies, if not carefully designed, can lead to job displacement and widen regional inequalities

However, solutions like decentralised renewables and sustainable transport offer co-benefits, showing that development and decarbonisation can align when supported by inclusive, well-planned transitions (UNDP India, 2022).

CONCLUSION

India’s decarbonisation efforts stand at a complex but promising intersection of domestic development and global climate responsibility. The country’s achievements in renewable energy expansion, emissions intensity reduction, and low-carbon innovation underscore its role as a climate leader among emerging economies. Yet, structural challenges—ranging from institutional fragmentation to technological and financing constraints—must be systematically addressed to sustain this momentum. As global temperatures rise and the carbon budget shrinks, India's policy actions will be increasingly pivotal in determining the fate of international climate targets. Balancing economic growth with environmental sustainability, India must now strengthen its institutional capacity, attract green investment, and embed equity into its transition strategy. The global stakes are high, and India’s leadership—grounded in both tradition and transformation—offers a blueprint for inclusive and ambitious climate action.

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CHAPTER 4

GREEN FINANCE AND DECARBONIZATION POLICY SYNERGY

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INTRODUCTION

In modern world decarbonization policy is of high priority and is necessary to mitigate the effects of climate change and reduce greenhouse gas emissions resulting from human activities. It provides a set of measures aimed at transitioning to a low-carbon economy and reducing dependence on fossil fuels. Decarbonization is not only important for combating climate change, but also has significant potential to improve the economy, energy security, and quality of life. It has a positive influence on such important processes as:

- Reducing greenhouse gas emissions. The main task is to reduce greenhouse gas emissions, which are the main cause of global warming and climate change.
- Combating climate change. Decarbonization is key to preventing the catastrophic consequences of climate change, such as extreme weather events, rising sea levels, and others.
- Improving air quality and public health. Decarbonization contributes to reducing air pollution, which has a positive impact on human health.
- Modernizing the economy. Decarbonization requires modernizing industry, transitioning to new technologies, and improving energy efficiency, which helps to increase the country's competitiveness.
- Ensuring energy security. The transition to renewable energy sources and increasing energy efficiency reduces dependence on energy imports and ensures a more stable energy supply.
- Stimulating economic growth. Investing in green technologies and developing renewable energy can be a powerful driver of economic growth and job creation.

So, decarbonozation has a great importance on the environment, life quality and economic growth and is important for sustainable development.

The decarbonization process involves restructuring the economy, in particular, modernization of the energy sector, which requires support at the state and international levels in the form of emission reduction policies, state decarbonization programs, etc., as well as significant investments in the modernization of production, transition to green energy, the abandonment of fossil fuels, etc. In this case green finance helps allocate required resources and shift investments into prioritized areas.

1. LITERATURE REVIEW

In contemporary academic discourse, green finance is regarded as a key instrument in achieving the goals of economic decarbonization, particularly under the intensifying concentration of climate-related risks. The search for synergy between financial instruments and policy measures aimed at reducing carbon emissions has become the subject of numerous interdisciplinary studies. Based on empirical data from China, Lee et al. (2023) argue that green financial policies directly contribute to decarbonization, particularly by supporting technological innovation, restructuring industrial composition, and fostering the development of renewable energy. Similar conclusions are presented in the study by Huang et al. (2024), which emphasizes that the effectiveness of a green financial system lies not merely in its scale, but in the strategic allocation of capital toward energy-saving technologies.

A large-scale international study by Mamun et al. (2022), covering 46 countries, confirms that the impact of green finance on emission reductions is sustainable in both the short and long term, especially in countries with well-developed financial markets and high levels of innovation. The study by Zhu et al. (2024) focuses on the transformation of energy consumption in China, where green capital supports the growth of environmentally oriented industries, particularly in regions with limited public funding for science. Meanwhile, a systematic review by Fu et al. (2024) synthesizes theoretical and empirical approaches to the link between finance and decarbonization, underscoring the need for standardization of green instruments and the harmonization of policy frameworks at the intergovernmental level.

On the other hand, the study by Amolo (2024) highlights the risks in developing countries, particularly limited access to capital, regulatory uncertainty, and the continued dominance of fossil fuel investments. Berensmann and Lindenberg (2016) stress that without clearly coordinated financial and environmental policies; investments in green projects will remain insufficient. Their work also analyzes the role of regulators, particularly central banks, and notes their capacity to reallocate capital flows through monetary stimuli and prudential supervision. Financial regulators play an equally critical role in shaping the institutional environment for climate-related disclosure and in minimizing the risks of greenwashing.

A novel perspective on policy synergy is introduced in the work of Fichtner et al. (2025), who propose the concept of "impact channels" through which private capital influences ecological transformation, including mechanisms such as climate ratings, litigation, and standardization. An interesting approach is offered by Lazaro et al. (2023), who analyze Brazil’s RenovaBio policy as a functioning model of a decarbonization credit market that promotes sustainable agriculture. Adebayo et al. (2024) examine the application of green bonds in the oil industry to support carbon capture technologies and enhance energy efficiency.

The integration of industrial and social innovations into the green transition is addressed in the study by Dhayal et al. (2023), which explores the potential of the transition to Industry 5.0, where green financial capital underpins the development of a circular economy, green logistics, and industrial modernization. A systematic review by Shah et al. (2023) highlights the importance of financial innovations in China and India, which act as catalysts for green technologies through a combination of environmental regulation and market mechanisms. Similarly, Wahyudi et al. (2023) demonstrate that current academic trends focus on the synthesis of finance, digitalization, and climate strategies.

Finally, at the macroeconomic level, the study by Han et al. (2023) shows that combining green financial policy with regional innovation networks creates a synergistic effect that enhances the quality of economic growth. This is echoed in the work of Rochet (2019), which views financial markets as essential infrastructure for internalizing externalities and generating sustainable incentives.

In contemporary academic discourse, it is increasingly emphasized that the effectiveness of decarbonization is determined not only by technological innovation but also by the scale and structure of financial flows capable of redirecting capital toward environmentally sustainable sectors of the economy. The Sixth Assessment Report of the IPCC clearly states that to achieve the ‘well-below 2 °C’ pathway, global environmental investment needs to at least triple by 2030 (IPCC, 2022). The International Energy Agency, in its revised 'Net Zero 2050' roadmap, estimates the threshold for annual 'green' capital investment at approximately USD 4 trillion, highlighting that the lion's share must be mobilized from private sources through adequate pricing and effective financial-political linkages (IEA, 2021). A sector-specific analysis presented in the World Energy Outlook 2024 underscores the critical importance of financial incentives in the electricity sector, heavy industry, and transport, where entry barriers for green technologies remain the highest (IEA, 2024).

The magnitude of the "financing gap" is detailed in the study by Kerr et al. (2025), which substantiates an annual financing requirement of ≥ USD 8.4 trillion for the Global South and stresses that without adjustments in carbon pricing policies and the development of appropriate market infrastructure, private capital will exhaust its potential. The Climate Action Monitor 2024 by the OECD further notes that only 9 out of 51 surveyed countries have comprehensive green finance roadmaps integrated with their Nationally Determined Contributions (NDCs) under the Paris Agreement (OECD, 2024). In its Finance and Investment for Industry Decarbonisation report, the OECD emphasizes the necessity for de-risking mechanisms and public-private partnerships in heavy industry (OECD, 2022).

At the regulatory level, the European Union remains a leader, with its Green Deal supported by the "InvestEU" plan and the Just Transition Fund, forming an integrated push-pull mechanism through direct budget support and regulatory implementation of a taxonomic framework (The European Green Deal). Complementing these efforts are the Sustainable Finance Disclosure Regulation (SFDR) requirements for ESG risk reporting in financial products, which have already triggered a reallocation of over EUR 1 trillion in assets during 2023–2024 (European Parliament, 2024). Moreover, the latest technical report from the EU Platform on Sustainable Finance expands taxonomy criteria to hard-to-abate sectors (EU Platform on Sustainable Finance, 2025).

Monetary and supervisory authorities are also shifting the financial paradigm. For instance, the Bank for International Settlements (IFC Bulletin No. 63) notes that central banks across jurisdictions increasingly incorporate climate data into macroprudential and monetary models. Their participation in the "G20 Data Gaps" initiatives fosters the standardization of transformational risk indicators (Nefzi, D., Noels, J. et al., 2025). The Climate Risk Landscape 2024 review by UNEP FI reports that the share of banks conducting climate stress testing increased from over 30% in 2021 to 65% in 2024 (Carlin, D. & Li, W., 2024).

Progress reports from the Net-Zero Banking Alliance reveal that 57% of participating institutions have already set sector-specific targets for reducing carbon intensity using science-based scenarios (United Nations Environment, 2024). In its GFSR-2025, the International Monetary Fund warns that unbalanced decarbonization policies may elevate the risk of asset stress transformation in high-carbon sectors, necessitating prudential buffers and new liquidity support instruments (Enhancing Resilience amid Global Trade Uncertainty, 2025).

Regarding market-based financing instruments, the global volume of green bond issuances has exceeded USD 3.2 trillion, with empirical studies confirming their capacity to significantly reduce the emissions intensity of issuing entities. Panel data analysis by Nguyen H. & Duong H. (2025) records a 7–10% reduction in fossil fuel consumption by issuing corporations within two years of green bond placement. Khanchel I. et al. (2025) find that these effects intensify with higher levels of institutional ownership, as shareholder oversight of decarbonization discipline increases. Similarly, Tsipas F. et al. (2024) demonstrate that in countries with mature renewable energy markets, green bond portfolios accelerate the deployment of new RES capacities by 12% faster than the control sample.

Additionally, the private sector is gradually institutionalizing decarbonization metrics. The World Bank Climate Finance Roadmap 2025 envisions consortium-based co-financing models with government risk-sharing not exceeding 30% (World Bank, 2024), while the updated Climate Change Action Plan 2021–25 promotes a “country-platform” approach, whereby NDC-related needs are embedded into partnership and lending strategies (World Bank, 2021). Research by the Bank for International Settlements on climate data underscores that the availability of transparent and comparable indicators is foundational for reducing transaction costs and launching new structured products such as transition-linked loans (Fortanier F., 2024).

Thus, the current research unequivocally points to the multi-level and cross-sectoral nature of the synergy between green financial policy and decarbonization strategies. Successful integration is only possible under conditions of coordination, transparency, political will, and institutional flexibility.

2. RESULTS

The constant increase in the use of fossil fuels, the growth of production and consumption lead to an increase in greenhouse gas emissions, which causes significant damage to the environment. Given the limited resources and the need to reduce the destructive impact on the ecology and environment, there is a need to change the structure of energy resources use in favor of renewable energy sources. Different regions have different levels of greenhouse gas emissions and own experience in decarbonization policies implementation. A case of the **European Union** is a good example of constant actions towards emissions reduction. Most leading EU states have a tendency to emissions reduction and move towards the set goals (fig. 1).

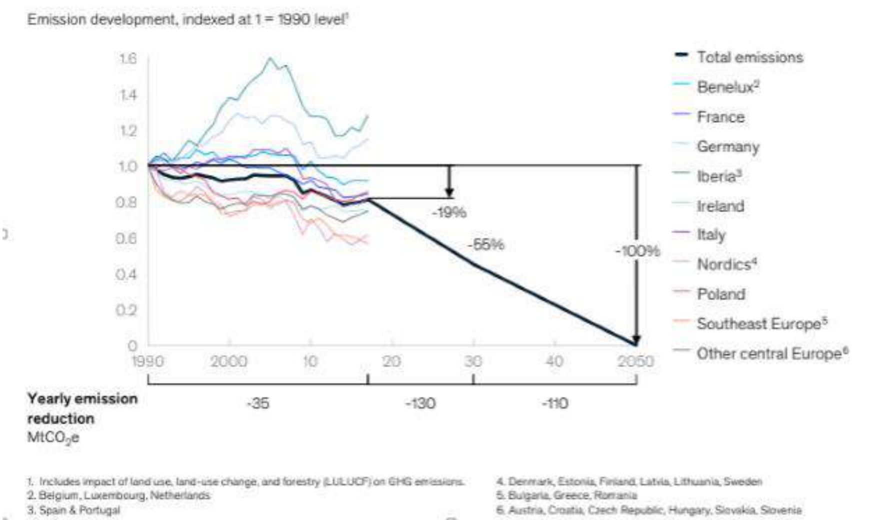

Figure 1. Greenhouse gas emissions dynamics in the EU
Source: McKinsey&Company (2020)

Different sectors of the economy have different volumes of GHG emissions. In the EU industry, power and transportation show the highest level of emissions (fig. 2). It means that these sectors need to be transformed more than others.

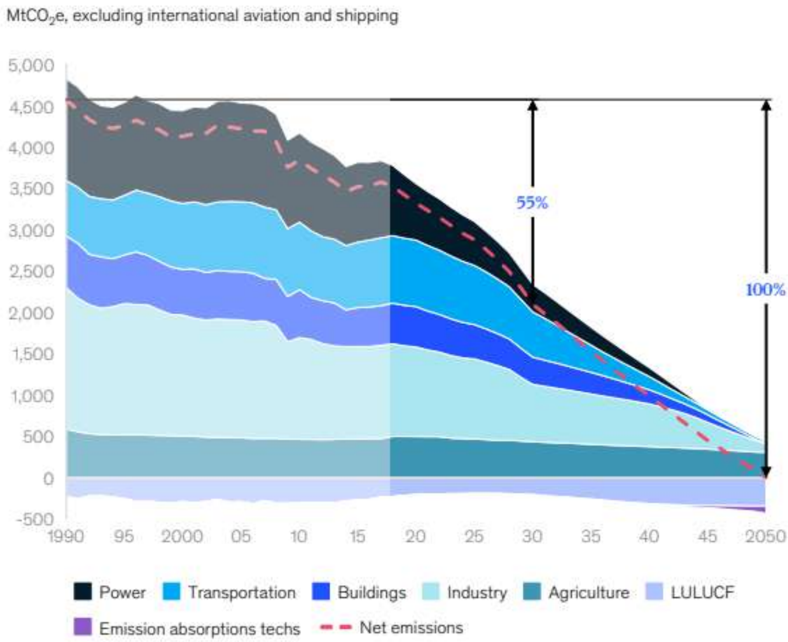

Figure 2. Total emissions per sector for EU-27
Source: McKinsey&Company (2020).

It is worth mentioning that integration groups such as the EU can achieve targeted goals easier than sole states because of compensation mechanism, so they can accumulate their relative advantages and lower transition costs (fig. 3).

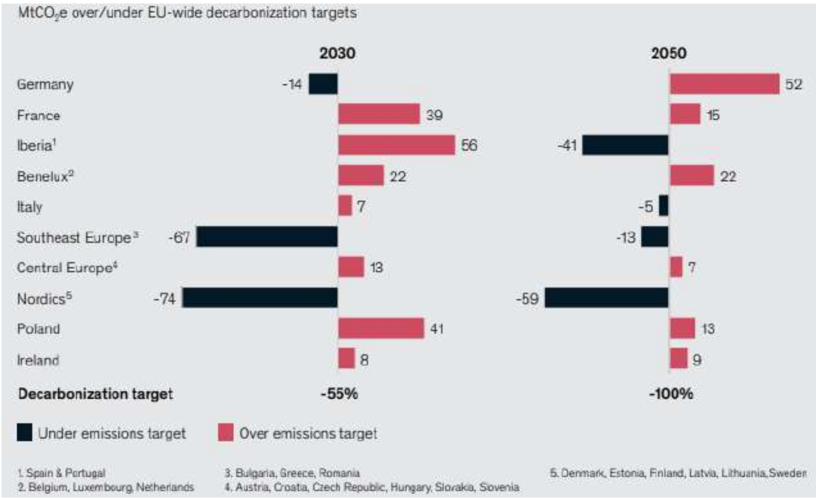

Figure 3. Total emissions reduction for EU-27

Source: McKinsey&Company (2020).

According to McKinsey&Company (2020) on the cost-optimal pathway, some countries' emissions reductions would compensate for others.

It is notable that the European Union has a history of meeting its decarbonization targets:

1. 1997 - Reducing GHG emissions by 8 % by 2012 according to the Kyoto Protocol. The EU over-delivered this target, reducing them by 18 percent.
2. 2010 - Reducing the continent's emissions by 20 percent by 2020. The EU surpassed that goal by 2018.
3. 2019 - the European Commission announced the European Green Deal aiming for climate neutrality. It is a new policy framework intended to accelerate greenhouse gas emissions reduction across the EU.

Among the policies under consideration is a law that would require the bloc to reduce GHG emissions by 55 percent relative to 1990 by 2030 and reach net-zero by 2050 McKinsey&Company, 2020).

3. REGULATORY FRAMEWORK

The European Green Deal serves as the strategic foundation for the EU's sustainability agenda (European Commission, 2019). It outlines the overarching goal of making Europe the first climate-neutral continent by 2050, setting in motion a wide range of legislative and regulatory initiatives.

It is not a law itself, but it catalysed the development of specific frameworks aimed at greening the economy, including supply chains.

This transition will require enormous investment: EU estimates project an additional €350 billion per year in clean energy investments this decade. To finance this, the EU is leveraging both public funds – e.g. dedicating €1 trillion from the 2021-2027 EU budget and NextGenerationEU recovery fund towards green objectives – and private capital, which must fill a remaining investment gap of at least €2.5 trillion (Brühl, 2021). Recognizing that private finance is crucial, the EU has enacted a comprehensive Sustainable Finance Strategy to guide capital toward decarbonization.

A keystone of the EU sustainable finance regulations is the EU Taxonomy for sustainable activities, introduced in 2020. The EU Taxonomy Regulation defines what qualifies as an environmentally sustainable economic activity (European Parliament & Council of the European Union, 2020). This classification system is crucial because it provides the technical basis for other legislative measures. It directly supports the Sustainable Finance Disclosure Regulation (SFDR) by helping financial market participants identify and disclose the sustainability characteristics of their investment portfolios (European Commission, n.d.). It also underpins the Corporate Sustainability Reporting Directive (CSRD) (European Parliament & Council of the European Union, 2022), by offering concrete criteria for companies to report the environmental sustainability of their operations and supply chains.

Instruments such as the EU Taxonomy Regulation, the Sustainable Finance Disclosure Regulation (SFDR), and the Corporate Sustainability Reporting Directive (CSRD) aim to embed sustainability into financial decision-making, enhance corporate transparency, and align private capital with climate objectives. Complementary initiatives, including the Corporate Sustainability Due Diligence Directive (CSDDD), the Carbon Border Adjustment Mechanism (CBAM), and the Deforestation-Free Products

Regulation, further extend these principles into supply chain governance by imposing new reporting, due diligence, and emissions accountability obligations on firms and their suppliers.

While the CSRD focuses on enhancing transparency through standardized sustainability reporting, the CSDDD establishes binding due diligence obligations for companies to identify, prevent, and mitigate adverse human rights and environmental impacts in their operations and supply chains (Corporate Sustainability Due Diligence Directive, 2025). Together, they promote greater accountability and ESG compliance throughout the value chain. The CSRD's entry into application expected in 2025 was postponed. In April 2025, the EU Council and Parliament formally approved the 'Stop-the-clock' mechanism – a directive (part of the "Omnibus I" package) that delays CSRD reporting application for "wave 2" large companies and listed SMEs by 2 years, now effective from 2027 instead of 2025, and postpones CSDDD transposition and initial enforcement (for the largest companies) by 1 year (Council of the European Union, 2025) (fig. 4). The CSDDD was initially expected to apply to the large companies starting from 2026.

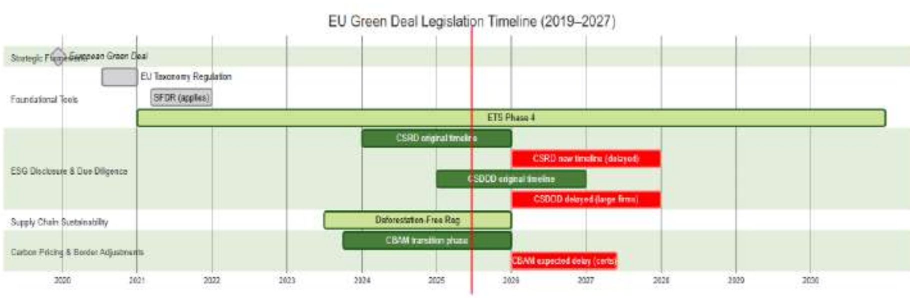

Figure 4. EU Green Deal Legislation Timeline (as of June 2025)
Source: conceptualized by the authors, AI-aided (ChatGPT) (syntax), created with mermaid.js.org

The EU Emissions Trading System (ETS), as a long-standing mechanism for carbon pricing within the EU, lays the groundwork for the Carbon Border Adjustment Mechanism (CBAM) (Corporate Sustainability Due Diligence Directive, 2025). CBAM is designed to address carbon leakage by imposing a carbon cost on certain goods imported into the EU. In essence, it brings carbon pricing into global trade by requiring importers to buy certificates equivalent to the CO_2 emissions embedded in products such as steel, cement, and fertilizers. By extending the logic of the EU Emissions Trading System (ETS) to imports, CBAM creates a level playing field between EU-based producers and foreign competitors, encouraging manufacturers outside the EU to reduce emissions if they wish to retain access to the European market.

This mechanism compels companies to gain deeper insight into the environmental footprint of their supply chains. It not only promotes emissions tracking and reporting across upstream operations but also incentivizes collaboration with suppliers to implement decarbonization strategies. This aligns closely with broader EU climate goals, particularly in advancing clean energy technologies, upgrading industrial infrastructure, improving energy efficiency, and supporting circular economy initiatives. These areas are also the focus of green finance instruments, with policies like the Sustainable Finance Disclosure Regulation (SFDR) and the EU Taxonomy providing financial incentives or penalties depending on the environmental impact of supply chain activities as captured by CBAM compliance data.

Together with the CSRD and CSDDD, CBAM forms part of a wider regulatory framework that underpins sustainable value chain governance. Financial institutions are increasingly incorporating emissions performance—particularly Scope 3 emissions—into their investment and lending criteria. Tools such as sustainability-linked loans and green supply chain finance offer favorable terms to companies that can demonstrate lower emissions across their supplier base, especially when verified under EU-aligned reporting standards.

Although the initial reporting phase of CBAM (2023–2025) remains intact, the start of certificate purchasing is now expected to be postponed until 2027, with actual financial obligations likely commencing in May of that year (S&P Global, 2025). This delay is intended to provide businesses, particularly smaller importers, with additional time to prepare the necessary data systems and compliance processes. While the timing of the cost burden shifts slightly, the core objective remains. The inclusion of a mass-based exemption threshold is also seen as a pragmatic step that eases compliance for smaller firms while still covering the vast majority of emissions, reportedly up to 99 per cent, thus striking a balance between environmental ambition and economic practicality.

The Deforestation-Free Products Regulation complements the CSDDD by targeting a specific environmental risk within supply chains. It prohibits the sale of products in the EU that are linked to deforestation, thus reinforcing corporate obligations to trace and verify the origins of raw materials – a core requirement also addressed under the due diligence framework of the CSDDD (European Commission, 2025).

With regard to these actual and potential delays, the official position of the European Council is that this move aims at cutting red tape, boosting competitiveness, and providing legal certainty. Indeed, it will give companies enough time to implement the systems necessary for the society and climate impact disclosure systems, and align with evolving standards. Further, considering the substantive amendments to CSRD and CSDDD, as well as the related ESRS, the delay is necessary to help avoid confusion from these simultaneous changes in legislation. In addition, it aligns with the broader EU's efforts to simplify legislation and reduce burdens, especially on SMEs.

On the other hand, while the delay eases immediate compliance burdens and helps businesses plan, it also raises concerns about consistency in the EU's green agenda. The 'Stop-the-clock' mechanism risks undermining credibility of the EU's sustainability framework and weakening its global leadership: despite the fact that it should not be regarded by the real sector as a "break" but rather as some additional time granted to streamline ESRS, simplify reporting templates, and clarify the scope, the approval of "Omnibus I" also can serve as an argument to highlight the contradictory nature of sustainable development commitments and the necessity to preserve the competitiveness of the EU industries, and member states at large, in times of global pressures and growing uncertainty.

The expected delay to CBAM will possibly postpone the financial internalization of climate risks across supply chains, and disincentivize early-mover investments in cleaner processes or green sourcing. On the positive side, it gives the time necessary to integrate CBAM data into broader ESG reporting (e.g., CSRD, SFDR), and a chance for financial institutions to align their green finance products (like supply chain transition loans or green trade finance) with upcoming carbon pricing signals. National and corporate strategies must use the delay to build data pipelines, traceability tools, and incentives for supplier transition, especially in carbon-intensive sectors.

While the core principles and regulatory frameworks of EU sustainability policy were developed during a relatively stable period (prior to the compounded global disruptions of the COVID-19 pandemic and the escalating geopolitical tensions post-2022), their implementation now unfolds under markedly different conditions. The recent EU decisions to delay the enforcement of key regulations, such as the CSRD, CSDDD, and CBAM, are officially framed as efforts to provide companies with the necessary time and clarity to comply. However, this shift raises the question of whether such postponements reflect an underlying tension between the EU's long-term commitments to sustainable development and the immediate imperatives of maintaining industrial competitiveness and economic stability in a volatile global context. Further study is warranted to assess whether these delays indicate a recalibration of sustainability ambitions under pressure, or a strategic realignment that seeks to preserve both environmental goals and economic resilience.

Another novel tool is the EU Climate Benchmarks regulation: since 2019 the EU has created Paris-Aligned and Climate Transition benchmark standards for financial indices, which only include companies on credible decarbonization trajectories, including full disclosure of the index carbon intensity and its alignment with a 1.5°C path. These benchmarks help investors allocate to low-carbon portfolios and encourage companies to reduce emissions to be included (Brühl, 2021).

Together, these policies are reshaping the landscape of supply chain management, where sustainability is no longer a voluntary or reputational concern but a regulated and increasingly financialized imperative. Access to green finance, eligibility for ESG-linked instruments, and participation in EU markets are progressively contingent on an organization's ability to trace, report, and reduce environmental impacts across its upstream and downstream operations.

At the same time, the evolving regulatory and financial environment is intersecting with a wave of technological innovation that is reshaping supply chain management at a structural level. Advanced digital tools, particularly artificial intelligence (AI), blockchain, quantum computing, and Internet of Things (IoT) technologies, are enabling new levels of transparency, traceability, and predictive decision-making. These innovations are especially critical for meeting the increasing demands of sustainability reporting, emissions tracking, and due diligence required under the CSRD, CSDDD, and CBAM.

For instance, AI-powered analytics can optimize logistics for carbon reduction, monitor supplier compliance in real time, and flag ESG risks across complex, multi-tiered networks. Quantum computing, though still emerging, promises to dramatically enhance supply chain scenario modelling and risk management, particularly for climate-related disruptions and regulatory compliance forecasting (SupplyChainBrain, 2024). Blockchain and distributed ledger technologies offer secure, verifiable records of product provenance, emissions data, and ethical sourcing, which is seen as an essential foundation for robust ESG assurance and green finance eligibility.

Beyond technology, innovations in green finance architecture, including sustainability-linked supply chain finance, performance-based ESG incentives, and dynamic pricing tied to carbon intensity, are helping companies align operational and financial strategies with sustainability goals. These tools not only facilitate compliance with new regulations but also create a competitive edge and market-driven momentum for decarbonization and responsible sourcing.

Together, these advancements position supply chains not just as a locus of regulatory risk, but as a frontier for sustainable innovation and value creation. As the EU refines its regulatory timelines and instruments, the convergence of policy, technology, and finance will increasingly define which firms are able to lead in the transition toward resilient, transparent, and low-carbon global trade systems.

4. GREEN BONDS AND MARKET INSTRUMENTS

Europe also leads in green bond development. The EU and its member states have become major issuers of green bonds (e.g. France and Germany issued sovereign green bonds, and the European Commission itself issued €250 billion in NextGenerationEU green bonds). By 2021, Europe accounted for roughly half of global green bond issuance. To bolster integrity, the European

Commission proposed a European Green Bond Standard (EU GBS). This voluntary standard (expected to be finalized in 2023/24) defines rigorous requirements for green bonds: proceeds must fund Taxonomy-aligned activities, issuers must publish allocation and impact reports, and external auditors supervised by ESMA must verify compliance. These strict criteria are designed to enhance transparency and investor confidence by ensuring bond funds genuinely contribute to decarbonization, thus avoiding greenwashing. Academic and policy analyses view the EU GBS as an important step to standardize green finance products and channel more private capital into high-quality green projects. In addition, EU policymakers have discussed innovative incentives – for example, a debated "green supporting factor" in banking capital rules (reducing capital requirements for green loans) to stimulate lending to low-carbon projects, and possible tax incentives (such as accelerated depreciation for green investments) to further spur private green investment (Brühl, 2021).

Although the EU accounts for only 7 % of global GHG emissions, the benefits of a net-zero Europe would be significant. A Europe on net-zero trajectory would accelerate investment in green technologies, test and refine global industrial strategies and market designs, and encourage other countries to make their own climate change goals more ambitious. Besides, European Commission`s climate change proposals, such as imposing a carbon border tax, would influence the carbon footprint of supply chains around the world.

Another case that is worth to analyse is developing countries` experience. Many developing countries (e.g. India, South Africa, Brazil, Indonesia, etc.) have in recent years begun leveraging green finance to support their decarbonization and sustainable development goals. While these countries contribute far less to historical emissions, they face the dual challenge of growing their economies and shifting to low-carbon pathways. Academic and institutional literature emphasizes innovative financing solutions – from blended finance to **public-private partnerships (PPPs)** – as critical to mobilize the large investments needed in these regions.

4.1 National Policies and Local Initiatives

An increasing number of emerging economies have launched national green finance strategies or institutions. India, for example, created a National Investment and Infrastructure Fund with a focus on green infrastructure and has seen several green bond issuances by public-sector entities for renewable energy. Brazil's central bank integrated climate risk into its banking supervision and encouraged sustainability-linked loans in agriculture. *South Africa* in 2022 released its **Green Finance Taxonomy**, aligned with the EU's framework, to guide investors toward climate-friendly projects and reduce ambiguity (National Treasury, Republic of South Africa, 2021). South Africa also set up a Climate Finance Facility to use concessional funds to de-risk clean projects. Such local efforts often draw on international best practices: for instance, the South African taxonomy was developed with technical support to ensure interoperability with global standards. Developing countries have also experimented with sovereign green bonds – e.g. Nigeria and Fiji were early issuers; by 2020-2022, others like Chile, Indonesia, Egypt, and Thailand sold green bonds to fund solar farms, sustainable transport, or adaptation measures. These issuances are academically notable for building local capital market capacity for green investment, though scholars call for rigorous impact tracking of the funded projects.

4.2 Blended Finance and PPPs

Given limited public coffers, *blended finance* (mixing public, philanthropic, and private investment) has gained traction as a way to fund decarbonization in developing countries. A Stanford review analyzed blended finance vehicles and found they are increasingly deployed to support clean energy transitions (National Treasury, Republic of South Africa, 2021). Key themes include the importance of structuring funds to provide first-loss capital or credit enhancements that attract private investors by reducing risk. For example, the **Global Energy Efficiency and Renewable Energy Fund (GEEREF)** – an EU-sponsored fund-of-funds – and the **Climate Public-Private Partnership (CP3)** program – backed by the UK and Asian Development Bank – both use public money to catalyze much larger private flows into renewables and energy efficiency projects in Africa, Asia, and Latin

America. Case studies of these funds show some success in raising private-to-public investment multiples, though also highlight issues like measuring "additionality" (whether projects would have happened without blended finance) and ensuring transparent impact reporting. Similarly, public-private partnerships have been employed for green infrastructure – for instance, PPP models are financing mass transit and wind farms in countries like India and Vietnam, often with multilateral development bank support. Academic assessments stress that well-designed PPP contracts can allocate risks appropriately and deliver projects on time but require robust governance to achieve environmental outcomes. Overall, blended finance and PPPs are seen as essential for scaling climate investment in developing markets but need to be greatly expanded to bridge the trillions in funding gap.

Based on the analysis of innovative green financing instruments and policies, a matrix was created "Policy Lever – Financial Channels" Matrix (table 1).

Table 1. 'Policy Lever – Financial Channels' Matrix

№	Policy lever	Financial channels	Principal financial instruments & structures
1	Carbon pricing and phase-out of fossil-fuel subsidies	A predictable carbon price (ETS, carbon tax) increases future cash-flows of low-carbon projects, raising their internal rate of return. Redirected subsidy savings expand fiscal space for green incentives.	– Emissions Trading Schemes (ETS) with free-allocation phase-down. – Carbon Contracts for Difference (CfD) guaranteeing a strike price. – Termination of tax rebates on diesel, coal, gas.
2	Targeted concessional and blended finance	Public lenders (DFIs, climate funds) accept first-loss or below-market returns; private lenders capture senior tranches, cutting weighted-average cost of capital (WACC) by 300-600 bp. Every public dollar can attract ≥ 5 private dollars ("crowd-in" effect).	-Blended-finance platforms (e.g., IFC's MCPP, GCF's Private Sector Facility). -Syndicated loans with pari-passu DFIs. -Risk-sharing facilities.
3	Capital-adequacy reform and MDB alignment	Lower green risk-weights and higher limits for long-tenor lending enlarge balance-sheet capacity. Multilateral Development Banks (MDBs) align portfolios to Paris	– Revised Basel III/IV risk-weight tables for climate-positive assets. – Hybrid capital instruments for MDBs.

		goals and recycle callable capital faster.	– Portfolio guarantees provided by donor trust funds.
4	Green taxonomies, data standards and mandatory ESG disclosure	Clear eligibility criteria reduce due-diligence costs and information asymmetry. Mandatory Task-Force-style disclosure (TCFD, ISSB) penalises “green-washing”, redirecting investor demand to verified assets.	– EU Taxonomy, ASEAN Taxonomy, China CSRC Green Catalogue. – Sustainable Finance Disclosure Regulation (SFDR) art. 8/9 funds. – Climate transition benchmarks.
5	National climate strategies integrated into budget processes (NDC tagging)	“Green tagging” of public expenditure creates an investable project pipeline with sovereign guarantees. Medium-term expenditure frameworks anchor private expectations.	– Climate-budget tagging systems (e.g., Indonesia, France). – Sovereign green bonds linked to tagged capital spending. – Public-private project preparation facilities.
6	Innovation support: R&D grants and tax credits	De-risks early-stage technologies (TRL 4-6) and bridges the “valley of death” to demonstration and first-of-a-kind (FOAK) plants. Lowers technology learning curves, enabling private equity entry.	– Competitive R&D grants (ARPA-E-type programmes). – Production tax credits (e.g., US IRA section 45X). – Milestone-based innovation prizes.
7	Credit enhancement: guarantees, insurance, first-loss capital	Public or philanthropic first-loss layers shift the loss-distribution curve, making projects bankable. Guarantees unlock local-currency financing in emerging markets.	– Partial risk guarantees (PRG) and political risk insurance (MIGA, ATI). – Green guarantee facilities (EIB, KfW). – Collateralised loan obligations with subordinated public tranche.
8	Sovereign transition frameworks: sustainability-linked bonds (SLB) and debt-for-climate swaps	Links coupon step-ups or face-value reductions to measurable climate KPIs, incentivising ambitious policies. Debt swaps free fiscal space for adaptation and mitigation investment.	– Sovereign SLBs with emissions-intensity targets (e.g., Chile 2023). – Debt-for-nature/climate swaps (e.g., Belize, Barbados). – Performance-based buy-down facilities.

Source: Conceptualized by the authors on the basis of Naran et. al., 2024

Hence, an "adaptive synergy" is forming between financial and political mechanisms, as regulatory signals—such as carbon pricing, taxonomy, and SFDR disclosures—enhance the attractiveness of green instruments, while their success in capital mobilization reinforces political trust and supports more ambitious climate objectives. A comparative analysis across over 40 countries identifies four typical configurations: budget-driven, market-de-risked, monetary-active, and hybrid. The highest environmental effectiveness at the lowest budgetary cost is demonstrated by states that combine taxonomical regulation with an active role of central banks and institutional investors. This typology serves as a foundation for the roadmap of regulators and financial institutions, aiming to optimize green finance portfolios, develop transition finance products, and implement resource-efficient incentives for sustainable development.

The results demonstrate that green finance policies have a positive impact on decarbonization through several key channels: 1) stimulating innovation in the field of green energy; 2) restructuring of industrial capacities; 3) increasing energy efficiency and supporting circular economy projects.

So, a mix of regulatory standards, strategic public funding, and market development is considered as a model for mobilizing finance at scale for decarbonization, albeit one that must continue evolving. Its effectiveness will ultimately be measured by how rapidly capital flows shift from high-carbon to low-carbon sectors, a trend that early data and disclosure reports are beginning to track.

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