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Conceptual approach and fundamental aspects for a low-carbon energy matrix

Abordagem conceitual e aspectos fundamentais para uma matriz energética de baixo carbono

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Abstract: The energy transition toward a low-carbon matrix is essential for mitigating climate change and meeting international targets such as those outlined in the Paris Agreement. This study analyzes the concepts and challenges of this transition, focusing on low-carbon technologies, carbon markets, and energy policies. A systematic literature review and a comparative analysis of successful cases were conducted, considering emission measurement methodologies and decarbonization strategies. The results indicate that energy diversification, combined with regulatory incentives and technological innovations, is fundamental to accelerating the transition. It is concluded that effective policies, sustainable financing, and integrated technological development are essential to achieving a resilient and low-carbon energy system.
Keywords: Decarbonization; Energy Policies; Circular Economy; Energy Efficiency; Carbon Credit Market; Energy Planning.

Resumo: *A transição energética para uma matriz de baixo carbono é essencial para mitigar as mudanças climáticas e cumprir metas internacionais como as do Acordo de Paris. Este estudo analisa os conceitos e desafios dessa transição, com foco em tecnologias de baixo carbono, mercado de carbono e políticas energéticas. Adotou-se uma revisão sistemática da literatura e a análise comparativa de casos bem-sucedidos, considerando metodologias de medição de emissões e estratégias de descarbonização. Os resultados indicam que a diversificação energética, aliada a incentivos regulatórios e inovações tecnológicas, é fundamental para acelerar a transição. Conclui-se que políticas eficazes, financiamento sustentável e desenvolvimento tecnológico integrado são essenciais para alcançar um sistema energético resiliente e de baixa emissão de carbono.*
Palavras-chave: Descarbonização; Políticas Energéticas; Economia Circular; Eficiência Energética; Mercado de Créditos de Carbono; Planejamento Energético

1 Introduction

The diversification of the energy matrix with low carbon sources represents a contemporary necessity for mitigating greenhouse gas (GHG) emissions, whose increasing atmospheric concentration is directly linked to global climate change (IPCC, 2021). In this context, renewable energy sources such as solar, wind and biomass emerge as technically viable and economically competitive alternatives, particularly in light of the significant reduction in photovoltaic technology costs of more than 80% in the past decade (IRENA, 2022). Beyond their scalability, these sources enable decentralized access to energy in remote areas, thereby contributing to energy equity (Nyangarika, 2024).

The transition to a low carbon economy requires not only the replacement of fossil fuel based energy sources but also the incorporation of carbon capture and storage (CCS) technologies for hard to abate industrial sectors such as cement, steel and plastics (Ritchie, Rosado and Roser, 2020). However, the absence of systematized data, combined with political instability, undermines the formulation of long term energy planning, particularly in developing countries, which must align themselves with the frameworks of Agenda 21 and Agenda 2030 (Relva et al., 2021). Agenda 21, formulated during the United Nations Conference on Environment and Development (Rio-92), constitutes a global effort to establish an action plan aimed at sustainable development, recognizing the risks of global warming, valuing the specificities of developing countries and promoting the empowerment of local communities in decision-making processes (Relva et al., 2021). Additionally, Agenda 2030 represents a subsequent advancement, structuring 17 Sustainable Development Goals (SDGs), among which SDG 7 stands out, addressing universal access to affordable, reliable and sustainable energy (Relva et al., 2021).

In addition to conventional renewable energy sources, green hydrogen, produced through water electrolysis powered by electricity from renewable sources, is a technically promising alternative for sectors where direct electrification is unfeasible. It has the potential to replace fossil fuels in energy intensive industries, particularly in long distance transport modes such as rail and maritime shipping (Marafon et al., 2024). Due to its predominantly renewable energy matrix, Brazil holds significant competitive potential in this emerging market (Fundação Getúlio Vargas, 2023).

In parallel, energy efficiency and emissions management strategies are gaining prominence. The quantification of carbon intensity, using tools such as the GHG Protocol and ISO 14064 standards, enables organizations to monitor their emissions and implement evidence-based decarbonization plans (IBTS, 2020). These practices, when integrated into sustainability reports, foster corporate transparency and reinforce the commitment to carbon neutrality.

However, the landscape of the energy transition remains fragmented, particularly regarding the integration of the pillars of sustainability, economic feasibility, and regulatory frameworks. Despite its central role in curbing climate change and fulfilling the Paris Agreement (UNFCCC, 2015), critical gaps persist in relation to equitable access to clean technologies, financing for sustainable projects, and institutional capacity building for decentralized energy management (Sovacool, 2021).

In this context, the present study is guided by the following research question: what are the main challenges and opportunities that shape the effectiveness of the energy transition toward a low carbon matrix, considering technological, regulatory, and socioeconomic dimensions? This formulation enables an understanding of how different contexts, across various countries, can structure public policies and market strategies oriented toward sustainability.

The rationale for this research lies in the need to systematize existing knowledge on the energy transition and identify factors that either facilitate or hinder its implementation. Although there is scientific consensus on the urgency of decarbonization, the literature reveals a gap regarding the integration of the various vectors of the transition, such as renewable energy, carbon markets, and energy efficiency, under a critical and applied perspective. Therefore, the objective of this study is to analyze the challenges and opportunities of the energy transition, with a focus on the implementation of renewable sources, the development of carbon pricing mechanisms, and the promotion of energy efficiency policies, in order to support sustainable strategies for decarbonizing the energy matrix. Figure 1 below presents the logical structure of the investigation, linking the contextualization of the problem, its theoretical and practical justification, the guiding objectives, and the expected contribution, thereby providing clarity to the methodological path adopted.

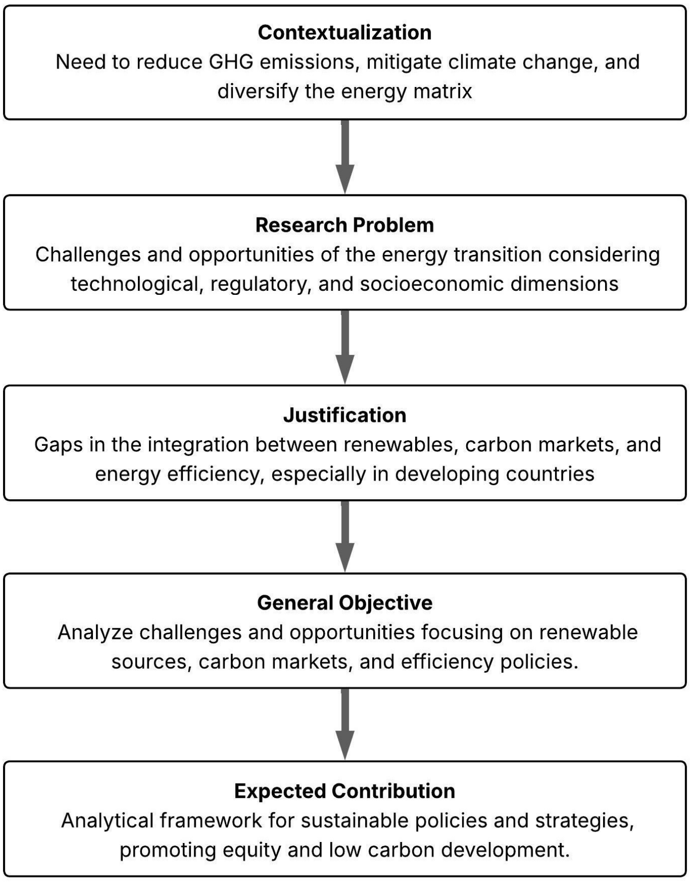

Figure 1: Logical framework of the study on the energy transition.

2 The carbon market and the energy transition

At the end of the nineteenth century, Svante August Arrhenius, Nobel laureate in Chemistry in 1903, had already posited that the rise in carbon dioxide driven by the Industrial Revolution would warm the Earth (Müller, 2002). In the 1970s, the United States Environmental Protection Agency found that several regions, especially Southern California, were not meeting prevailing air quality standards (Convery and Dunne, 2003). Convery and Dunne (2003) note that, in these areas, both new emission sources and facilities seeking to expand were required to offset incremental emissions by purchasing reduction credits from preexisting emitting units that had already implemented certified cuts. This pragmatic approach, which balanced economic development with the protection of air quality, was gradually expanded, particularly with the 1990 Clean Air Act Amendments, which authorized different emissions trading systems (Convery and Dunne, 2003).

The forerunner of global discussions and negotiations on climate change was the United Nations Conference on the Human Environment, held in Stockholm in June 1972, which for the first time recognized global environmental risks and the need for joint efforts by governments and industry (FUNAG, 2006).

In 1992, during the United Nations Conference on Environment and Development, known as the Earth Summit, held in Rio de Janeiro, 186 countries recognized the need for international cooperation to confront climate change and adopted the United Nations Framework Convention on Climate Change. This global treaty aimed to stabilize greenhouse gas (GHG) concentrations at levels that would prevent dangerous human interference with the climate system (UNFCCC, 2015). To monitor and coordinate actions on the issue, the Conference of the Parties (COP) was established to convene annually to assess progress and set new targets (UNFCCC, 2015).

Following the 1992 Earth Summit (Rio-92), the Kyoto Protocol emerged as the first international treaty to control greenhouse gas emissions, supported by 55 countries responsible for 55 percent of global GHG emissions (Pessini and Sganzerla, 2016). Carbon credits were created, allowing countries that did not meet their emission targets to purchase allowances from others. Although framed within the green economy, this practice has been criticized for enabling the circumvention of environmental targets and the continued emission of greenhouse gases (Pessini and Sganzerla, 2016). In this context, countries with reduced emissions can sell credits to higher-emitting countries, receiving one credit for each metric ton of CO_2 reduced, with the European Union and Japan being the largest traders of these credits (EPE, 2020).

Another important globally adopted environmental measure was the Montreal Protocol, which aims to control and phase out substances harmful to the ozone layer, such as chlorofluorocarbons (CFCs). These substances are widely used in products such as aerosols, refrigeration systems, and fire extinguishers, and they have a high ozone-depleting potential, as highlighted by UNEP (2012). By the end of 2010, production of these substances had been reduced to about 45,000 metric tons, a 98 percent decrease relative to 1987 levels. This significant outcome was achieved through sustained support from the governments that ratified the protocol and effective collaboration with international and local partners (UNEP, 2012).

In 2016, the Paris Agreement, signed by 195 countries, replaced the Kyoto Protocol, establishing more comprehensive and stringent targets for reducing greenhouse gas (GHG) emissions and explicitly incorporating emerging economies such as Brazil (Brasil, 2020). Under this agreement, each country defines its own GHG reduction targets, and Article 6 encourages voluntary cooperation to implement Nationally Determined Contributions (NDCs) with an emphasis on raising climate ambition, promoting sustainable development, and safeguarding environmental integrity (Brasil, 2020).

Article 6 of the Paris Agreement sets the foundations for international cooperation among the Parties to achieve their GHG mitigation goals through market-based instruments and non-market approaches (CNI, 2023). It is central to the operationalization of a global carbon market, providing mechanisms to increase ambition, advance sustainable development, and enable the trading of carbon credits (CNI, 2023).

The article is subdivided into three main provisions (CNI, 2023):

Article 6.2 (Internationally Transferred Mitigation Outcomes, ITMOs): enables countries to transfer among themselves surplus mitigation outcomes from their Nationally Determined Contributions (NDCs). Such cooperation must uphold environmental integrity, avoid double counting, and ensure corresponding adjustments to the targets of the countries involved.

Article 6.4 (Sustainable Market Mechanism, SMM): replaces the former Clean Development Mechanism (CDM) under the Kyoto Protocol. It establishes a certification system for emission-reduction projects, with the possibility of trading the carbon credits generated. This mechanism is designed for both governments and the private sector.

Article 6.8 (Non-Market Approaches, NMAs): aims to promote international cooperation through voluntary actions that do not involve direct financial transactions, such as technology transfer, climate finance, and technical assistance, particularly in developing countries.

The regulation allows Clean Development Mechanism (CDM) projects registered after 2013 to migrate to the new framework until the end of 2023, subject to government approval and maintaining criteria such as additionality, verification, and registry (CNI, 2023). The full operationalization of Article 6 is expected to be consolidated in subsequent years through the Supervisory Body of the United Nations Framework Convention on Climate Change (UNFCCC), which will be responsible for reviewing methodologies and safeguarding environmental integrity. The new international carbon market aims to mobilize climate finance, promote transparency, and encourage more ambitious climate targets (CNI, 2023). Discussions on the carbon market remain current, particularly with the 30th United Nations Climate Change Conference (COP30) held in Belém, Brazil, in 2025 (Brasil, 2025).

What follows is the historical evolution of carbon prices, expressed in US dollars per metric ton of CO_2 equivalent, across distinct regulated carbon markets worldwide between 2018 and 2023. Figure 2 illustrates the behavior of the main pricing systems, highlighting significant variation among jurisdictions in terms of climate ambition and institutional maturity. The European Union exhibits the highest and most volatile prices, whereas other regions, such as China and the Regional Greenhouse Gas Initiative (RGGI) in the northeastern United States, operate at more modest and relatively stable levels. This comparison helps elucidate price formation dynamics and market responses to regulatory, economic, and climatic changes.

The highest value was observed in the European Union Emissions Trading System (EU ETS), which exceeded USD 100 per tCO_2e in 2022, a result that may be associated with greater regulatory stringency. In contrast, the lowest price was recorded in China's national system, remaining below USD 10 per tCO_2e since its inception in 2021.

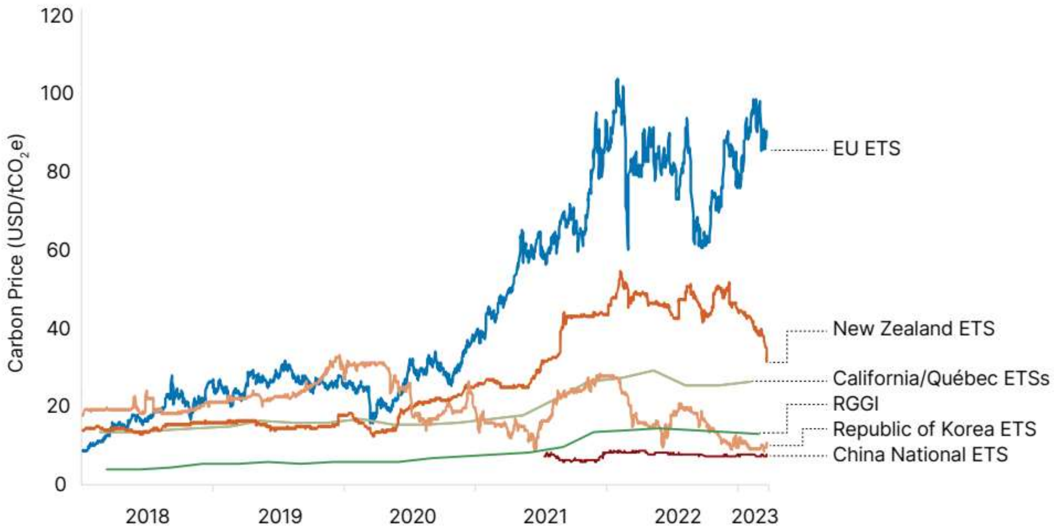

Figure 2: Historical evolution of carbon prices across different Emissions Trading Systems (ETS). Source: World Bank (2023).

3 Carbon market instruments

The concept of the carbon market rests on the premise that pollution from carbon emissions should carry a cost, enabling firms that reduce their emissions below a specified limit to sell surplus allowances to those unable to meet their targets (EPE, 2020).

This emissions trading system, known as cap-and-trade, sets an overall cap on greenhouse gas emissions for a given period, which is divided into emission allowances distributed among participating firms (Trennepohl, 2022). Companies that reduce emissions below their allocation may sell excess allowances to others that cannot achieve their goals, thereby creating an allowance market and incentivizing cost-effective abatement, since firms have a financial incentive to innovate and cut emissions (Trennepohl, 2022).

The European Union Emissions Trading System (EU ETS) is one of the world's largest and oldest cap-and-trade schemes. Implemented in 2005, it covers more than 11,000 installations in sectors such as power and industry, yet it has faced persistent challenges, including initial overallocation of allowances and price volatility (EPE, 2020). Recent reforms, such as the introduction of the Market Stability Reserve (MSR), have helped stabilize prices and enhance the system's effectiveness in driving emission reductions (EPE, 2020).

According to the Technical Note on Bill No. 182/2024 (Observatório do Clima, 2024), carbon taxes are levies applied directly to greenhouse gas (GHG) emissions. This form of taxation sets a fixed price per metric ton of CO_2 emitted, encouraging firms to reduce their emissions to avoid additional costs. The benefits of carbon taxes include cost predictability for companies and the generation of government revenue that can be reinvested in sustainability projects. A key drawback is that the tax's effectiveness depends on setting an appropriate carbon price that is sufficiently high to incentivize abatement (Observatório do Clima, 2024). In this landscape, there are also offset systems that allow companies and individuals to compensate their GHG emissions by investing in projects that reduce or remove carbon from the atmosphere, including reforestation, forest conservation, and renewable energy development (EPE, 2020).

Recent changes to the European Union Emissions Trading System (EU ETS) represent a deepening of the bloc's climate strategy, consistent with the European Green Deal and the goal of achieving climate neutrality by 2050 (European Commission, 2019). These reforms aim primarily to strengthen the carbon price signal, accelerate decarbonization in the covered economic sectors, and expand the scope of the regulatory system (European Commission, 2019). A central pillar of the reform is alignment with the "Fit for 55" legislative package, approved in 2023, which sets a target to reduce the European Union's net emissions by at least 55% by 2030 relative to 1990 levels (European Commission, 2019) (World Bank, 2023).

Another significant advancement is the creation of EU ETS II, planned for 2027, which will introduce a separate emissions trading system for fuels used in residential and commercial buildings, road transport, and small industries. This expansion will broaden the reach of the European system and impose direct carbon costs on end consumers, with compensatory measures such as the Social Climate Fund foreseen to mitigate regressive socioeconomic impacts (World Bank, 2023; European Commission, 2019).

The reform also provides for the gradual phaseout of free allocation of emission allowances, a mechanism used to mitigate the risk of carbon leakage, that is, the relocation of emissions to jurisdictions with laxer regulation (World Bank, 2023). Between 2026 and 2034, this allocation will be progressively eliminated and replaced by the Carbon Border Adjustment Mechanism (CBAM), which applies a carbon price to imports in sectors such as steel, cement, aluminum, and fertilizers, thereby ensuring a level playing field with domestically produced goods covered by the EU ETS (World Bank, 2023). Additionally, since 2024 the system has included the maritime sector, covering CO_2 emissions from ships above 5,000 gross tonnage for both intra-European routes and international voyages with origin or destination in the European Union, reinforcing the bloc's commitment to address sectors that are traditionally hard to decarbonize (EU, 2023).

Finally, Mungroo et al. (2014) highlight the strengthening of Monitoring, Reporting, and Verification (MRV) mechanisms through the incorporation of digital technologies that enhance the traceability and reliability of emissions data. Emerging tools, such as blockchain— a distributed ledger technology that organizes data in chained, cryptographically secured blocks— and smart contracts, have been evaluated as effective solutions to automate verification, prevent fraud, and ensure the environmental integrity of traded carbon credits (Mungroo et al., 2014). Figure 3 presents the most relevant structural changes implemented in the EU ETS from 2023 onward.

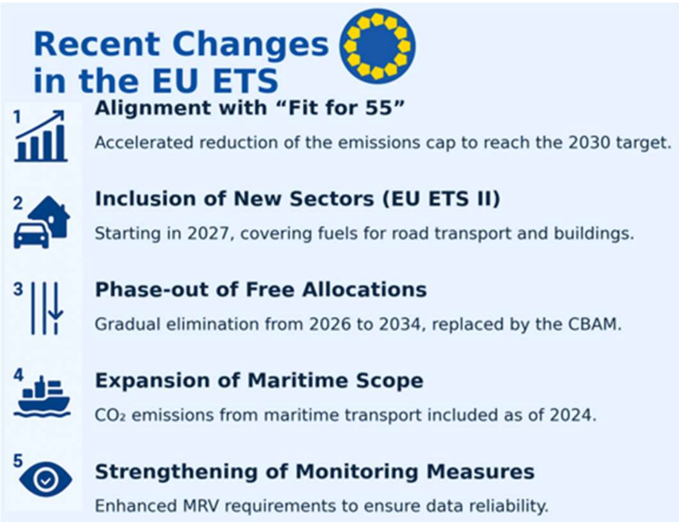

Figure 3: Recent changes in the European Union Emissions Trading System (EU ETS). Source: Authors.

4 Technologies and innovations for the low-carbon transition

Renewable energy has already become the dominant option for expanding power capacity in many countries, consolidated by technological maturity and economic competitiveness, particularly in the context of recent increases in fossil fuel prices (IRENA, 2022). This shift has stimulated the creation of green jobs in sectors such as solar and wind energy, energy efficiency, and clean technologies (ILO, 2018). Ensuring a just transition, however, requires investment in reskilling and upskilling for workers in carbon-intensive industries, including oil and coal (ILO, 2018).

Figure 4 shows the projected regional distribution of energy-sector employment through 2050, reflecting the growing role of sustainable technologies in global socioeconomic development (IRENA, 2020).

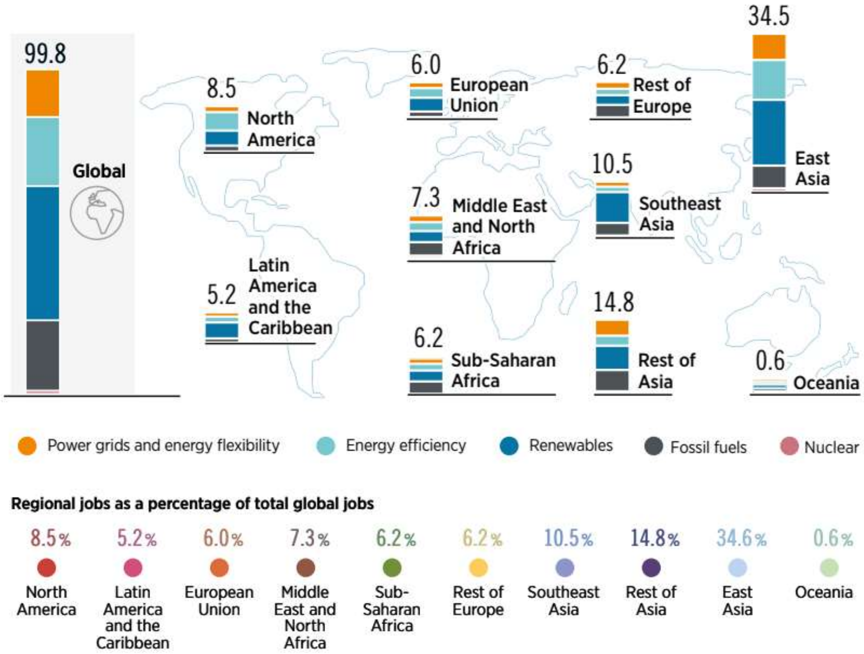

Figure 4. Regional distribution of energy sector employment in 2050 under the Energy Transformation Scenario, by region (in millions). Source: IRENA (2020).

In the Brazilian context, the State of Espírito Santo stands out for its wind potential, with a theoretical capacity sufficient to meet up to four months of national energy demand and a positive impact on job creation (Atlas Eólico Onshore e Offshore do ES, 2022). The Atlas Eólico Onshore e Offshore do ES (2022) reports a total theoretical generation potential of 160,000 gigawatts (GW) per year, of which 142,080 GW come from offshore winds and 18,307 GW from onshore resources. Beyond the energy contribution, the wind sector also delivers strong economic and social benefits. According to projections by the Brazilian Wind Energy Association (ABEEólica, 2018), each megawatt of installed wind capacity can generate up to 15 direct and indirect jobs.

Figure 5, drawn from the Atlas Eólico Onshore e Offshore do ES (2022), presents the wind potential map for Espírito Santo at a 200 m height reference in the spring season. The aforementioned study highlights that the dark red areas, located along the coastline and offshore regions, indicate the highest wind speeds, above 10 m/s. These zones are ideal for wind power generation due to the high persistence and intensity of the winds. This substantial potential is especially concentrated in the coastal belt, where conditions are broadly favorable for the installation of utility-scale wind turbines.

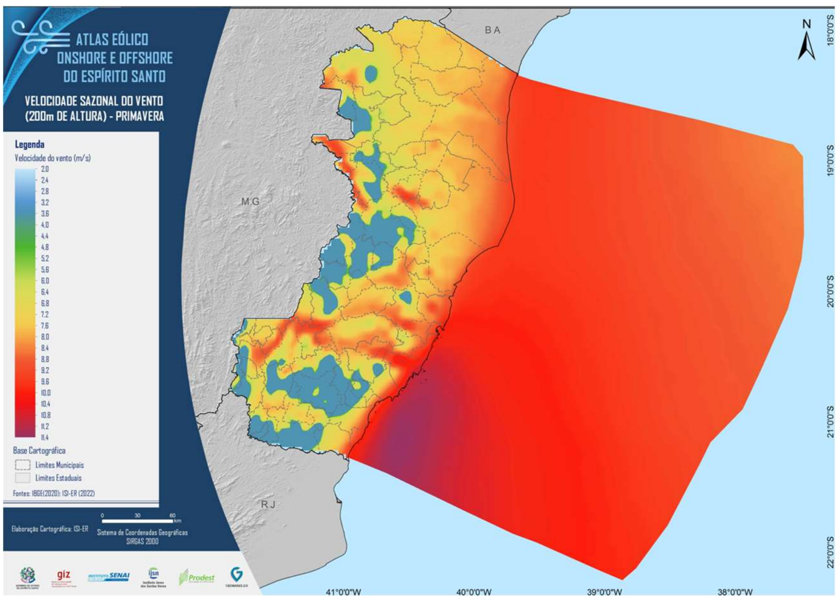

Figure 5: Wind map of Espírito Santo. Source: Atlas Eólico Onshore e Offshore do ES (2022).

Beyond the expansion of renewable sources, decarbonizing the energy sector requires the development of complementary technologies capable of providing flexibility, efficient storage, and grid stability (IEA, 2023b). In this context, recent progress in lithium-ion batteries for energy storage, together with green hydrogen and grid digitalization, has helped consolidate the global energy transition (IEA, 2023b; IEA, 2024).

According to IEA (2024), lithium-ion batteries have achieved significant advances in energy density, safety, and cost reduction. The report also notes that in 2023 the average price of battery packs fell by 14 percent due to lower prices of critical metals. This trend is illustrated in Figure 6, provided by IEA (2024), which presents the evolution of prices for the main metals used in lithium-ion battery manufacturing, as well as the variation in the average price of battery packs from 2015 to 2024.

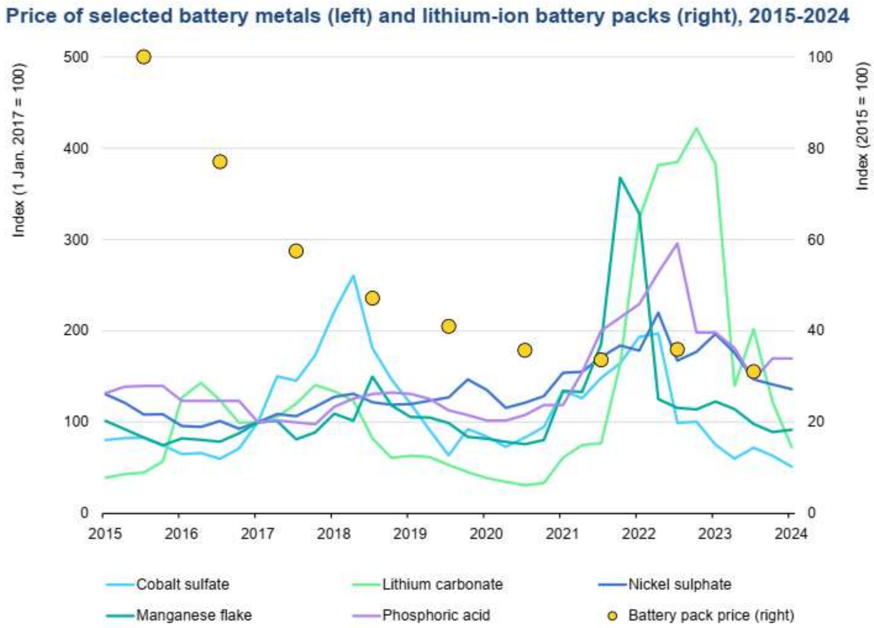

Figure 6. Prices of selected battery metals (left axis) and lithium-ion battery packs (right axis), 2015–2024. Source: IEA (2024). Note: Values were indexed using 2015 as the base year (index = 100), enabling percentage-based comparison of changes over time.

The evolution of battery prices is also clearly depicted in Figure 7, which presents average price indices by cell chemistry and geographic region for the period 2020 to 2023 (IEA, 2024). In the first panel, despite fluctuations in raw-material costs, particularly lithium, lithium-iron-phosphate (LFP) batteries remained priced below nickel–cobalt–aluminium (NCA) and nickel–manganese–cobalt (NMC) counterparts throughout the period. A progressive narrowing of the cost gap between NMC and LFP is also evident, reflecting process optimisation and the increased use of lower-cost materials such as manganese (IEA, 2024).

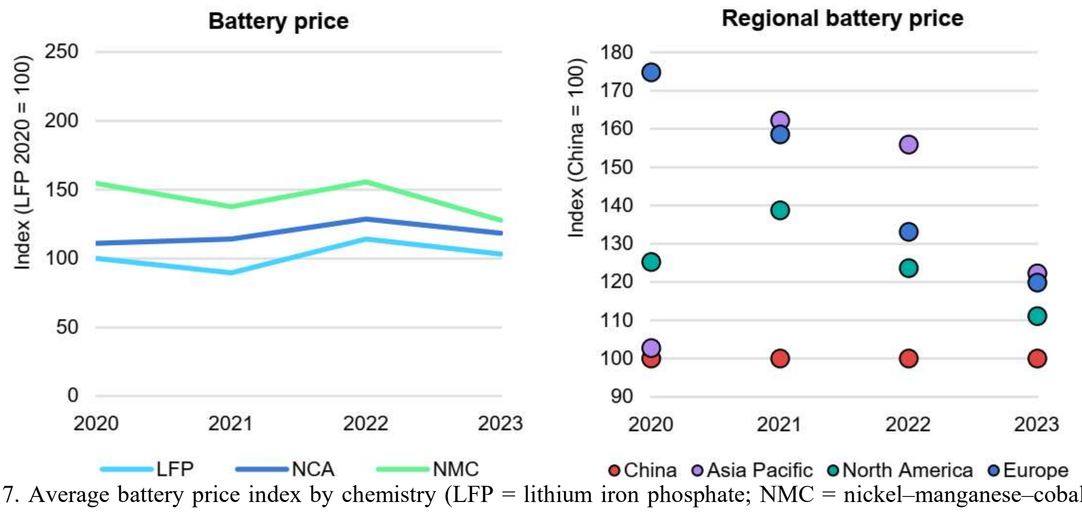

Figure 7. Average battery price index by chemistry (LFP = lithium iron phosphate; NMC = nickel–manganese–cobalt; NCA = nickel–cobalt–aluminium) and region, 2020–2023. Prices indexed to China (100), covering both local production and imports. Source: IEA (2024).

In the second panel of Figure 7, regional battery prices likewise display a convergence trend, although substantial differences persist across major markets. Batteries manufactured in China continued to exhibit the lowest costs, whereas those produced in North America and Europe remained higher priced, even when imports are considered. This dynamic underscores China's central role as the cost-competitiveness leader in the automotive battery sector, driven by vertical integration of the supply chain and technological leadership in innovative pack architectures such as cell-to-pack (cells mounted directly into the structure) and cell-to-chassis (cells integrated into the vehicle chassis) (IEA, 2024).

Figure 8 shows the evolution of hydrogen production for different vehicle types between 2020 and 2022, disaggregated by vehicle category and region. On the left, there is steady growth in hydrogen production allocated to cars, buses, and commercial vehicles, with cars accounting for the largest share. Production for buses and commercial vehicles also rises over the period, reflecting the increasing adoption of hydrogen in public transport and heavy-duty fleets. Between 2020 and 2022, production for cars increased from about 5 kt to 11 kt; for buses, from 8 kt to 10 kt; and for commercial vehicles, from 2 kt to 12 kt, providing evidence of substantial growth across all segments (IEA, 2023a).

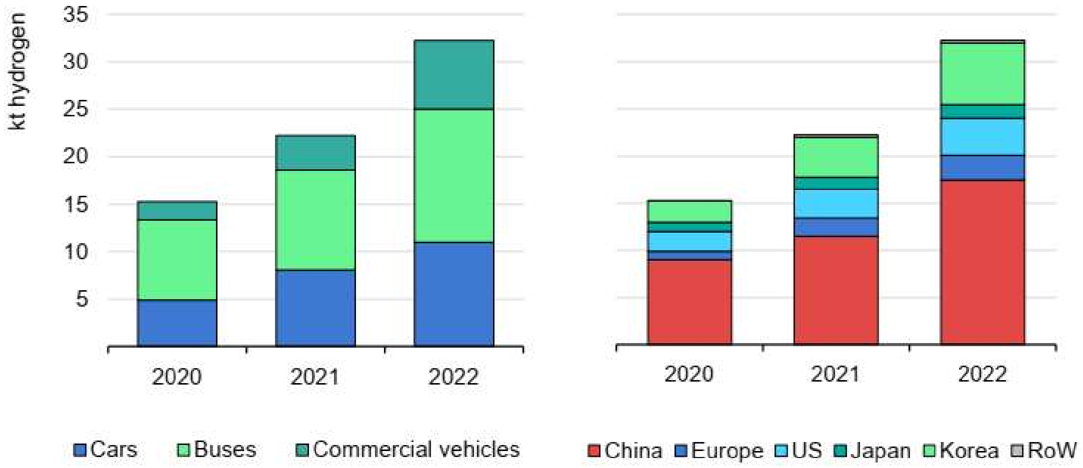

Figure 8. Hydrogen production by vehicle type (C = cars, B = buses, CV = commercial vehicles) and by region (CH = China, EU = Europe, US = United States, JP = Japan, KR = Korea, RoW = Rest of World), 2020–2022. Source: IEA (2023a).

On the right-hand side of Figure 8, China stands out as the global leader in hydrogen production, followed by Europe and the United States, both of which also show rising output. Between 2020 and 2022, China's production increased from 8 kt to more than 18 kt, Europe's from 1 kt to about 3 kt, and the United States from 2 kt to 4 kt. This expansion reflects decarbonization policies adopted across several regions, with particular emphasis on the use of hydrogen for sustainable transport (IEA, 2023a). The continued growth in hydrogen production, especially in China, signals a broader global shift toward hydrogen as a clean energy solution and advances the transition to a low-carbon future.

5 Models and applications of strategies for reducing GHG emissions

Reducing greenhouse gas emissions is a central challenge in global climate change mitigation strategies. Several nations have implemented targeted policies and innovative technologies to decrease their carbon footprint and transition toward low-carbon economies. Although in 2019 the United States, Russia, and South Korea ranked among the world's largest greenhouse gas emitters, significant reductions were recorded between 1990 and 2019: 18.9% in the United States, 25.7% in Russia, 37.3% in Brazil, and 30.0% in the European Union (WRI Brasil, 2020).

Among the most notable cases in the transition to low-carbon energy, the Nordic countries such as Iceland, Denmark, Norway and the United Kingdom have demonstrated leadership and innovation. The Nordic nations have implemented robust public policies, substantial investments in renewable energy sources and energy efficiency initiatives, while also promoting low-carbon lifestyles (Urban and Nordensvärd, 2018). Measures such as the expansion of wind, solar and hydropower generation, the electrification of transport and the adoption of carbon capture and storage technologies have consolidated their position as pioneers in decarbonization. The United Kingdom, in turn, has stood out for adopting comprehensive climate policies, including carbon pricing and emissions trading schemes (Sithole et al., 2016). Within the Nordic context, Norway, a traditional oil exporter and one of the highest per capita CO_2 emitters in 1990, achieved significant reductions in the energy and transport sectors. In 2013, the Norwegian Environment Agency reported that 80% of the country's emissions were concentrated in waste incineration, energy supply and transport using combustion vehicles (Nabeshima, 2015). The industrial sector remains one of the main contributors to greenhouse gas emissions, particularly in energy-intensive industries (Zhu, 2023). To advance toward a low-carbon economy, industries have gradually been adopting more energy-efficient technologies, integrating renewable energy sources and implementing carbon reduction measures (Li, 2023).

In the transport sector, which accounts for approximately 15% of total global emissions (IEA, 2025b) (Ouyang et al., 2014), strategies to reduce emissions include vehicle electrification, the use of alternative fuels, and the optimization of transport networks to reduce congestion and improve efficiency (Yang et al., 2019). The integration of digital technologies can also contribute to lowering carbon emissions in the transport sector (Lee et al., 2022).

In the Brazilian context, an example is the study conducted by Fearnside et al. (2009), which combined system dynamics modelling with scenario analysis to assess the impacts of deforestation and greenhouse gas emissions in the area influenced by the Manaus–Porto Velho highway (BR-319). The study covered projections from 2007 to 2050 and introduced an innovative approach by parameterizing the relationship between deforestation and road expansion, using satellite imagery from northwestern Rondônia to calibrate the model.

The diversity of socioeconomic, political and technological contexts among nations has resulted in distinct approaches to decarbonization and climate change mitigation. As noted by Urban and Nordensvärd (2018), while developed countries such as the Nordic nations and the United Kingdom have leveraged robust public policies, institutional stability and social acceptance to implement advanced low-carbon strategies, emerging economies have adopted adaptive solutions based on their own resources and local challenges. Recent reports, such as the Global Energy Review 2024 by the International Energy Agency (IEA, 2025a), highlight that successful strategies do not rely exclusively on technological innovation but also on the ability to adapt to regional conditions and to design flexible public policies. In this context, Table 1 presents a comparative analysis of four countries, namely China, India, Brazil and the United Kingdom, outlining their main decarbonization strategies, the factors that have supported their progress, and the key advantages and challenges they have faced in their pathways toward low-carbon economies, as reported by IEA (2025a), Brasil (2019) and Brasil (2017). This comparison makes it possible to understand not only the solutions implemented but also the contextual elements that determine the success or limitations of these policies in different national settings.

Table 1. Strategies, success factors, and challenges in decarbonization across different countries. Sources: IEA (2025a), Brasil (2020), and Brasil (2017).

Country	Key Strategies	Main Advantages	Main Challenges
China	Rapid expansion of solar and wind energy; Significant progress in vehicle electrification.	Cost reduction and rapid implementation enabled by national industrial scale; Early achievement of 2030 renewable energy targets strengthens climate credibility.	Heavy reliance on coal for electricity generation; Decline in residential distributed generation investments after subsidy reductions.
India	Record growth in solar photovoltaic capacity; Expansion of wind energy.	Competitive progress in renewable energy auctions; Reduction in dependence on imported fossil fuels	Power mix still heavily reliant on coal; Structural limitations for full integration of intermittent sources, such as storage and grid infrastructure.
Brazil	Expansion of solar generation, both utility-scale and distributed; Initial growth in the electric vehicle market; Renewable electricity matrix;	High attractiveness of the net-metering compensation model; Technological diversification of the energy mix and attraction of private investment.	Decline in new wind power installations; Low penetration of electric vehicles due to limited infrastructure and high upfront costs.

	Biofuels (RenovaBio); Vehicle efficiency (Rota 2030).		
United Kingdom	Implementation of the Zero Emission Vehicle (ZEV) mandate; Expansion of the electric fleet.	Clear regulatory framework fosters the adoption of clean technologies; International benchmark in electric mobility and vehicle-to-grid integration.	Sustaining growth depends on charging infrastructure and continued support; Potential regional disparities in access to technologies.

7 Challenges and opportunities in the energy transition

Low-carbon technologies such as solar power, wind energy, green hydrogen, and carbon capture and storage (CCS) entail high upfront costs, which include the installation of solar plants, wind farms, and CCS systems that require capital-intensive investments, compounded by the need for specialized equipment and critical materials such as lithium, cobalt, and rare earth elements (Castro et al., 2024). In addition, financing these technologies poses a considerable challenge, since in emerging markets access to credit is limited and high interest rates make the cost of capital prohibitive. For more vulnerable communities, the lack of subsidies and financial incentives perpetuates the use of more affordable but highly polluting energy sources (Castro et al., 2024).

Silva and Pereira (2021) emphasize that the limitations of current energy infrastructures represent one of the main obstacles to the transition toward low-carbon technologies. Conventional power grids, designed under a centralized model and reliant on fossil fuel sources, have low operational flexibility, which hinders the integration of intermittent renewable sources such as solar and wind power, whose variability is directly conditioned by climatic factors. Modernizing these grids is essential and involves the implementation of Smart Grids, which are capable of managing decentralized energy flows and handling generation variability (Silva and Pereira, 2021).

The transition to electric vehicles (EVs) depends on a robust network of charging stations, which remains insufficient in many countries. Furthermore, the expansion of this infrastructure faces challenges related to high installation and maintenance costs, dependence on overloaded power grids, and limited accessibility in rural or remote areas. According to projections from the Plano Nacional de Energia (PNE), Brazil will still rely on fossil fuels until 2030, while technologies such as biofuels and hybrid vehicles are expected to experience moderate advances (EPE, 2021a). Additionally, many low-carbon technologies have not yet reached the maturity required to compete with traditional alternatives. For instance, green hydrogen faces technical challenges related to the efficiency of water electrolysis, which consumes large amounts of renewable electricity, making its large-scale adoption difficult (EPE, 2021b).

The Empresa de Pesquisa Energética (EPE, 2024) highlights that the energy transition and the adoption of sustainable technologies are fostering a low-carbon economy, with positive impacts on global economic growth. Key benefits include lower operational costs compared to fossil fuel sources, since after the initial investment the generated energy is virtually free, reducing cost volatility. Efficient industrial processes and circular economy practices minimize waste and maximize resource use. An analysis of capital costs for wind energy projects in Brazil shows that the average reference CAPEX (Capital Expenditure) for offshore wind power is BRL 15,000 per kW, while for onshore wind power the average is BRL 5,275 per kW (EPE, 2024). There are also incentives for sustainable economic growth, with the potential to boost long-term development by attracting investments in innovative sectors such as clean technologies, energy efficiency, and resilient infrastructure. Global reports estimate that the transition to a low-carbon economy could generate trillions of dollars in investments by 2050, promoting development across multiple industries (EPE, 2021a).

Global investments in clean technologies, as shown in Figure 9, have grown significantly in recent years, according to aggregated financial indicators for the five largest solar photovoltaic panel and battery manufacturing companies between 2017 and 2024. Revenue data show that the combined revenues of the top five solar panel companies increased from USD 10 billion in the first quarter of 2017 to over USD 100 billion in the last quarter of 2022, before experiencing a slight decline in the first three quarters of 2023. For battery manufacturers, revenue followed a similar growth trend, rising from USD 26 billion in 2017 to nearly USD 200 billion by the third quarter of 2023, reflecting the growing demand for electric vehicles and energy storage solutions (IEA, 2023d).

The second variable presented in Figure 9, operating profits, shows a sharp increase for battery manufacturers, which rose significantly between 2017 and 2024, particularly after 2022, driven by the growing demand for lithium batteries. In contrast, solar panel manufacturers recorded growth that was steadier in recent years. In the third section of Figure 9, capital expenditures also rose more sharply for battery manufacturers, reaching nearly USD 30 billion in 2024, reflecting the expansion of battery production. Solar panel manufacturers, on the other hand, invested around USD 10 billion, with a more modest increase (IEA, 2023c).

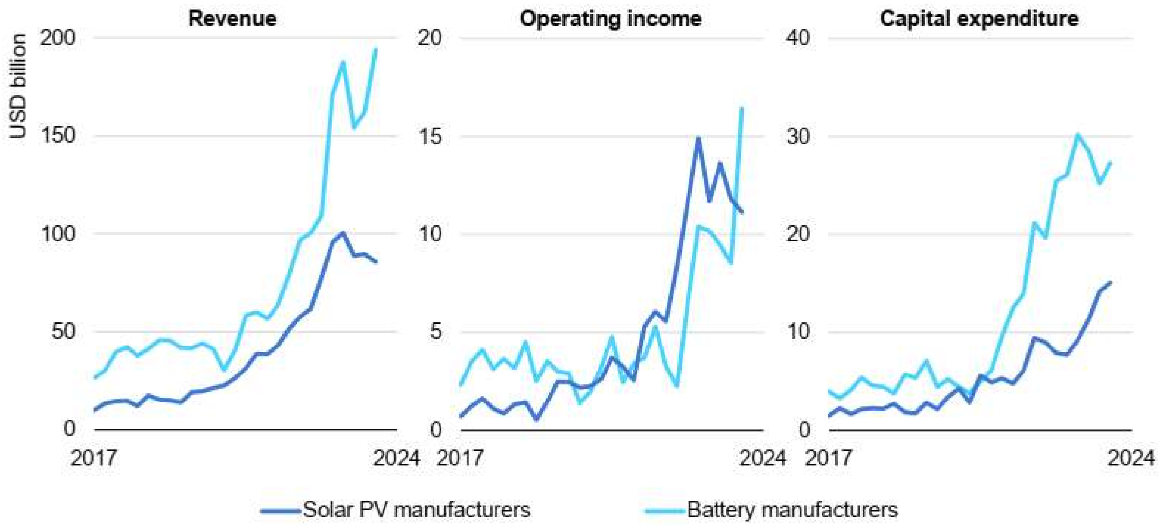

Figure 9. Aggregated financial indicators for the five largest photovoltaic (PV) solar panel and battery manufacturing companies, 2017–2024. Source: IEA (2023c).

As illustrated in Figure 10, investments in clean technology manufacturing indicate that the sector is undergoing significant expansion. In 2023, investment in five clean energy technologies reached USD 200 billion, a substantial increase compared to USD 115 billion in 2022, representing 70% growth. Most of these investments were directed toward the manufacturing of photovoltaic solar panels and batteries, with facilities for these technologies accounting for 95% of total investments in 2023 (IEA, 2023c). China continued to dominate the sector, with three-quarters of global clean technology investment in 2023, although its share fell from 85% in 2022 to 75%, according to IEA (2023c) data. The European Union and the United States made significant advances, together accounting for 16% of total investment, an increase of 11% compared to 2022 (IEA, 2023c).

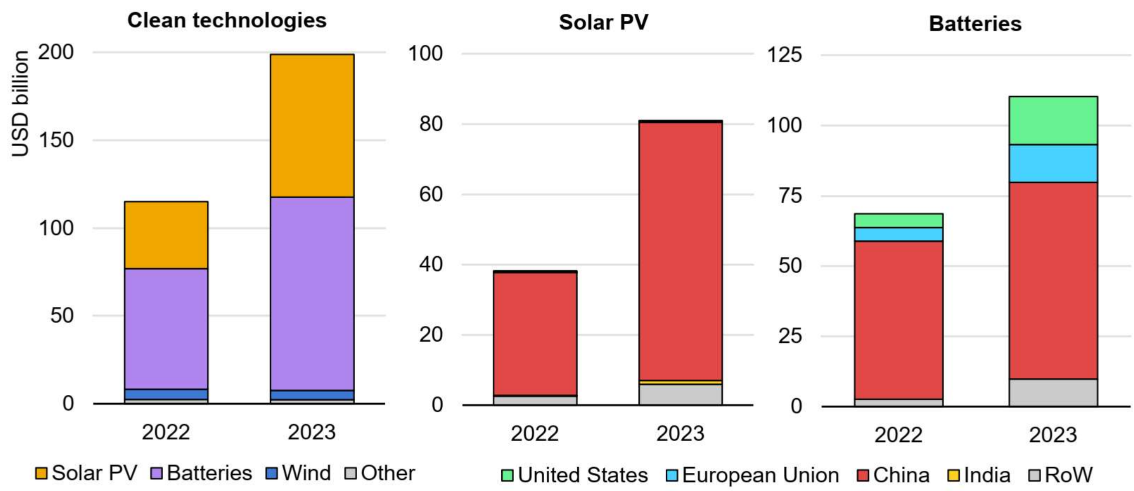

Figure 10. Investment in clean technology manufacturing by technology and region, 2022–2023. Source: IEA (2023c).

8 Final considerations

The transition to a low-carbon energy matrix is essential to achieving global climate change mitigation goals. The technologies and methodologies discussed in this article offer viable solutions to reduce emissions across economic sectors, yet they still face significant challenges, including economic, political, and technological barriers.

For this transition to occur effectively, joint collaboration among governments, the private sector, and civil society will be required, along with continuous investment in research and development to drive innovation in low-carbon technologies. Only through this collective effort will it be possible to advance toward a more sustainable economy that is resilient to the impacts of climate change.

The energy transition and the pursuit of carbon neutrality are pivotal milestones in addressing the global challenges of climate change and promoting a sustainable future. Throughout this work, both the barriers and the opportunities associated with this process were examined, highlighting the complexity and the importance of a multidimensional approach.

Initially, the discussion addressed economic and technical challenges, emphasizing how high upfront costs, the maturity level of low-carbon technologies, and infrastructure limitations represent significant obstacles. Nevertheless, it was noted that coordinated efforts, technological advances, and financial incentives can progressively reduce these barriers over time.

Economic and innovation opportunities were presented as a counterpoint, demonstrating how the shift toward a low-carbon economy can stimulate new markets, create jobs, and foster technological advancements. This transformation not only mitigates environmental impacts but also generates broad economic benefits, strengthening the resilience of both local and global economies.

In the outlook for 2030 and beyond, the role of emerging technologies such as renewable energy, green hydrogen, and carbon capture was highlighted, along with the public policies required to drive the transition. The feasibility of achieving carbon neutrality across different sectors—such as energy, transport, industry, and agriculture—was also analyzed, acknowledging that decarbonization pathways vary according to the specific characteristics of each area.

Ultimately, carbon neutrality is not only an environmental goal but also an opportunity to reimagine the global economy and production systems. The transition requires international cooperation, continuous innovation, and the engagement of governments, businesses, and citizens. With robust policies and technological advancements, it is possible to transform challenges into drivers of development, ensuring a sustainable and prosperous future for the next generations.

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