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Carbon Markets as a Policy Instrument for Climate Change Mitigation: Evolution, Challenges and Future Perspectives

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Abstract

Carbon markets have become one of the most widely adopted market-based instruments for mitigating greenhouse gas emissions and promoting cost-effective climate policies. By assigning an economic value to carbon emissions, these mechanisms create financial incentives for firms and governments to reduce emissions while maintaining economic efficiency. Since the adoption of the Kyoto Protocol in 1997, emissions trading systems and carbon offset mechanisms have expanded significantly across developed and emerging economies. By 2021, more than sixty carbon pricing initiatives had been implemented worldwide, covering approximately one-fifth of global greenhouse gas emissions.

Despite their growing relevance, carbon markets continue to generate intense academic debate regarding their environmental effectiveness, market efficiency, distributional impacts, and institutional governance. Supporters argue that emissions trading systems provide flexibility, stimulate technological innovation, and achieve emission reductions at lower costs than traditional command-and-control regulation. Critics, however, question the adequacy of carbon prices, the allocation of emission permits, price volatility, additionality of offsets, and the risk of carbon leakage across jurisdictions.

This article provides a comprehensive review of the evolution of carbon markets from both theoretical and practical perspectives. The study analyses the economic foundations of carbon pricing, examines the development of compliance and voluntary carbon markets, and evaluates the performance of the main international carbon trading schemes implemented before ending 2021. Particular attention is devoted to the European Union Emissions Trading System (EU ETS), the California Cap-and-Trade Program, and mechanisms established under the Kyoto Protocol.

The paper also discusses the principal challenges facing carbon markets, including governance issues, transparency, market integrity, and international coordination under Article 6 of the Paris Agreement. Finally, the article identifies future research directions and policy recommendations aimed at improving the effectiveness of carbon markets as instruments for achieving global decarbonization objectives.

Keywords: Carbon markets; Emissions Trading System; Carbon pricing; Climate policy; Carbon offsets; EU ETS; Greenhouse gas emissions.

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1. Introduction

Climate change represents one of the most significant environmental, economic, and social challenges facing contemporary societies. Scientific evidence accumulated over the last several decades demonstrates that anthropogenic greenhouse gas (GHG) emissions have substantially altered the Earth's climate system, increasing global temperatures and intensifying extreme weather events, biodiversity loss, and ecosystem degradation (IPCC, 2021). The urgency of limiting global warming has motivated governments to implement increasingly ambitious climate policies designed to reduce carbon emissions while sustaining economic development.

Among the wide range of policy instruments available, market-based mechanisms have emerged as one of the most influential approaches for addressing climate change. Unlike traditional command-and-control regulations, which prescribe specific technologies or emission limits, market-based instruments rely on economic incentives that encourage firms to identify the least costly pathways for reducing emissions (Stavins, 2008). Carbon pricing, in particular, seeks to internalize the environmental externalities associated with greenhouse gas emissions by incorporating the social cost of carbon into production and consumption decisions.

The theoretical foundations of carbon markets originate from environmental economics and welfare theory. Pigou (1920) first proposed the use of corrective taxes to internalize negative externalities generated by pollution. Later, Coase (1960) demonstrated that clearly defined property rights and low transaction costs could facilitate efficient resource allocation through market negotiations. Building upon these concepts, emissions trading systems (ETSs) establish tradable emission permits that allow market participants to buy and sell emission allowances while maintaining an overall emissions cap. This cap-and-trade approach combines environmental certainty with economic flexibility, allowing emissions reductions to occur where marginal abatement costs are lowest (Tietenberg, 2006).

The internationalization of carbon markets accelerated following the adoption of the Kyoto Protocol in 1997, which introduced three flexible mechanisms aimed at reducing the global costs of climate mitigation: International Emissions Trading (IET), Joint Implementation (JI), and the Clean Development Mechanism (CDM). These mechanisms represented the first large-scale attempt to establish international carbon trading as an instrument for achieving legally binding emission reduction commitments (UNFCCC, 1998).

Since then, carbon markets have experienced substantial expansion. The European Union Emissions Trading System, launched in 2005, has become the largest multinational carbon market and remains the cornerstone of European climate policy (Ellerman et al., 2010). Similar systems have subsequently been implemented in California, Québec, New Zealand, South Korea, several Chinese pilot regions, and other jurisdictions worldwide (ICAP, 2021). Alongside compliance markets, voluntary carbon markets have also grown rapidly, driven by increasing corporate commitments toward carbon neutrality and environmental, social, and governance (ESG) objectives (Miltenberger et al., 2021).

By 2021, the World Bank estimated that more than sixty-four carbon pricing initiatives were operating globally, including emissions trading systems and carbon taxes, collectively covering approximately 21% of global greenhouse gas emissions (World Bank, 2021). However, despite this remarkable expansion, carbon markets still account for only a fraction of worldwide emissions, and many existing systems maintain carbon prices below levels considered necessary to achieve the objectives established under the Paris Agreement.

Academic debate surrounding carbon markets remains highly active. Proponents argue that emissions trading minimizes compliance costs, stimulates technological innovation, and provides firms with flexibility in achieving environmental targets (Porter & van der Linde, 1995; Stavins, 2019). Critics, however, highlight persistent concerns regarding price volatility, overallocation of permits, market manipulation, carbon leakage, distributional equity, and the environmental integrity of offset credits (Green, 2021). Furthermore, questions remain regarding the interaction between carbon markets and complementary climate policies such as renewable energy subsidies, energy efficiency standards, and industrial decarbonization strategies.

The adoption of the Paris Agreement in 2015 introduced a new phase in the evolution of international carbon markets. Article 6 established the legal framework for enhanced international cooperation through internationally transferred mitigation outcomes (ITMOs) and new market mechanisms designed to replace the Kyoto Protocol's flexible mechanisms. Although negotiations regarding Article 6 continued until the Glasgow Climate Conference (COP26) in 2021, these developments reflected growing international recognition of the role that carbon markets may play in achieving global net-zero emission objectives.

Given these developments, a comprehensive review of carbon markets is particularly relevant. Existing literature often focuses on individual emissions trading systems or specific policy mechanisms, while fewer studies provide an integrated overview of the evolution, theoretical foundations, institutional architecture, and future challenges of carbon markets from a global perspective.

Accordingly, this article aims to synthesize the existing literature on carbon markets published up to 2021, examining their theoretical foundations, institutional evolution, operational mechanisms, and empirical performance. The paper further discusses the principal limitations affecting current carbon markets and identifies future policy directions that may enhance their effectiveness in supporting international climate mitigation efforts.

The remainder of this article is organized as follows. Section 2 reviews the theoretical foundations and evolution of carbon markets. Section 3 analyses the principal carbon market mechanisms currently in operation. Section 4 evaluates their effectiveness and identifies the main challenges affecting their implementation. Section 5 discusses future perspectives under the Paris Agreement, while the final section summarizes the principal conclusions and policy implications.

2. Literature Review and Theoretical Background

2.1. The Economic Foundations of Carbon Markets

The economic rationale for carbon markets is rooted in the theory of externalities developed within welfare economics. Climate change represents one of the largest market failures ever identified because the environmental damages associated with greenhouse gas emissions are generally not reflected in market prices. Consequently, producers and consumers tend to emit more carbon dioxide than is socially optimal, generating significant environmental costs that are borne collectively rather than by the polluters themselves (Stern, 2007).

The concept of negative externalities was originally formalized by Pigou (1920), who argued that governments should impose corrective taxes equivalent to the marginal external damage generated by pollution. According to Pigouvian theory, an appropriately calibrated carbon tax would align private production costs with social costs, thereby encouraging firms to reduce emissions while allowing markets to allocate resources efficiently.

Although Pigouvian taxation remains one of the principal instruments for carbon pricing, subsequent developments in environmental economics introduced alternative market-based approaches capable of achieving similar environmental objectives with greater flexibility under certain institutional conditions.

A major theoretical breakthrough emerged through the work of Coase (1960), who demonstrated that clearly defined property rights and voluntary bargaining could theoretically internalize environmental externalities without direct government intervention, provided that transaction costs remained sufficiently low. While the assumptions of the Coase theorem rarely hold in large-scale environmental problems such as climate change, its central insight—that pollution rights may be allocated and traded efficiently—provided the intellectual foundation for emissions trading systems.

Building upon these theoretical contributions, Dales (1968) proposed one of the earliest practical models of tradable pollution permits. Under this approach, regulators establish an overall emissions cap while allowing firms to exchange emission permits according to their individual abatement costs. Companies capable of reducing emissions at relatively low costs sell surplus allowances, whereas firms facing higher mitigation costs purchase additional permits. This market mechanism ensures that aggregate emissions reductions are achieved where they are economically least expensive.

The theoretical superiority of tradable permits over uniform emission standards was further demonstrated through the work of Montgomery (1972), who mathematically proved that emissions trading minimizes aggregate abatement costs regardless of the initial allocation of permits, assuming competitive markets and perfect information. This result became one of the most influential findings in environmental economics and remains the theoretical cornerstone of modern emissions trading systems.

Environmental economists subsequently emphasized that carbon pricing differs fundamentally from conventional environmental regulation because it allows decentralized decision-making. Rather than prescribing specific technologies or production methods, carbon markets encourage firms to identify their own least-cost mitigation strategies, thereby promoting innovation and technological flexibility (Tietenberg, 2006).

From a policy perspective, market-based instruments also reduce the informational burden placed upon regulators. Governments determine the environmental objective—namely the overall emissions cap—but individual firms retain discretion regarding how those reductions are achieved. This flexibility explains why emissions trading has frequently been described as a "quantity-based" instrument compared with carbon taxation, which represents a "price-based" policy instrument (Weitzman, 1974).

The distinction between price-based and quantity-based regulation remains central to climate policy debates. Weitzman's influential analysis demonstrated that the relative efficiency of taxes versus tradable permits depends largely upon the relative slopes of marginal damage and marginal abatement cost curves. When uncertainty regarding abatement costs dominates environmental uncertainty, taxes may outperform permit systems. Conversely, when environmental thresholds are critical—as is often argued for climate stabilization—quantity-based instruments such as emissions trading may provide greater environmental certainty.

These theoretical considerations have continued to shape policy discussions regarding carbon pricing throughout the development of international climate governance.

2.2. From Environmental Regulation to Carbon Pricing

Prior to the emergence of market-based instruments, environmental policy relied predominantly upon command-and-control regulation. Governments established uniform emission limits, mandated pollution-control technologies, or imposed sector-specific environmental standards intended to reduce pollution levels. Although these approaches often succeeded in improving environmental quality, they were frequently criticized for imposing unnecessarily high compliance costs while discouraging technological innovation (Hahn & Stavins, 1992).

Beginning in the 1980s, policymakers increasingly explored economic instruments capable of achieving environmental objectives more efficiently. One of the earliest successful applications involved sulfur dioxide emissions in the United States under the Acid Rain Program established by the 1990 Clean Air Act Amendments. The program demonstrated that emissions trading could generate substantial environmental improvements while reducing compliance costs compared with conventional regulatory approaches (Schmalensee & Stavins, 2017).

The apparent success of sulfur dioxide trading significantly influenced subsequent climate policy discussions. Throughout the 1990s, emissions trading gained increasing political acceptance as governments searched for mechanisms capable of addressing global climate change without imposing excessive economic burdens upon industry.

The Kyoto Protocol represented the first international agreement to incorporate market-based flexibility mechanisms into legally binding climate commitments. Rather than prescribing uniform national mitigation strategies, the Protocol recognized that greenhouse gas emissions constitute a global pollutant whose environmental impacts are independent of their geographical origin. Consequently, emissions reductions could be achieved wherever they proved most economically efficient.

Three principal flexibility mechanisms were introduced: International Emissions Trading (IET), Joint Implementation (JI), and the Clean Development Mechanism (CDM). Together, these instruments established the institutional architecture for international carbon trading and stimulated the development of carbon accounting methodologies, monitoring systems, verification procedures, and carbon credit certification standards (UNFCCC, 1998).

The creation of these mechanisms represented a significant transformation in environmental governance by shifting policy emphasis from technology regulation toward outcome-based environmental performance.

2.3. Evolution of Carbon Market Research

Academic interest in carbon markets expanded considerably following the implementation of the Kyoto Protocol and the launch of the European Union Emissions Trading System in 2005. Early research primarily examined theoretical efficiency gains associated with emissions trading, emphasizing cost minimization and optimal permit allocation (Ellerman et al., 2010).

As empirical evidence accumulated, research increasingly focused upon evaluating the actual performance of carbon markets. Several important research streams emerged.

The first examined environmental effectiveness. Scholars investigated whether emissions trading systems generated measurable reductions in greenhouse gas emissions beyond business-as-usual scenarios. Empirical studies generally concluded that well-designed emissions trading systems contributed to significant emission reductions, although the magnitude of these effects depended heavily upon cap stringency and permit allocation mechanisms (Martin, Muûls, de Preux, & Wagner, 2014).

A second research stream investigated economic competitiveness. Critics initially feared that carbon pricing would reduce industrial competitiveness by increasing production costs and encouraging firms to relocate carbon-intensive activities toward jurisdictions with weaker environmental regulations—a phenomenon commonly described as carbon leakage (Babiker, 2005). However, subsequent empirical evidence suggested that leakage effects remained relatively limited within most existing carbon markets, although energy-intensive industries continued to warrant particular attention (Branger & Quirion, 2014).

Innovation constituted a third major research area. Building upon the Porter Hypothesis (Porter & van der Linde, 1995), numerous studies explored whether carbon pricing stimulated technological innovation by encouraging firms to invest in cleaner production processes. Several empirical analyses found positive relationships between carbon pricing and low-carbon innovation, particularly in renewable energy technologies and industrial energy efficiency improvements (Calel & Dechezleprêtre, 2016).

More recently, researchers began examining financial aspects of carbon markets. Carbon allowances increasingly attracted institutional investors, leading scholars to analyze market liquidity, price discovery, volatility, speculative behaviour, and interactions between carbon prices and broader financial markets (Chevallier, 2011).

By the late 2010s, the literature had evolved beyond evaluating individual emissions trading systems toward broader questions concerning global carbon market integration, international governance, corporate net-zero strategies, and the rapidly expanding voluntary carbon market.

This diversification reflected the growing complexity of carbon markets as they evolved from relatively isolated regulatory instruments into central components of international climate governance.

2.4. Compliance Markets versus Voluntary Carbon Markets

One of the most significant developments in carbon market literature has been the distinction between compliance markets and voluntary carbon markets.

Compliance markets operate under legally binding regulatory frameworks established by governments or international agreements. Firms covered by emissions caps must surrender emission allowances equivalent to their verified greenhouse gas emissions. Failure to comply generally results in substantial financial penalties alongside future compliance obligations.

Examples include the European Union Emissions Trading System, the California Cap-and-Trade Program, the Regional Greenhouse Gas Initiative (RGGI), New Zealand's Emissions Trading Scheme, South Korea's ETS, and China's regional pilot systems prior to the launch of its national market.

Voluntary carbon markets differ fundamentally because participation is not mandated by regulation. Instead, corporations, financial institutions, non-governmental organizations, and individuals voluntarily purchase carbon credits to offset emissions, achieve corporate sustainability commitments, or support broader environmental objectives.

Corporate demand for voluntary offsets expanded rapidly after 2015 as increasing numbers of multinational firms announced carbon neutrality and net-zero commitments aligned with Environmental, Social and Governance (ESG) strategies (Miltenberger et al., 2021).

Despite this rapid growth, voluntary markets have attracted substantial academic criticism. Concerns frequently focus upon the environmental integrity of offset projects, particularly regarding additionality, permanence, leakage, baseline estimation, and double counting (Schneider & La Hoz Theuer, 2019).

Additionality remains perhaps the most controversial issue. Carbon credits should represent emission reductions that would not have occurred in the absence of carbon finance. Demonstrating this counterfactual condition is inherently difficult because project developers must estimate hypothetical baseline scenarios that cannot be directly observed. Consequently, several studies have questioned whether certain offset projects generate genuine climate benefits (Cames et al., 2016).

Permanence represents another significant challenge, particularly for nature-based solutions such as afforestation and forest conservation. Carbon stored within biological ecosystems may subsequently be released through wildfires, disease outbreaks, illegal logging, or future land-use changes, thereby reversing previously credited emission reductions.

Finally, increasing attention has focused upon governance and transparency. The coexistence of multiple voluntary certification standards—including the Verified Carbon Standard (VCS), Gold Standard, Climate Action Reserve, and American Carbon Registry—has created concerns regarding methodological consistency, credit quality, and market credibility (Green, 2021).

Nevertheless, despite these criticisms, voluntary carbon markets continue to expand rapidly and are widely expected to complement compliance markets in supporting global decarbonization efforts throughout the coming decades.

3. Carbon Market Mechanisms

3.1. The Architecture of Carbon Markets

Carbon markets have evolved into a diverse set of policy instruments designed to reduce greenhouse gas emissions while minimizing the overall economic costs of climate mitigation. Although considerable differences exist among jurisdictions, most carbon markets share a common institutional architecture based on three essential components: the establishment of an emissions cap, the allocation of emission allowances, and the creation of a trading mechanism through which regulated entities may exchange emission rights.

The cap-and-trade model represents the dominant form of emissions trading implemented worldwide. Under this approach, public authorities establish a maximum quantity of greenhouse gas emissions permitted within a specific period. This emissions cap is subsequently divided into tradable allowances, each representing the legal authorization to emit a predetermined quantity of carbon dioxide equivalent (CO_2e). Firms whose emissions remain below their allocated allowances may sell excess permits, whereas companies exceeding their allocation must purchase additional allowances or reduce emissions through technological improvements (Ellerman et al., 2010).

The environmental effectiveness of a cap-and-trade system depends primarily upon the stringency of the emissions cap rather than the market price itself. While allowance prices provide incentives for firms to invest in emissions reductions, total emissions remain constrained by the quantity of allowances issued by regulators. Consequently, emissions trading combines environmental certainty with economic flexibility, allowing reductions to occur wherever marginal abatement costs are lowest (Tietenberg, 2006).

The allocation of allowances constitutes one of the most influential design decisions affecting both environmental performance and political acceptability. During the initial phases of many emissions trading systems, governments relied heavily upon free allocation based on historical emissions—a practice commonly referred to as grandfathering. This approach sought to facilitate political acceptance by limiting compliance costs for energy-intensive industries. However, extensive free allocation also generated concerns regarding windfall profits, reduced market efficiency, and weakened incentives for technological innovation (Ellerman & Buchner, 2007).

In response to these criticisms, more recent carbon markets have increasingly adopted auction-based allocation mechanisms. Auctioning improves price transparency, enhances market efficiency, generates public revenues that may finance climate policies, and reduces opportunities for regulatory capture. The progressive expansion of allowance auctions within the European Union Emissions Trading System illustrates this transition toward greater market maturity.

Carbon markets also require robust monitoring, reporting, and verification (MRV) systems to ensure environmental integrity. Accurate emissions accounting is essential because the credibility of emissions trading depends entirely upon confidence that reported emissions correspond to actual environmental outcomes. Consequently, most compliance markets impose standardized reporting methodologies, independent third-party verification, and substantial penalties for non-compliance (ICAP, 2021).

Beyond these institutional components, carbon markets increasingly interact with broader financial systems. Carbon allowances have evolved from purely regulatory instruments into financial assets traded by industrial firms, banks, investment funds, and specialized carbon market intermediaries. This financialization has improved market liquidity but has simultaneously generated concerns regarding speculative trading and excessive price volatility (Chevallier, 2011).

Overall, the institutional architecture of modern carbon markets reflects an ongoing effort to reconcile environmental effectiveness, economic efficiency, administrative feasibility, and political acceptability within increasingly complex climate governance frameworks.

3.2. The Kyoto Protocol Flexible Mechanisms

The Kyoto Protocol represented the first international agreement to operationalize carbon markets at the global level. Adopted in 1997 and entering into force in 2005, the Protocol established legally binding greenhouse gas reduction commitments for industrialized countries while introducing three market-based flexibility mechanisms intended to reduce the overall costs of compliance (UNFCCC, 1998).

The first mechanism, International Emissions Trading (IET), allowed Annex I countries with surplus emission allowances to transfer unused emission rights to other countries experiencing difficulties in meeting their commitments. In theory, this mechanism enabled emission reductions to occur wherever they could be achieved at the lowest cost while maintaining overall environmental integrity.

The second mechanism, Joint Implementation (JI), permitted developed countries to finance emission reduction projects within other Annex I countries. Verified emission reductions generated by these projects could then be credited toward the investor country's Kyoto commitments. Joint Implementation primarily supported projects in Eastern Europe and economies undergoing economic transition following the dissolution of the Soviet Union.

The third mechanism, the Clean Development Mechanism (CDM), rapidly became the most influential component of the Kyoto architecture. Unlike Joint Implementation, the CDM enabled developed countries to finance emission reduction projects within developing countries lacking binding emissions targets. Certified Emission Reductions (CERs) generated through approved projects could subsequently be used by Annex I countries to comply with their Kyoto obligations.

The Clean Development Mechanism attracted considerable international participation and financed thousands of renewable energy, methane capture, waste management, industrial efficiency, and forestry projects across Latin America, Asia, and Africa. By reducing mitigation costs while facilitating technology transfer and sustainable development, the CDM sought to create mutual benefits for both developed and developing economies (World Bank, 2021).

Nevertheless, the mechanism also generated substantial criticism. Numerous studies questioned whether many registered projects satisfied the principle of additionality—that is, whether the emission reductions would have occurred in the absence of carbon finance (Schneider, 2009). Other researchers identified weaknesses in baseline estimation methodologies, inconsistent verification procedures, and uneven geographical distribution, with a disproportionate concentration of projects in China, India, and Brazil.

Furthermore, the rapid expansion of Certified Emission Reduction credits contributed to an oversupply within international carbon markets during the early 2010s. Combined with reduced industrial activity following the global financial crisis, this oversupply substantially depressed carbon prices, thereby weakening incentives for additional emissions reductions.

Despite these shortcomings, the Kyoto mechanisms established the institutional foundations upon which subsequent international carbon markets were constructed. Many methodological innovations—including emissions accounting protocols, project validation procedures, independent verification standards, and carbon credit certification systems—continue to influence contemporary carbon market governance.

3.3. The European Union Emissions Trading System

The European Union Emissions Trading System (EU ETS) represents the world's largest multinational carbon market and is widely regarded as the most influential experiment in emissions trading implemented to date. Established in 2005, the system constitutes the central pillar of European climate policy and covers approximately 40% of total greenhouse gas emissions within the European Union (European Commission, 2021).

The EU ETS currently regulates emissions from electricity generation, heavy industry, aviation within the European Economic Area, and several energy-intensive manufacturing sectors. More than 10,000 industrial installations participate in the system across all EU Member States as well as Iceland, Liechtenstein, and Norway.

The evolution of the EU ETS can be divided into four principal phases.

Phase I (2005–2007)

The first trading period functioned primarily as a pilot phase intended to establish institutional infrastructure and allow market participants to gain practical experience with emissions trading.

However, several design weaknesses quickly emerged. National governments substantially overestimated future emissions when allocating allowances, resulting in an excessive supply of permits. Once verified emissions data became publicly available, market participants realized that allowances exceeded actual emissions, causing carbon prices to collapse dramatically during 2007 (Ellerman et al., 2010).

Although Phase I failed to generate significant emission reductions, it successfully demonstrated that multinational emissions trading was administratively feasible.

Phase II (2008–2012)

The second phase coincided with the Kyoto Protocol commitment period and introduced more stringent emissions caps together with improved monitoring and reporting requirements.

Nevertheless, the global financial crisis substantially reduced industrial production throughout Europe, generating another surplus of allowances. Falling energy demand combined with generous free allocation again depressed carbon prices, limiting incentives for long-term low-carbon investment.

These experiences highlighted the importance of adjusting allowance supply in response to macroeconomic fluctuations.

Phase III (2013–2020)

The third phase introduced major structural reforms.

Rather than allowing individual Member States to determine national allocation plans, the European Commission established a single EU-wide emissions cap. Auctioning progressively replaced free allocation as the principal distribution mechanism for electricity producers, while harmonized allocation rules improved consistency across Member States.

Perhaps the most significant reform involved the creation of the Market Stability Reserve (MSR), designed to remove surplus allowances from circulation whenever market oversupply exceeded predetermined thresholds. The MSR substantially strengthened market confidence and contributed to a significant recovery in allowance prices during the late 2010s.

By 2021, EU Allowance (EUA) prices exceeded €60 per tonne of CO_2, representing the highest carbon prices observed since the creation of the system.

3.4. Lessons from the European Experience

The European experience has generated one of the largest bodies of empirical evidence concerning emissions trading.

First, numerous studies conclude that the EU ETS has contributed to measurable reductions in greenhouse gas emissions beyond those attributable solely to economic recession or complementary renewable energy policies (Bayer & Aklin, 2020). Although estimates vary across sectors, the consensus suggests that emissions trading has produced meaningful environmental benefits while maintaining industrial competitiveness.

Second, the system has demonstrated remarkable institutional adaptability. Unlike many environmental policies, the EU ETS has undergone continuous reform in response to observed market imperfections. Revisions concerning auctioning, market stability, benchmark allocation, and emissions caps illustrate an iterative policy-learning process rarely observed within international environmental governance.

Third, evidence increasingly indicates that carbon pricing has stimulated technological innovation. Firms facing sustained carbon costs have increased investments in energy efficiency, renewable electricity, industrial electrification, and low-carbon production technologies. Patent analyses reveal positive relationships between carbon pricing and clean technology innovation, particularly among regulated sectors (Calel & Dechezleprêtre, 2016).

Nevertheless, important challenges remain. Carbon leakage continues to represent a concern for trade-exposed industries, particularly steel, cement, chemicals, and aluminium. In response, the European Union has maintained transitional free allocation mechanisms while simultaneously exploring complementary measures such as the Carbon Border Adjustment Mechanism proposed under the European Green Deal.

Another persistent challenge concerns price volatility. Although higher carbon prices strengthen incentives for decarbonization, excessive short-term volatility may increase investment uncertainty and reduce the effectiveness of long-term industrial planning. Consequently, policymakers continue debating the appropriate balance between market flexibility and regulatory intervention.

Despite these remaining challenges, the EU ETS is widely regarded as the international benchmark against which most subsequent emissions trading systems have been designed.

3.5. Carbon Markets Beyond Europe: Comparative International Experiences

Although the European Union Emissions Trading System has become the international reference for emissions trading, several jurisdictions have developed carbon markets adapted to their own economic structures, political institutions, and environmental objectives. These experiences have significantly enriched the global understanding of emissions trading by demonstrating that no single institutional model is universally applicable. Instead, successful carbon markets require regulatory frameworks tailored to national circumstances while maintaining core principles of environmental integrity, transparency, and economic efficiency.

The international expansion of emissions trading has also facilitated policy learning. Governments have increasingly incorporated lessons derived from earlier systems, avoiding some of the design weaknesses observed during the initial implementation of the EU ETS while introducing innovative institutional features intendd to improve market performance.

3.5.1. California Cap-and-Trade Program

The California Cap-and-Trade Program constitutes one of the most sophisticated subnational carbon markets currently operating worldwide. Established under the California Global Warming Solutions Act (AB 32), the program formally began operations in 2013 with the objective of supporting the state's ambitious greenhouse gas reduction targets.

Unlike several earlier emissions trading systems, California adopted a comprehensive regulatory framework from its inception. The market covers electricity generation, industrial facilities, fuel distributors, and natural gas suppliers, representing approximately 80% of statewide greenhouse gas emissions (California Air Resources Board, 2021).

One of the defining characteristics of the California system is its extensive use of auction-based allowance allocation. Rather than relying predominantly on grandfathering, a substantial proportion of allowances are distributed through regular public auctions, generating considerable fiscal revenues. These revenues are subsequently reinvested in climate mitigation programs, public transportation, renewable energy projects, energy efficiency initiatives, and environmental justice policies.

The California market also incorporates a price containment mechanism through both auction reserve prices and an Allowance Price Containment Reserve (APCR). These mechanisms reduce excessive price volatility while preserving market flexibility, thereby addressing one of the principal criticisms directed toward earlier emissions trading systems.

Another innovative feature is the formal linkage established with Québec's emissions trading system through the Western Climate Initiative (WCI). This linkage allows allowances to be traded across jurisdictions, increasing market liquidity while reducing overall compliance costs. The California-Québec partnership represents one of the first successful examples of cross-border carbon market integration and demonstrates the feasibility of international cooperation below the national level.

Empirical evaluations generally conclude that California's emissions trading program has contributed to substantial emission reductions without producing significant adverse effects on economic growth or industrial competitiveness (Burtraw et al., 2018). Nevertheless, debates continue regarding distributional impacts, particularly concerning the potential concentration of localized air pollution within disadvantaged communities despite overall reductions in greenhouse gas emissions.

3.5.2. Regional Greenhouse Gas Initiative (RGGI)

The Regional Greenhouse Gas Initiative represents the first mandatory cap-and-trade program implemented within the United States. Officially launched in 2009, the initiative currently includes several northeastern states cooperating voluntarily to reduce carbon dioxide emissions from the electricity generation sector.

Unlike the California system, RGGI applies exclusively to fossil fuel power plants with generating capacities exceeding 25 megawatts. Although this narrower sectoral scope limits overall emissions coverage, it has allowed participating states to implement relatively simple administrative procedures while achieving measurable reductions in emissions from electricity production.

A distinctive characteristic of RGGI is its almost complete reliance on auctioning rather than free allocation. Nearly all emission allowances are sold through quarterly auctions, and participating states invest auction revenues in renewable energy deployment, building energy efficiency improvements, consumer energy assistance programs, and technological innovation.

Several independent evaluations conclude that RGGI has successfully reduced carbon emissions while simultaneously generating net economic benefits through lower energy consumption, increased investment, and reduced public health expenditures associated with improved air quality (Murray & Maniloff, 2015).

Because the initiative operates across multiple independent jurisdictions without federal oversight, RGGI has also demonstrated that decentralized climate governance can produce meaningful environmental outcomes through voluntary interstate cooperation.

3.5.3. New Zealand Emissions Trading Scheme

New Zealand introduced its national emissions trading system in 2008, becoming one of the first countries outside Europe to adopt economy-wide carbon pricing.

The New Zealand Emissions Trading Scheme (NZ ETS) differs from most other systems because it includes forestry alongside energy, industrial processes, waste management, and transportation. The incorporation of forestry reflects the country's unique economic structure and recognizes the important role that forest carbon sequestration plays within New Zealand's national climate strategy.

Initially, the NZ ETS allowed unrestricted use of international Kyoto credits. While this approach substantially reduced compliance costs, it also exposed the domestic market to large inflows of inexpensive international credits, leading to extremely low carbon prices during several years. As a consequence, domestic incentives for emissions reductions weakened considerably.

Subsequent reforms progressively restricted access to international credits while strengthening domestic market governance. Price controls, improved allowance allocation, and revised emissions caps have contributed to greater market stability during recent years.

The New Zealand experience illustrates both the opportunities and risks associated with integrating domestic emissions trading systems into broader international carbon markets.

3.5.4. South Korea Emissions Trading Scheme

South Korea launched its national emissions trading system in 2015, becoming the first East Asian country to establish a nationwide mandatory carbon market.

The Korean ETS covers approximately 70% of national greenhouse gas emissions, including electricity generation, manufacturing, aviation, buildings, transportation, and waste management.

Given the strategic importance of export-oriented heavy industry within the Korean economy, policymakers initially relied heavily upon free allocation in order to minimize competitiveness concerns. However, the system gradually introduced greater auctioning while simultaneously strengthening monitoring and verification procedures.

Early empirical evidence suggests that the Korean ETS has successfully established carbon pricing as a central component of national climate policy. Nevertheless, relatively limited market liquidity and conservative allowance allocation have constrained price formation during its initial years of operation.

Researchers frequently identify South Korea as an example of gradual institutional development in which emissions trading evolves incrementally alongside broader industrial policy objectives.

3.5.5. China's Emerging National Carbon Market

China represents the world's largest greenhouse gas emitter and therefore occupies a central position within global climate governance. Throughout the 2010s, the Chinese government established seven regional pilot emissions trading systems in cities and provinces including Beijing, Shanghai, Shenzhen, Guangdong, Tianjin, Chongqing, and Hubei.

These pilot programs served as experimental laboratories through which policymakers evaluated alternative allocation methods, monitoring procedures, registry systems, and trading rules under different regional economic conditions.

Building upon these experiences, China officially launched its national emissions trading system in July 2021.

During its initial phase, the Chinese national ETS covered approximately 2,200 electricity generation companies responsible for more than four billion tonnes of carbon dioxide annually, making it immediately the world's largest carbon market in terms of covered emissions (ICAP, 2021).

Unlike the EU ETS, China's initial market employed an emissions intensity approach rather than an absolute emissions cap. Allowance allocation depended upon benchmark emissions per unit of electricity generated, reflecting China's concern regarding continued economic growth and energy security.

Although many observers initially criticized relatively low carbon prices and limited sectoral coverage, the establishment of China's national carbon market represented a landmark development within international climate policy. Given the country's dominant role in global manufacturing and energy consumption, future expansion of the Chinese ETS is expected to exert considerable influence upon worldwide carbon pricing.

The Chinese experience also demonstrates the importance of institutional sequencing. Rather than immediately implementing a comprehensive national system, policymakers relied upon gradual experimentation, regional pilot programs, and continuous regulatory learning before scaling the market nationally.

3.6. Comparative Assessment of International Carbon Markets

Despite substantial institutional diversity, several common lessons emerge from the international experience with emissions trading.

First, environmental effectiveness depends primarily upon the ambition of the emissions cap rather than the existence of trading itself. Carbon markets characterized by generous allowance allocation consistently produce lower carbon prices and weaker incentives for technological innovation. Conversely, progressively tightening emissions caps strengthen market credibility while encouraging long-term investment in low-carbon technologies.

Second, allowance allocation mechanisms significantly influence both economic efficiency and political feasibility. Although free allocation may facilitate initial implementation by reducing opposition from regulated industries, prolonged reliance upon grandfathering often generates windfall profits and weakens market incentives. Auction-based allocation increasingly appears to represent international best practice, particularly when auction revenues are transparently reinvested in climate mitigation and social transition policies.

Third, robust monitoring, reporting, and verification systems constitute indispensable institutional foundations. Regardless of market design, emissions trading cannot function effectively without credible emissions accounting and independent verification procedures.

Fourth, carbon markets benefit substantially from regulatory predictability. Investors making long-term decisions regarding industrial decarbonization require confidence that future carbon prices will remain sufficiently robust to justify capital-intensive investments. Frequent regulatory uncertainty may therefore undermine the effectiveness of carbon pricing even when current allowance prices appear adequate.

Finally, international experience demonstrates that emissions trading should not be viewed as an isolated climate policy instrument. The most successful jurisdictions combine carbon markets with complementary policies promoting renewable energy, energy efficiency, industrial innovation, research and development, and sustainable infrastructure. Rather than replacing other climate policies, emissions trading functions most effectively as one component of a broader decarbonization strategy.

Collectively, these international experiences indicate that carbon markets have matured considerably since their introduction under the Kyoto Protocol. Although important design challenges remain, accumulated empirical evidence suggests that well-designed emissions trading systems can contribute meaningfully to greenhouse gas mitigation while preserving economic flexibility and encouraging technological innovation.

4. Benefits and Limitations of Carbon Markets

4.1. Environmental Effectiveness

The principal objective of carbon markets is to reduce greenhouse gas emissions in a cost-effective manner. Consequently, one of the most extensively debated issues within the academic literature concerns whether emissions trading systems have generated genuine environmental improvements beyond those that would have occurred under alternative policy scenarios.

From a theoretical perspective, cap-and-trade systems provide a high degree of environmental certainty because total emissions are determined by the regulatory cap rather than by market behaviour. Provided that monitoring and enforcement mechanisms function effectively, aggregate emissions cannot exceed the quantity of allowances issued by the regulator. This characteristic distinguishes emissions trading from carbon taxation, where emissions outcomes remain uncertain because firms respond differently to identical price signals (Weitzman, 1974).

Empirical evidence accumulated during the first two decades of carbon market implementation generally supports the conclusion that well-designed emissions trading systems contribute to measurable emission reductions. Studies evaluating the European Union Emissions Trading System indicate that regulated installations reduced emissions significantly compared with similar firms operating outside the system (Bayer & Aklin, 2020). Although the magnitude of estimated reductions varies across sectors and methodologies, the overall evidence suggests that emissions trading has generated genuine environmental benefits.

Several mechanisms explain these reductions. First, carbon pricing increases the relative cost of carbon-intensive production, encouraging firms to adopt cleaner technologies, improve energy efficiency, substitute fuels, or modify production processes. Second, emissions trading creates continuous incentives for incremental improvements because every additional tonne of avoided emissions represents a potential financial gain through the sale of unused allowances. Third, progressively declining emissions caps establish predictable long-term expectations that encourage strategic investment in decarbonization technologies.

However, environmental effectiveness depends critically upon regulatory design. Early phases of several emissions trading systems were characterized by generous allowance allocation, resulting in carbon prices too low to induce substantial behavioural change. The experience of Phase I of the EU ETS clearly illustrates this problem, as the overallocation of allowances substantially weakened environmental incentives despite the existence of a functioning carbon market (Ellerman et al., 2010).

The literature also emphasizes that carbon markets rarely operate in isolation. Renewable energy subsidies, energy efficiency regulations, environmental standards, and technological innovation policies frequently interact with emissions trading systems. Disentangling the individual contribution of carbon pricing from these complementary measures therefore represents a considerable empirical challenge.

Nevertheless, despite methodological complexities, the emerging consensus suggests that emissions trading has contributed positively to climate mitigation, particularly when accompanied by progressively tightening emissions caps and effective regulatory oversight.

4.2. Economic Efficiency and Cost-Effectiveness

Economic efficiency constitutes perhaps the strongest theoretical argument supporting carbon markets. Unlike uniform regulatory standards, emissions trading allows firms facing lower abatement costs to undertake larger emissions reductions while firms with higher marginal costs purchase allowances. This decentralized decision-making minimizes total compliance costs across the regulated economy (Montgomery, 1972).

The flexibility provided by emissions trading is particularly valuable because mitigation costs vary substantially among industries. Electricity producers may rapidly substitute renewable generation for fossil fuels, whereas sectors such as cement, steel, chemicals, and aviation currently face more limited technological alternatives. Carbon markets allow these differences to be reflected through market transactions rather than through centralized regulatory decisions.

Numerous ex ante modelling exercises predicted substantial cost savings from emissions trading compared with command-and-control regulation (Tietenberg, 2006). Subsequent empirical evaluations have generally confirmed these predictions. Firms participating in emissions trading systems have demonstrated considerable heterogeneity in their mitigation strategies, suggesting that market flexibility has indeed allowed emissions reductions to occur where they are least expensive.

Moreover, emissions trading reduces the informational burden placed upon governments. Regulators need only determine the overall emissions cap rather than identifying the optimal emissions reduction strategy for every regulated installation. Firms themselves possess superior information regarding production technologies, investment opportunities, and operational constraints, allowing decentralized markets to allocate emissions reductions more efficiently than centralized planning.

However, actual market efficiency depends upon several assumptions that may not hold perfectly in practice. Transaction costs, imperfect information, market concentration, regulatory uncertainty, and administrative complexity may reduce the theoretical efficiency gains predicted by economic models.

Particularly important are transaction costs associated with monitoring, reporting, verification, allowance trading, legal compliance, and market participation. These costs may disproportionately affect smaller firms, reducing participation and potentially limiting market liquidity.

Nevertheless, despite these practical limitations, the literature continues to regard emissions trading as one of the most economically efficient climate policy instruments currently available.

4.3. Innovation and Technological Change

Beyond immediate emissions reductions, carbon markets seek to influence long-term technological development by creating persistent financial incentives for innovation.

This argument is closely associated with the Porter Hypothesis, which proposes that appropriately designed environmental regulation may stimulate innovation sufficiently to offset part of the associated compliance costs (Porter & van der Linde, 1995). Carbon pricing provides continuous incentives for firms to identify cleaner production technologies because every reduction in emissions decreases future compliance costs.

Empirical evidence increasingly supports this hypothesis. Analyses of patent registrations indicate that firms regulated under the EU ETS increased investment in low-carbon technologies relative to comparable firms operating outside the system (Calel & Dechezleprêtre, 2016). Similar findings have been reported for renewable energy technologies, industrial process improvements, energy efficiency equipment, and carbon management systems.

Importantly, carbon markets encourage not only incremental efficiency improvements but also more fundamental technological transitions. Rising carbon prices improve the economic competitiveness of renewable electricity, electrification technologies, hydrogen production, carbon capture and storage, and advanced industrial processes.

Furthermore, emissions trading generates dynamic efficiency benefits extending beyond individual firms. As demand for low-carbon technologies increases, learning effects, economies of scale, and knowledge spillovers contribute to broader technological progress throughout the economy.

Nevertheless, the innovation effects of carbon markets depend critically upon expectations regarding future carbon prices. If firms perceive carbon prices as temporary or politically unstable, incentives for long-term research and development may remain weak despite relatively high current prices.

Consequently, policy credibility has become increasingly recognized as a crucial determinant of innovation outcomes.

4.4. Carbon Leakage and International Competitiveness

One of the most persistent criticisms of carbon markets concerns the possibility of carbon leakage.

Carbon leakage occurs when carbon pricing increases production costs within regulated jurisdictions, encouraging firms to relocate carbon-intensive production toward countries lacking comparable climate policies. In such cases, domestic emissions decline while global emissions remain unchanged—or may even increase if production shifts toward less efficient facilities (Babiker, 2005).

Theoretical models initially predicted potentially significant leakage effects, particularly for internationally traded energy-intensive products. Concerns were especially pronounced in sectors such as steel, aluminium, cement, fertilizers, refining, and chemicals, where production costs are highly sensitive to energy prices and international competition is intense.

However, empirical evidence accumulated during the operation of the EU ETS suggests that actual leakage has generally been smaller than originally anticipated (Branger & Quirion, 2014). Several explanations have been proposed.

First, energy costs often represent only one component of overall production costs, reducing incentives for relocation.

Second, relocating industrial facilities involves substantial capital expenditures, organizational disruption, regulatory uncertainty, and logistical complexity.

Third, many multinational firms increasingly face climate-related expectations from investors, consumers, and financial markets, reducing the attractiveness of relocating production solely to avoid carbon pricing.

Nevertheless, carbon leakage remains a legitimate concern for specific sectors characterized by high trade intensity and narrow profit margins.

To address these risks, policymakers have adopted several complementary measures.

The European Union initially relied upon generous free allocation for industries considered exposed to international competition. More recently, policy discussions have increasingly focused on the Carbon Border Adjustment Mechanism (CBAM), which seeks to equalize carbon costs between domestic producers and imported goods by applying carbon-related adjustments at the border.

If successfully implemented, border carbon adjustments may substantially reduce incentives for industrial relocation while encouraging broader international convergence in carbon pricing.

4.5. Distributional Effects and Social Equity

Although carbon markets are primarily evaluated according to environmental and economic criteria, increasing attention has been devoted to their social implications.

Carbon pricing may disproportionately affect lower-income households because energy expenditures generally represent a larger share of household budgets among economically vulnerable populations. Rising electricity prices, heating costs, and transportation expenses may therefore generate regressive distributional impacts unless appropriate compensatory measures are implemented.

Similarly, regional disparities may emerge within countries. Areas heavily dependent upon coal mining, fossil fuel extraction, or energy-intensive manufacturing may experience employment losses during industrial decarbonization, whereas regions specializing in renewable energy technologies may benefit from new investment opportunities.

These concerns have contributed to growing recognition of the importance of a "just transition" framework accompanying climate policies.

Auction revenues generated through emissions trading provide governments with opportunities to mitigate distributional impacts. Revenue recycling may finance direct household compensation, reductions in labour taxation, investments in public transportation, renewable energy deployment, workforce retraining, or regional economic diversification.

Consequently, the social acceptability of carbon markets increasingly depends not only upon environmental performance but also upon how carbon pricing revenues are redistributed throughout society.

4.6. Carbon Price Volatility and Market Stability

One of the most persistent criticisms directed toward emissions trading systems concerns the volatility of carbon prices. While market-based mechanisms are designed to determine allowance prices through supply and demand interactions, excessive price fluctuations may reduce investment certainty and weaken incentives for long-term decarbonization.

Carbon prices perform two essential economic functions. In the short term, they influence operational decisions by encouraging firms to substitute cleaner production methods whenever doing so is economically advantageous. In the long term, carbon prices guide capital allocation decisions by affecting the expected profitability of investments in renewable energy, industrial electrification, energy efficiency, hydrogen technologies, and carbon capture systems.

For these long-term investment decisions, price predictability is often more important than temporary price peaks. Investors evaluating projects with operational lifetimes of twenty or thirty years require confidence that carbon pricing will remain sufficiently robust over extended periods. Sudden market collapses or prolonged periods of low allowance prices may substantially reduce incentives for technological transformation.

The European Union Emissions Trading System provides an instructive example. During its initial phases, generous allowance allocation and reduced industrial production following the global financial crisis generated substantial permit surpluses. Carbon prices fell to levels widely considered insufficient to stimulate significant technological innovation or industrial decarbonization (Ellerman et al., 2010).

In response, policymakers introduced the Market Stability Reserve (MSR), which automatically adjusts allowance supply according to predefined market conditions. The MSR removes allowances from circulation during periods of persistent oversupply and reintroduces allowances when shortages emerge, thereby reducing extreme price fluctuations while preserving market-based price formation.

Other jurisdictions have implemented alternative stabilization mechanisms. California employs auction reserve prices that establish a minimum allowance value, while additional strategic reserves help prevent excessive price increases during periods of unexpectedly strong demand.

The literature increasingly suggests that hybrid systems combining market flexibility with carefully designed stabilization mechanisms may outperform purely laissez-faire carbon markets by reducing uncertainty without undermining economic efficiency (Aldy & Stavins, 2012).

4.7. Additionality and the Integrity of Carbon Offsets

The environmental credibility of carbon markets depends fundamentally upon the integrity of the emission reductions they generate. This issue becomes particularly important within carbon offset mechanisms, where emission reductions occur outside the regulated entity purchasing the credits.

Among all methodological challenges associated with offsets, additionality has attracted the greatest academic attention.

A carbon offset project satisfies additionality only if the associated emission reductions would not have occurred in the absence of carbon finance. In other words, carbon credits should represent genuinely incremental climate benefits rather than rewarding activities that would have been implemented regardless of the offset market.

Determining this counterfactual condition is inherently difficult because it requires comparison between observed project outcomes and hypothetical scenarios that cannot be directly measured.

Several methodologies have been developed to assess additionality, including investment analysis, barrier analysis, common practice assessments, and financial viability evaluations. Nevertheless, each approach involves substantial uncertainty regarding baseline assumptions and future project behaviour.

Empirical evaluations have questioned the additionality of numerous projects registered under the Clean Development Mechanism. Some renewable energy projects, for example, may have become financially viable even without carbon revenues due to declining technology costs, supportive public policies, or increasing electricity demand (Cames et al., 2016).

Similarly, industrial gas destruction projects generated particularly large volumes of Certified Emission Reductions despite relatively low implementation costs, creating concerns that certain incentives may have unintentionally encouraged continued production of high-emission gases solely to generate carbon credits.

These experiences illustrate the importance of continuously improving project evaluation methodologies in order to preserve market credibility.

4.8. Permanence, Leakage and Double Counting

Beyond additionality, several other methodological challenges affect the environmental integrity of carbon markets.

Permanence refers primarily to biological carbon sequestration projects such as afforestation, reforestation, and forest conservation. Unlike geological carbon storage or avoided industrial emissions, biological carbon reservoirs remain vulnerable to future disturbances including wildfires, pest outbreaks, illegal logging, droughts, and land-use change.

If previously stored carbon is subsequently released into the atmosphere, earlier emission reductions may be partially or completely reversed. This temporal uncertainty complicates the valuation of nature-based carbon credits and has stimulated the development of buffer reserves, insurance mechanisms, and long-term monitoring requirements within voluntary carbon markets.

Leakage represents another important concern. In project-based offset systems, emissions reductions achieved within one geographical area may unintentionally increase emissions elsewhere. Forest conservation projects, for example, may simply shift deforestation activities toward neighbouring regions rather than reducing overall forest loss.

Accurately measuring leakage effects requires broader landscape-level analysis extending beyond individual project boundaries. Consequently, several certification standards have progressively strengthened their methodologies by incorporating regional monitoring approaches.

Double counting constitutes an additional governance challenge, particularly following the adoption of the Paris Agreement.

Double counting occurs whenever identical emission reductions are simultaneously claimed by multiple entities. For example, a host country might include a project within its nationally determined contribution (NDC), while a foreign corporation simultaneously purchases offset credits generated by the same project to support its own carbon neutrality claims.

Such situations artificially inflate reported climate progress because identical emission reductions are counted multiple times.

The negotiations surrounding Article 6 of the Paris Agreement devoted considerable attention to preventing double counting through corresponding adjustments and harmonized accounting procedures. By the conclusion of COP26 in Glasgow, important progress had been achieved in establishing common accounting principles, although practical implementation remained an evolving area of international climate governance.

4.9. Governance and Institutional Credibility

The long-term success of carbon markets depends not only upon economic incentives but also upon institutional credibility.

Market participants must maintain confidence that allowance allocation, emissions accounting, regulatory enforcement, and market supervision operate transparently and consistently. Weak governance may undermine environmental effectiveness even when market design appears theoretically sound.

Robust monitoring, reporting and verification (MRV) systems therefore represent indispensable components of modern carbon markets. Independent verification agencies, standardized emissions accounting protocols, digital allowance registries, and public disclosure requirements all contribute to maintaining confidence among regulators, investors, and civil society.

Governance challenges become particularly complex within international carbon markets because multiple jurisdictions frequently apply different legal frameworks, accounting methodologies, and verification standards.

The rapid expansion of voluntary carbon markets has further highlighted these issues. Numerous certification organizations—including the Verified Carbon Standard (VCS), Gold Standard, American Carbon Registry, and Climate Action Reserve—have developed independent methodological frameworks. While methodological diversity encourages innovation, it may also create inconsistencies regarding credit quality, transparency, and environmental integrity (Green, 2021).

Consequently, recent academic literature increasingly emphasizes the need for greater international harmonization of carbon accounting standards together with stronger independent oversight.

Institutional trust has therefore become as important as market efficiency in determining the long-term legitimacy of carbon pricing.

4.10. Financialization of Carbon Markets

As carbon markets have matured, emission allowances have progressively evolved from purely regulatory instruments into financial assets traded by a growing range of market participants.

Initially, emissions trading primarily involved regulated industrial firms seeking compliance with environmental obligations. Over time, however, commercial banks, investment funds, commodity traders, pension funds, and specialized financial institutions entered carbon markets to provide liquidity, facilitate risk management, and exploit arbitrage opportunities.

Financial participation generates several important benefits.

Increased liquidity improves price discovery, reduces bid-ask spreads, facilitates hedging strategies, and enables regulated firms to manage future compliance costs more effectively.

Nevertheless, financialization has also generated concerns regarding speculative trading. Some observers argue that excessive participation by non-compliance investors may increase price volatility, disconnect carbon prices from underlying emissions fundamentals, or contribute to market bubbles.

Empirical evidence remains mixed. While several studies identify increasing financial integration between carbon markets and broader commodity markets, most conclude that speculation has not fundamentally undermined market performance (Chevallier, 2011). Instead, financial participation appears to have contributed positively to market liquidity while requiring appropriate regulatory oversight to prevent market manipulation.

Consequently, future carbon markets will likely continue balancing environmental regulation with financial market supervision.

4.11. Synthesis of Benefits and Limitations

The accumulated international experience demonstrates that carbon markets constitute neither a universal solution nor an ineffective policy instrument. Rather, their performance depends fundamentally upon institutional design, regulatory ambition, and complementary climate policies.

Where emissions caps remain sufficiently stringent, allowance allocation avoids persistent oversupply, monitoring systems maintain high credibility, and long-term policy signals remain stable, carbon markets have consistently contributed to measurable emissions reductions while preserving economic flexibility.

Conversely, poorly designed systems characterized by generous allowance allocation, weak governance, uncertain regulatory frameworks, or inadequate monitoring have frequently produced low carbon prices, limited environmental incentives, and declining public confidence.

The literature published up to 2021 increasingly converges on several broad conclusions.

First, carbon pricing is necessary but not sufficient for achieving deep decarbonization. Second, institutional quality matters as much as market design. Third, emissions trading performs best when integrated with complementary policies supporting renewable energy, industrial innovation, energy efficiency, and infrastructure investment. Finally, international coordination will become increasingly important as national carbon markets expand under the framework established by the Paris Agreement.

Rather than evaluating carbon markets in isolation, future research should increasingly examine their interaction with broader economic transformation processes required to achieve global net-zero emissions during the twenty-first century.

5. Discussion

The rapid expansion of carbon markets during the last two decades reflects a profound transformation in global climate governance. Whereas environmental regulation historically relied upon prescriptive standards and technology mandates, contemporary climate policy increasingly incorporates market-based instruments capable of aligning environmental objectives with economic incentives. This evolution illustrates a broader shift from command-and-control regulation toward policy frameworks that seek to internalize environmental externalities while preserving market flexibility.

The literature reviewed throughout this article indicates that carbon markets have moved beyond their initial experimental phase. Early debates focused primarily on the theoretical feasibility of emissions trading and its potential efficiency advantages over traditional environmental regulation. By contrast, contemporary research increasingly evaluates practical implementation issues, institutional quality, market governance, and long-term interactions between carbon pricing and broader decarbonization strategies.

One of the clearest findings emerging from the international experience is that the effectiveness of carbon markets depends far more upon institutional design than upon the trading mechanism itself. Emissions trading is neither inherently successful nor inherently ineffective. Rather, environmental outcomes are determined by regulatory ambition, allowance allocation, monitoring quality, and policy credibility.

This conclusion helps explain the considerable variation observed across jurisdictions. Carbon markets characterized by stringent emissions caps, transparent governance, robust monitoring systems, and predictable regulatory frameworks have generally produced stronger environmental outcomes than systems relying upon generous free allocation or politically constrained emissions targets.

The European Union Emissions Trading System illustrates this institutional learning process particularly well. Initial implementation revealed significant weaknesses associated with overallocation and insufficient carbon prices. However, successive reforms—including centralized cap setting, expanded auctioning, benchmark allocation, and the introduction of the Market Stability Reserve—substantially improved market performance. Rather than representing policy failure, these reforms demonstrate the adaptive capacity of emissions trading institutions.

Similar patterns emerge across other jurisdictions. California incorporated many lessons learned from earlier European experiences by introducing price stabilization mechanisms and extensive auctioning from the outset. China's gradual implementation strategy, based upon regional pilot programs prior to national deployment, likewise reflects an incremental approach emphasizing institutional experimentation before large-scale implementation.

Collectively, these experiences suggest that successful carbon markets evolve through continuous policy learning rather than through static regulatory design.

5.1. Carbon Markets within the Broader Climate Policy Mix

An important conclusion emerging from recent literature concerns the complementary rather than substitutive role of carbon markets within climate policy.

Early economic models frequently analysed carbon pricing as a stand-alone policy instrument capable of delivering economically efficient emissions reductions across the entire economy. In practice, however, governments rarely rely exclusively upon carbon pricing.

Instead, emissions trading increasingly operates alongside renewable energy subsidies, energy efficiency standards, public infrastructure investment, industrial innovation policies, research and development support, sustainable finance initiatives, and sector-specific regulations.

This policy interaction generates both opportunities and challenges.

On one hand, complementary measures may accelerate technological transitions by overcoming market failures that carbon pricing alone cannot address. Knowledge spillovers, network externalities, infrastructure constraints, and behavioural barriers frequently justify additional policy intervention beyond emissions trading.

On the other hand, overlapping climate policies may reduce demand for emission allowances, lowering carbon prices and potentially weakening market incentives if emissions caps are not adjusted accordingly.

Consequently, future policy design should increasingly consider the interaction among multiple climate instruments rather than evaluating individual policies in isolation.

Carbon markets should therefore be understood as one component of a broader decarbonization architecture rather than as a comprehensive solution to climate change.

5.2. International Coordination under the Paris Agreement

Another central theme emerging from the literature concerns the growing importance of international coordination.

Climate change represents a global collective action problem because greenhouse gas emissions generate worldwide environmental consequences irrespective of their geographical origin. Consequently, fragmented national carbon markets may reduce domestic emissions while creating incentives for carbon leakage, regulatory arbitrage, or inconsistent accounting practices.

The Paris Agreement represents an important step toward greater international coordination by establishing common long-term climate objectives while allowing individual countries to determine nationally appropriate mitigation strategies through their Nationally Determined Contributions (NDCs).

Within this framework, Article 6 introduces new opportunities for international carbon market cooperation.

Unlike the Kyoto Protocol, which primarily allocated obligations among developed countries, the Paris Agreement seeks broader participation across developed and developing economies alike. This expansion substantially increases the potential scale of international carbon trading while simultaneously creating more complex governance challenges.

Particularly significant are the accounting rules intended to prevent double counting of internationally transferred mitigation outcomes.

If successfully implemented, these mechanisms may facilitate more integrated global carbon markets capable of reducing overall mitigation costs while preserving environmental integrity.

Nevertheless, important institutional questions remained unresolved at the beginning of 2022. Operational guidance regarding Article 6 had only recently been finalized during COP26 in Glasgow, and practical implementation would require considerable technical coordination among participating countries.

Consequently, the coming years were expected to represent a critical period in determining whether international carbon markets could evolve into an effective component of global climate governance.

5.3. Emerging Corporate Demand and the Expansion of Voluntary Markets

One of the most significant developments observed during the period leading to 2021 was the rapid expansion of voluntary carbon markets.

Unlike compliance markets driven by legal obligations, voluntary markets increasingly reflect corporate climate commitments, investor expectations, and consumer preferences regarding environmental sustainability.

Hundreds of multinational corporations announced carbon neutrality or net-zero objectives during the late 2010s. These commitments generated growing demand for high-quality carbon credits capable of compensating residual emissions while companies pursued broader decarbonization strategies.

This development significantly altered the role of voluntary carbon markets.

Historically, voluntary offsets represented relatively small niche markets primarily associated with corporate social responsibility initiatives.

By 2021, however, voluntary carbon markets had begun evolving into strategically important components of corporate climate governance.

Nevertheless, this rapid expansion also intensified concerns regarding offset quality, transparency, and credibility.

Increasing demand may create incentives for rapid credit issuance unless verification methodologies remain sufficiently rigorous. Consequently, future market development depends heavily upon strengthening certification standards, harmonizing accounting methodologies, and improving disclosure requirements.

Ultimately, the credibility of voluntary markets will depend less upon their rate of growth than upon the environmental integrity of the credits they generate.

5.4. Implications for Future Research

Although research concerning carbon markets has expanded considerably, several important knowledge gaps remained evident by the end of 2021.

First, relatively limited empirical evidence exists regarding the long-term innovation effects of sustained carbon pricing. Most existing studies analyse relatively short time horizons, whereas technological transitions often require decades to materialize fully.

Second, further investigation is needed concerning interactions between carbon markets and sustainable finance.

The rapid growth of Environmental, Social and Governance (ESG) investing, green bonds, climate disclosure standards, and corporate transition planning creates new institutional relationships that remain insufficiently explored within the environmental economics literature.

Third, future research should examine the integration of compliance and voluntary carbon markets.

Historically, these two systems developed largely independently. However, increasing corporate participation in climate mitigation may gradually reduce this separation, creating opportunities as well as governance challenges requiring further academic attention.

Fourth, additional comparative research is required concerning carbon market performance across developing economies.

Most empirical evidence continues to originate from Europe, North America, and a limited number of high-income countries. Expanding carbon pricing throughout emerging economies will likely require institutional adaptations reflecting different administrative capacities, energy systems, and economic structures.

Finally, increasing attention should be devoted to social acceptance.

Public support for carbon pricing depends not only upon environmental effectiveness but also upon perceptions of fairness, transparency, and distributional equity. Understanding these behavioural dimensions represents an increasingly important interdisciplinary research agenda involving economics, political science, psychology, and public policy.

5.5. Policy Implications

The evidence reviewed throughout this article suggests several practical implications for policymakers.

First, carbon markets should prioritize environmental credibility over rapid expansion. Robust monitoring, transparent governance, and progressively tightening emissions caps are essential for maintaining market confidence.

Second, auction-based allowance allocation appears preferable to prolonged free allocation, particularly when auction revenues are reinvested in low-carbon innovation, energy transition programs, and social compensation measures.

Third, price stability mechanisms deserve careful consideration. While preserving market flexibility, regulators should minimize excessive price volatility that may discourage long-term investment.

Fourth, carbon markets should be integrated with complementary climate policies rather than expected to achieve deep decarbonization independently.

Finally, international cooperation under the Paris Agreement should remain a strategic priority. Harmonized accounting standards, stronger verification procedures, and effective implementation of Article 6 will be essential for ensuring that future international carbon markets contribute meaningfully to global climate objectives.

Taken together, these findings reinforce the conclusion that carbon markets constitute one of the most promising market-based instruments currently available for climate mitigation. However, their long-term success will ultimately depend upon continuous institutional improvement, international cooperation, and sustained political commitment.

6. Conclusions

Climate change has progressively transformed from an environmental concern into one of the defining economic and policy challenges of the twenty-first century. As governments seek effective instruments capable of reducing greenhouse gas emissions while maintaining economic competitiveness, carbon markets have emerged as one of the principal market-based mechanisms supporting the global transition toward low-carbon development.

This article has reviewed the theoretical evolution, institutional architecture, practical implementation, and principal challenges associated with carbon markets, considering the scientific literature published in 2021. The review demonstrates that emissions trading systems have evolved considerably since the adoption of the Kyoto Protocol, moving from relatively experimental policy instruments toward increasingly sophisticated components of national and international climate governance.

The theoretical foundations of carbon markets remain firmly grounded in environmental economics. Building upon the concepts of externalities, property rights, and market efficiency developed by Pigou, Coase, Dales, Montgomery, and subsequent scholars, emissions trading seeks to internalize the social costs of greenhouse gas emissions while allowing firms to identify the least-cost pathways for emissions reduction. This combination of environmental certainty and economic flexibility continues to distinguish carbon markets from more prescriptive regulatory approaches.

The empirical evidence reviewed throughout this article generally supports the conclusion that well-designed carbon markets contribute to measurable emissions reductions. Experiences in the European Union, California, the Regional Greenhouse Gas Initiative, New Zealand, South Korea, and China indicate that emissions trading can successfully reduce greenhouse gas emissions while encouraging technological innovation and preserving economic efficiency. Although the magnitude of these effects varies across jurisdictions, the accumulated evidence suggests that carbon pricing has become an increasingly important component of climate policy.

Nevertheless, the review also highlights that carbon markets are not self-executing policy instruments. Their effectiveness depends fundamentally upon institutional quality, regulatory credibility, and continuous policy adaptation. Early experiences demonstrated that overly generous allowance allocation, insufficient monitoring systems, weak governance, and prolonged periods of low carbon prices significantly reduced market effectiveness. Conversely, subsequent reforms introducing stricter emissions caps, greater reliance on auctioning, improved monitoring and verification procedures, and market stabilization mechanisms substantially enhanced environmental performance.

One of the central findings emerging from the literature concerns the importance of policy learning. Rather than representing fixed institutional arrangements, successful carbon markets have evolved through continuous regulatory adjustment. The progressive reforms implemented within the European Union Emissions Trading System, together with the gradual development strategies adopted by California and China, illustrate the value of adaptive governance in improving long-term market performance.

The review further demonstrates that carbon markets function most effectively when integrated into broader climate policy frameworks. Renewable energy policies, industrial innovation strategies, sustainable finance initiatives, energy efficiency programs, and research and development investments complement carbon pricing by addressing additional market failures that emissions trading alone cannot fully resolve. Accordingly, carbon markets should not be viewed as isolated policy instruments but rather as one element within comprehensive decarbonization strategies.

Particular attention has also been devoted to the growing importance of voluntary carbon markets. Corporate commitments to carbon neutrality and net-zero emissions have generated unprecedented demand for carbon offsets, creating new opportunities for private-sector participation in climate mitigation. However, the credibility of these markets depends critically upon addressing persistent concerns regarding additionality, permanence, leakage, transparency, and double counting. Strengthening governance standards therefore represents a prerequisite for maintaining confidence among market participants and broader society.

The analysis likewise identifies several challenges that will shape the future evolution of carbon markets. International coordination under Article 6 of the Paris Agreement, the expansion of emissions trading into developing economies, greater harmonization of carbon accounting standards, and improved integration between compliance and voluntary markets all represent major priorities for policymakers and researchers alike.

From a theoretical perspective, future research should increasingly examine the interaction between carbon pricing and wider processes of technological transformation, sustainable finance, corporate climate governance, and behavioural change. While considerable progress has been achieved in evaluating the direct effects of emissions trading, important questions remain regarding long-term innovation dynamics, institutional interactions, and the political economy of climate policy.

In conclusion, the evidence available up to 2021 indicates that carbon markets constitute one of the most effective market-based instruments currently available for supporting greenhouse gas mitigation. Although they cannot independently achieve the deep structural transformations required to meet long-term climate objectives, well-designed carbon markets provide an essential economic framework capable of encouraging emissions reductions, stimulating technological innovation, and promoting cost-effective climate action. Their future success will ultimately depend upon maintaining environmental integrity, strengthening institutional governance, and fostering greater international cooperation within an increasingly interconnected global climate policy landscape.

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