Global Electricity-Carbon Market Nexus: A Systematic Review of Synergistic Efforts toward a Net-Zero Power Sector

Jingbo Wang[a], Jianfeng Wen[a], Chao Long[a], Bo Yang[b], Lin Jiang[a,*]

[a] Department of Electrical Engineering and Electronics, University of Liverpool, L69 3GJ Liverpool, UK.

[b] Faculty of Electric Power Engineering, Kunming University of Science and Technology, 650500 Kunming, China;

* Corresponding author: Lin Jiang, E-mail: ljiang@liverpool.ac.uk

Abstract: Climate change remains a critical global challenge, with power generation as the leading contributor to carbon dioxide emissions. Achieving the net-zero target demands not only a profound transformation of the power sector but also the effective synergy of electricity and carbon markets. Electricity-carbon synergy contributes to optimizing resource allocation and promoting green economic transformation with advancements in renewable energy and smart grid technologies. This study follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol to conduct a systematic review. It analyzes the nexus between electricity and carbon markets from a global perspective, examining their synergistic efforts to promote decarbonization in the power sector. A structured analytical framework is applied to assess the development and characteristics of electricity and carbon markets worldwide. Studies on electricity-carbon synergy are categorized by geographic region and evaluated using eleven key indicators, including covered sectors, models, methodologies, policy relevance, emission targets, identified strengths, and limitations. Internal and external factors influencing electricity-carbon synergy are assessed within a broader techno-socio-economic-political framework, identifying challenges and providing practical suggestions. This review combines a global comparative perspective with a multi-dimensional indicator framework, a synergy stage classification, and a comparative review of representative modeling approaches. The findings provide strategic insights and practical policy guidance for enhancing the design and implementation of integrated electricity-carbon market mechanisms, thereby supporting the development of net-zero power systems.

Keywords: Electricity-carbon synergy; Net-zero emissions; Power sector decarbonization; Emissions trading system; Electricity market; Carbon market

Abbreviations

AI	Artificial intelligence	**MRV**	measurement, reporting, and verification
APS	Announced Pledges Scenario	**NEM**	National Electricity Market
CBAM	Carbon Border Adjustment Mechanism	**PRISMA**	Preferred reporting items for systematic reviews and meta-analyses
CGE	Computable general equilibrium	**PV**	Photovoltaic
CO_2	Carbon dioxide	**RES**	Renewable energy sources
DiD	Difference-in-differences	**RGGI**	Regional Greenhouse Gas Initiative
ETS	Emissions trading systems	**RPS**	Renewable portfolio standards
EU	European Union	**SD**	System dynamics
EUA	European Union allowance	**STEPS**	Stated Policies Scenario

GDP	Gross domestic product	**SWOT**	Strengths-weaknesses-opportunities-threats
GHG	Greenhouse gas	**TGC**	Tradable green certificates
IEA	International Energy Agency	**UK**	United Kingdom
IoT	Internet of Things	**VAR**	Vector Autoregressive

1. Introduction

Climate change is a challenging global issue, driven primarily by greenhouse gas (GHG) emissions from human activities such as fossil fuel combustion and deforestation [1]. In response, the global community embraces a net-zero emissions roadmap [2] to achieve the target of limiting warming to 1.5°C as stipulated in the 2015 Paris Agreement [3]. Currently, power generation accounts for the largest source of global carbon dioxide (CO_2) emissions [4]. However, it also represents the leading sector in the transition to net-zero emissions, driven by the large-scale application of renewable energy such as solar and wind power [5]. Therefore, a well-designed energy transition and structural transformation within the power sector are crucial for reducing carbon emissions [6]. To meet the growing electricity demand while reducing power generation emissions, the exploitation of renewable energy continues to make steady progress in providing clean electricity [7]. With the substantial increase in renewable energy deployment [8], economic rebalancing, and the normalization of hydropower conditions, emissions from the global electricity market are predicted to decline in 2025 [9].

Global electricity decarbonization is shaped by interlinked trends in renewable deployment, carbon intensity, carbon-market policy, and regional energy structures. Figure 1 presents a comprehensive demonstration of global electricity transition trends. Figure 1 (a) shows the increase in electricity generation from various renewable energy sources (RES) between 2000 and 2024 [10], reflecting the accelerating deployment of clean energy technologies. Figure 1(b) displays per capita electricity generation by source for some representative countries in 2024 [11]. This breakdown illustrates the imbalance in electricity access, consumption levels, and the carbon intensity of generation mixes. Some economies are dominated by low-carbon sources (e.g., Sweden, Canada), while others remain heavily reliant on fossil fuels. Figure 1(c) presents the regional distribution of carbon intensity in 2024 [12], measured in grams of CO_2 equivalent per kilowatt-hour of electricity generated, highlighting

significant disparities in emission performance across global power systems. Figure 1(d), which depicts the global status of carbon pricing in 2024, will be further discussed in the following paragraph.

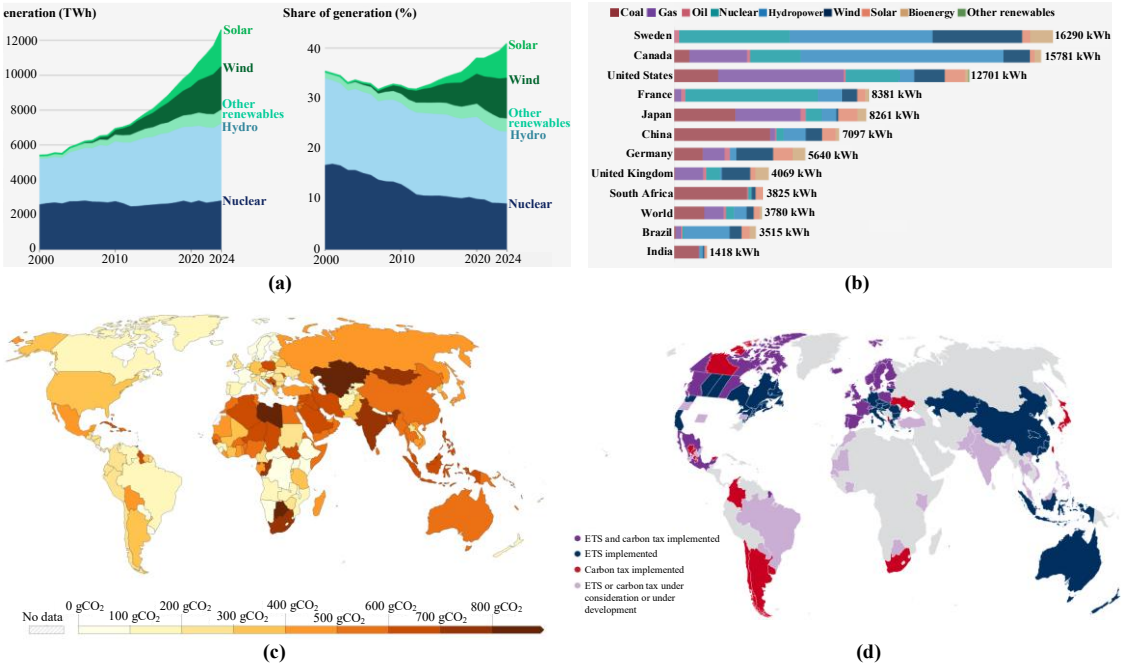

Fig. 1. Global electricity decarbonization patterns: generation trends, emission intensity, carbon pricing policies, and per capita structure. (a) Electricity generation by source from 2000 to 2024. (b) Per capita electricity generation by energy source in selected countries for 2024. (c) Regional carbon intensity of electricity generation in 2024. (d) Global status of carbon pricing implementation in 2024.

In parallel with the energy transition and technological advances, several market-oriented approaches have gained prominence [13,14]. These include emissions trading systems (ETS), carbon taxation, and carbon offsets, which serve as key tools to incentivize decarbonization. Together, they demonstrate both the urgency of climate mitigation and the importance of market-based mechanisms. The two most common carbon pricing mechanisms are cap-and-trade systems (also known as ETS) and carbon taxes. In a cap-and-trade scheme, a cap is set on total emissions, and allowances are allocated or auctioned to market participants who can trade them, thereby introducing market-based flexibility [15]. In contrast, carbon taxes impose a fixed price on carbon emissions, offering price certainty but lacking volume guarantees. A third hybrid approach combines elements of both, incorporating market stability mechanisms or floor/ceiling prices. Furthermore, even among ETS frameworks, heterogeneity exists in

coverage scope, allocation strategies, sectoral linkages, and market maturity. For instance, the EU ETS employs a centralized, phase-based approach, while China's national ETS initially covers only the power sector and lacks full market liquidity. Until now, regions with ETS in place represent 58% of the world's gross domestic product (GDP), and approximately one-third of the global population lives in areas where ETS are executed [16]. Based on the statistical data from the World Bank, the current ETS and carbon tax implementation status in 2024 is illustrated in Fig. 1 (d) [17]. It should be noted that all subfigures in Fig. 1 are compiled from publicly available datasets reported in the cited references, with minor formatting adjustments for visual consistency.

Although the electricity and carbon markets traditionally operate independently, they share a common target of reducing emissions. Both markets aim to promote a transition towards cleaner, more efficient, and lower-carbon energy consumption [18], upon which strong interdependency and mutual influence are created between the two markets [19]. This interaction, referred to as electricity-carbon synergy, describes how carbon price signals influence electricity dispatch, investment, and technology choices, while electricity market dynamics in turn shape carbon market outcomes. For instance, the production and consumption of power generation companies result in carbon emissions, while carbon pricing directly affects the costs of these companies [20]. Therefore, there is a significant correlation between the electricity and carbon markets regarding participants, transaction prices, and traded products [21]. The establishment of effective synergy between the two markets is not only desirable but also necessary. Without such coordination, several adverse consequences may arise. First, policy redundancy and regulatory conflicts can arise when electricity and carbon policies operate in parallel without alignment [22], resulting in overlapping instruments that increase compliance costs without enhancing effectiveness [23]. Second, distorted market signals may appear if electricity prices fail to fully internalize carbon costs or if carbon prices do not reflect electricity market dynamics [24]. Third, the misallocation of resources and inconsistent investment signals may discourage long-term planning and delay technological deployment, ultimately undermining decarbonization progress [25]. In contrast, strong electricity-carbon synergy ensures that carbon price signals are consistently transmitted into electricity operations and investment decisions. This synergy optimizes resource allocation, reduces institutional

frictions, and creates a mutually reinforcing mechanism that accelerates the low-carbon transformation of the power system [25]. Effective integration of these two markets is therefore essential for promoting clean energy development, enhancing policy efficiency, and achieving net-zero goals. As electricity and carbon markets continue to improve in response to changes in the economic and energy landscape, their mutual influence and synergistic effects are expected to become increasingly significant.

In recent years, as global ETS gradually expands [26], there has been growing research and discussion regarding electricity-carbon synergy. Countries worldwide are also committed to designing synergistic mechanisms of electricity-carbon markets as this promotes energy structure optimization, incentivizes low-carbon technologies, and drives green economic transformation. Previous research on their coupling has produced valuable insights, but most studies are confined to specific regions or single policy frameworks, limiting their generalizability. Moreover, only fragmented indicator systems are employed that hinder cross-study comparison, and few provide integrated analyses that simultaneously address technical, economic, policy, and institutional dimensions. Furthermore, there is a lack of a comprehensive comparison of modeling approaches and their implications for market design. As a result, the global picture of how electricity and carbon markets interact, the maturity of their synergies, and the common challenges they face remains incomplete. Targeted insights to support coordinated progress toward net-zero power systems are still inadequate.

Therefore, this work addresses these gaps through a systematic review conducted in full accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol. Building on an extensive screening of global literature and market data, this work provides a multi-dimensional comparative assessment that integrates four distinctive elements: (i) an eleven-indicator evaluation framework enabling structured cross-regional comparison; (ii) a synergy stage classification that captures the maturity and adaptability of integrated systems; (iii) a comparison of diverse modeling approaches and their policy implications; and (iv) a strengths-weaknesses-opportunities-threats (SWOT) based analysis to contextualize drivers, bottlenecks, and risks within a broader techno-socio-economic-political framework. By combining these components, the review delivers strategic insights and forward-looking recommendations to guide market designers, policymakers, and researchers in

advancing effective electricity-carbon market integration under the net-zero agenda. The rest of this work is organized as follows: Section 2 outlines the systematic review methodology, including the literature screening process and the analytical framework adopted. Section 3 provides an overview of the development status of electricity and carbon markets worldwide. Section 4 undertakes a comparative analysis of the existing research regarding electricity-carbon market synergy using diverse evaluation indicators. In Section 5, SWOT analysis is employed to identify the internal and external factors influencing market dynamics, upon which strategic prospects are proposed for future development. Section 6 concludes the review.

2. Materials and Methodology

This section introduces the materials and methodologies adopted for literature screening and analysis.

2.1 Review screening method

This work employs a systematic review approach in strict accordance with the PRISMA guidelines [27]. PRISMA is an internationally recognized protocol that offers a standardized, transparent, and replicable process for literature identification, screening, eligibility assessment, and inclusion [28]. In contrast to a narrative review, this approach provides higher rigor and reproducibility. In general, studies in this review are selected, screened, and appraised through a four-stage PRISMA process.

First, the literature search is conducted across three major academic databases: Web of Science, Scopus, and Google Scholar, covering publications from 2014 to 2024. This timeframe aligns with a decade of global policy evolution in carbon trading and electricity market liberalization. To capture studies focusing on the intersection of power systems and carbon governance, a set of core keywords is employed, including "electricity-carbon", "power-carbon", and "electricity and carbon market". These search terms are used in combination with Boolean operators to broaden the scope and retrieve literature from interdisciplinary domains such as energy economics, environmental policy, engineering systems, and climate governance.

A total of 9565 records are initially retrieved across the three platforms: 2854 from Web of Science, 3051 from Scopus, and 3660 from Google Scholar. Specific exclusion criteria are applied in line with PRISMA stages, as follows:

- Screening stage: Duplicate records and non-English publications are removed. Titles and abstracts are further examined for initial screening. After this step, 4776 studies remain. Then, studies are excluded if they are out of scope (e.g., addressing only electricity or only carbon markets without interaction) or if they are commentary pieces, editorials, or non-peer-reviewed sources. After this stage, 1118 studies remain.
- Eligibility stage: Full texts are reviewed to assess relevance, methodological detail, and data transparency. Records are excluded when full-text access is unavailable or when the study lacks methodological detail, analytical depth, relevant datasets for electricity-carbon synergy, or fails to provide findings relevant to electricity-carbon synergy. After this step, 116 studies remain.
- Final inclusion: Final inclusion requires that studies meet all screening and eligibility criteria, with additional confirmation through reference cross-checking. To ensure evidence credibility, the journal impact factor is employed as an auxiliary quality filter, removing studies published in journals with an impact factor below 3. Ultimately, 85 studies are included.

These stage-specific removals and their corresponding record counts are clearly demonstrated in Fig. 2. This multi-stage, protocol-driven methodology enables systematic inclusion of high-quality literature and supports a coherent and evidence-based review. To improve analytical robustness, only studies that explicitly articulate the research objectives and provide sufficient methodological transparency are included. Such transparency mainly involves model descriptions, simulation parameters, or clearly defined policy scenarios. Special attention is paid to comparative studies that employ formal modeling approaches. Examples include computable general equilibrium (CGE), system dynamics (SD), econometric analysis, regional policy evaluations, and scenario-based forecasts, all of which align with the study's objective of cross-regional comparison. Additionally, official statistical data, regulatory reports, and white papers from government agencies and international organizations, e.g., the International Energy Agency (IEA) and World Bank, are used to support regional assessments and policy context evaluations.

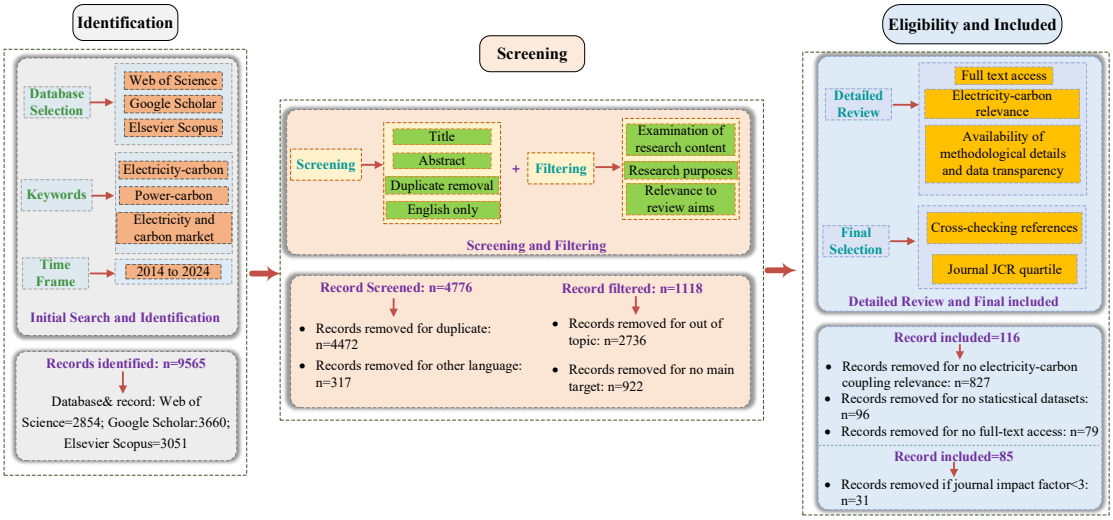

Fig. 2. Literature screening and selection process based on the PRISMA framework.

Given the review's global comparative scope, the number of eligible studies varies substantially across regions. For certain regions, such as the United Kingdom (UK), the final set of studies meeting the inclusion criteria is limited. This disparity reflects the current distribution of peer-reviewed research rather than author selection bias. To address this, this review supplements the analysis with relevant contextual sources such as government reports and market design documents to ensure a balanced comparison.

2.2 Analytical framework

Following the screening of literature, this review applies a multi-layered analytical framework designed to systematically evaluate existing contributions and propose forward-looking solutions. The adopted structured analytical framework in this study comprises four interlinked modules: (i) a contextual review, which draws on literature, datasets, and official reports to examine the status and progress of global electricity and carbon markets; (ii) an integrated literature analysis, which combines an eleven-indicator evaluation matrix with a comparative discussion of modeling approaches and synergy stage comparisons across regions; (iii) a SWOT analysis to contextualize findings within broader techno-socio-economic-political settings; and (iv) solutions and perspectives for future developments, which turn the analytical results into strategic recommendations. As illustrated in Fig. 3, four modules are sequentially connected to ensure that the review's conclusions are supported by transparent selection criteria,

objective evaluation standards, and reproducible analysis procedures.

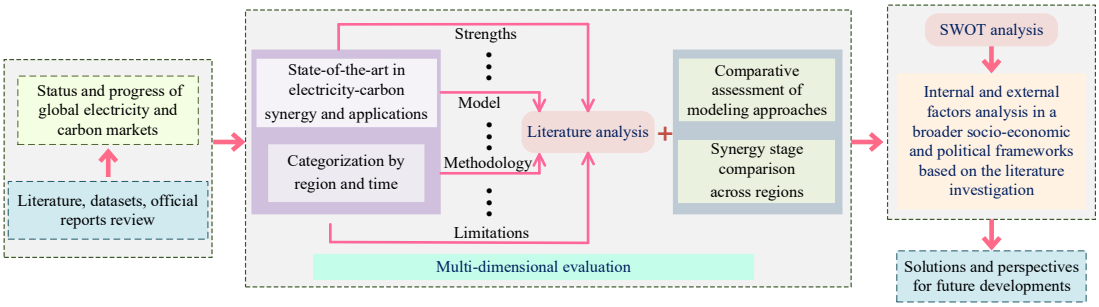

Fig. 3. Overall analytical framework of this review.

First, the contextual review lays the empirical foundation by tracing the evolution and current status of electricity and carbon markets across regions, including policy trajectories, carbon pricing mechanisms, electricity market structures, and decarbonization roadmaps. Next, an integrated analysis of electricity-carbon market synergy research is conducted. To reflect global diversity, studies are categorized into three geographic groups, i.e., Europe, Asia Pacific, and North America, and analyzed chronologically within each group to capture temporal trends. Within each group, the evaluation framework considers eleven critical indicators, including modeling methods, sectoral coverage, geographic scope, policy orientation, and the advantages and disadvantages identified in each study. In addition, modeling approaches and synergy development stages are compared across regions to capture methodological diversity and contextual differences. Furthermore, a SWOT diagnostic framework is incorporated to evaluate internal and external factors affecting electricity-carbon synergy within broader socio-technical and political contexts. Finally, based on the preceding analyses, this review proposes practical suggestions from multiple perspectives for future research and policy design. These suggestions aim to address key risks and promote coordinated development between electricity and carbon markets.

3. Global Electricity and Carbon Markets

This section delves into the current development status of global electricity and carbon markets, which adopts a region-focused introduction, emphasizing areas with carbon markets implemented.

3.1 Electricity market status

3.1.1 Asia Pacific

By 2025, Asia is expected to account for half of the world's electricity consumption, and one-third of global electricity will be consumed by China [29,30]. However, due to its heavy reliance on coal, China has the highest CO_2 intensity of electricity generation among the analyzed regions, at 590 g CO_2/kWh in 2023, compared to a global average of 455 g CO_2/kWh [4]. Over the past two decades, China has rapidly transformed its electricity market from a state-controlled model to one encouraging competition and market pricing. China is now the largest producer of renewable energy, particularly solar and wind [31], installing a record 130 GW of solar photovoltaic (PV) in the first three quarters of 2023 [4]. New policies aim to further boost renewable energy growth and issue carbon offsets, such as green electricity certificates [32]. Australia's electricity market is notable for its high penetration of renewable energy, especially solar power. The National Electricity Market (NEM), covering the eastern and southern states, is regarded as one of the most sophisticated electricity markets worldwide. In 2023, renewable energy capacity approached 6 GW, with South Australia achieving a milestone where wind and solar exceeded 75% of its energy mix [4]. Australia's energy transition is driven by policies aimed at reducing emissions and increasing renewable energy capacity [33], with targets now reflected in national law. Other Asian countries, such as South Korea, Japan, and India also vigorously promote renewable energy and improve electricity market structures.

3.1.2 Europe

Europe is at the forefront of sustainable electricity market development, beginning with liberalization reforms in the late 1990s [34]. These reforms promoted cross-border electricity trade and independent regulatory frameworks [35]. The implementation of the Clean Energy for All Europeans Package further strengthens the regulatory framework to support the deployment of renewable energy and grid modernization [36]. Currently, the European electricity market is characterized by a high degree of market coupling and integration. In March 2023, the European Commission proposed reforms to the current electricity market rules. The aim was to promote renewable energy, protect against market manipulation, and enhance price stability [37]. However, challenges remain, such as declining demand and the need for

substantial grid upgrades. For the UK, electricity demand fell by 3.4% in 2023 [4], with renewable generation falling by about 5% [8], as electricity consumption slowed due to high energy prices and weak economic growth. In 2022, the UK became a net electricity exporter for the first time [38] as continental Europe purchased cheaper UK electricity. However, this reversed in 2023, with net imports of about 25 TWh. A series of reforms has been launched for the electricity market to incentivize decarbonization, improve security, and ensure affordable prices [39].

3.1.3 North America

The United States has a diverse electricity market that includes both regulated and deregulated regions. Independent system operators and regional transmission organizations manage grid operations and wholesale markets [40]. Significant progress has been achieved in integrating wind and solar energy, driven by federal incentives like the production and investment tax credit and state renewable portfolio standards (RPS) [40]. Its grid infrastructure is continuously being upgraded to accommodate more renewables, but challenges such as grid reliability and transmission bottlenecks persist [41]. Canada's electricity market is unique with its abundant hydroelectric resources [42], heavily regulated by provincial governments. Provinces like Ontario and Alberta have liberalized their markets to increase competition. Canada is expanding its renewable capacity in wind, solar, and biomass to cut GHG emissions and move towards a low-carbon economy [43].

3.2 Carbon market status

This subsection focuses on global carbon markets, detailing their current status and progress with a focus on regions that have established robust carbon trading systems. Based on the statistical data from the International Carbon Action Partnership [16], as of 2024, there are currently 36 ETS in operation globally with another 22 systems in various stages of consideration and development, as shown in Fig. 4(a). These systems collectively account for 18% of global GHG emissions.

3.2.1 Asia Pacific

China's national ETS commenced operation in 2021 and is the largest ETS in the world,

covering approximately 4.5 Gt CO_2 emissions annually from the power sector [44]. Based on the report from IEA, China's carbon market employs an intensity-based design with free allocation, as demonstrated in Fig. 4(b). Over the last two years, China's carbon market has established a stable framework, with rising transaction prices, expanding trading volumes, and improved liquidity. In February 2024, the State Council issued new regulations to support industry expansion, long-term cap setting, and the development of stronger ETS [16]. Australia's carbon market history includes the 2012-2014 carbon pricing mechanism, replaced by the emissions reduction fund and the safeguard mechanism [45]. This structure incentivizes practices that reduce or sequester carbon emissions and sets baselines for large emitters. Australia's carbon market has focused on regulatory measures and market-based incentives to drive emission reductions in recent years [16]. For South Korea [46], its national ETS was launched in 2015, covering power generation, industry, construction, waste, and transport sectors, making it the first nationwide cap-and-trade system in Asia [47].

3.2.2 Europe

The European Union (EU) is the first economic entity to initiate a market for trading CO_2 emissions, setting a leading example in using market mechanisms to incentivize corporate emission reductions [48]. Launched in 2005, the EU ETS is the most mature carbon market globally, aiming to reduce GHG emissions through a cap-and-trade scheme [49]. Based on the EU ETS handbook [50], the core allocation mechanism combines free allocation and auctioning, with the proportion of auctioning increasing annually, as shown in Fig. 4(c).

The EU ETS has progressed through several phases, with the fourth phase spanning 2021 to 2030 [51]. This phase currently covers about 45% of the EU's GHG emissions, including power generation, manufacturing, and aviation [52]. It caps the total amount of emissions for covered facilities, allowing companies to receive or purchase emission allowances and trade them as needed. EU ETS has successfully reduced extensive emissions, especially in the power sector, and has influenced the design of other carbon markets worldwide. However, it also faces challenges such as market volatility and concerns over the competitiveness of international trade industries. Following Brexit, the UK established its own emissions trading scheme (UK ETS) in January 2021, aligning with the UK's net-zero by 2050 target and mirroring the EU

ETS structure [53]. The UK ETS covers energy-intensive industries, power generation, and aviation, accounting for about one-third of the UK's GHG emissions.

3.2.3 North America

The United States lacks a nationwide carbon market, but regional and state-level initiatives are crucial for carbon pricing and emission reduction. The Regional Greenhouse Gas Initiative (RGGI) [54], started in 2009, involves Northeastern and Mid-Atlantic states in a cap-and-trade program targeting power sector emissions. RGGI has effectively reduced emissions by auctioning allowances and reinvesting proceeds in energy efficiency and renewable projects. California's cap-and-trade program was launched in 2013, covering power generation [55], industrial processes, and transportation fuels. It links with Quebec's system, creating a broader North American carbon market and aiming to reduce California's GHG emissions to 40% below 1990 levels by 2030. Figure 4(d) illustrates the electricity decarbonization trajectory of the United States. It shows the relationship between low-emissions electricity generation and the share of electricity in total final energy consumption in the United States from 2010 to 2035, based on IEA data [56]. Under both the Stated Policies Scenario (STEPS) and the Announced Pledges Scenario (APS), the share of clean electricity is expected to rise significantly, particularly beyond 2030.

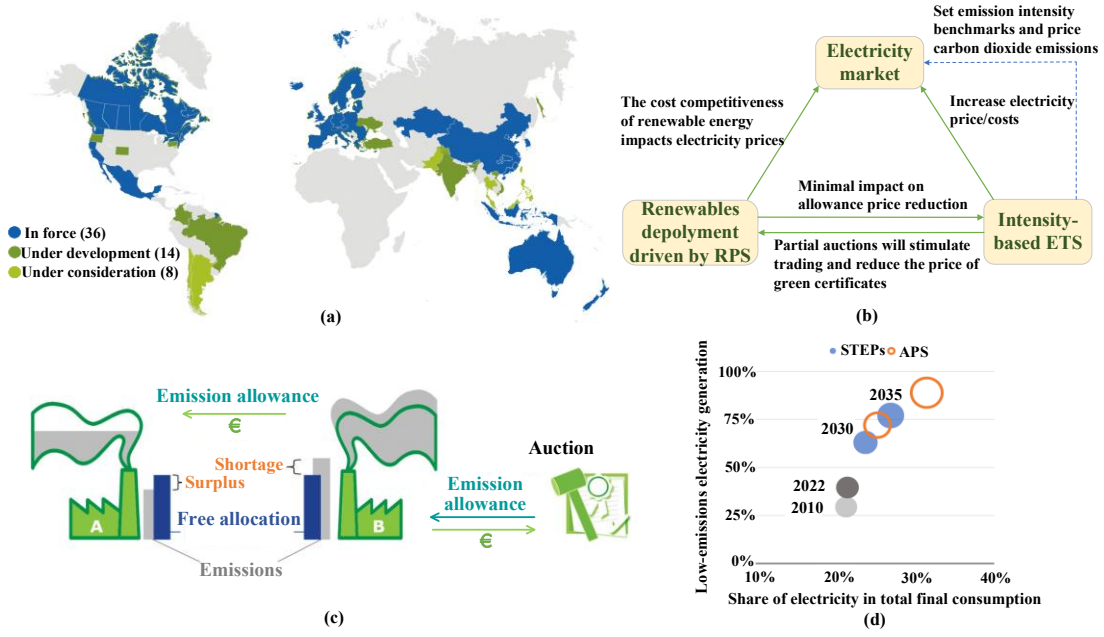

Fig. 4. Global and regional ETS development and execution mechanisms. (a). Global ETS development status as of 2024. (b). China's intensity-based ETS mechanism. (c). Core structure of the European Union ETS. (d). Projected evolution of electricity

decarbonization in the United States under the STEPS and the APS from 2010 to 2035.

Canada's carbon pricing strategy combines federal and provincial initiatives, balancing environmental goals with economic considerations. Established in 2016, the Pan-Canadian framework on clean growth and climate change outlined the national strategy, aiming to reduce GHG emissions to 30% below 2005 levels by 2030 [57].

4. Comparative Analysis of Global Electricity-Carbon Synergy

Synergistic mechanisms between electricity and carbon markets refer to bidirectional interactions. Carbon price signals influence electricity market operations, while electricity-market dynamics shape carbon market outcomes. In this coupled framework, the carbon market internalizes the environmental cost of power generation by assigning a price to emissions. This mechanism directly affects electricity dispatch, investment decisions, and long-term technology choices. Conversely, electricity market outcomes, such as generation mix, demand profiles, and network constraints, feed back into carbon market performance by determining the actual volume of emissions subject to pricing and trading. This reciprocal influence creates a feedback loop. It can either reinforce or weaken decarbonization incentives, depending on market design, regulatory alignment, and system maturity. Understanding these mechanisms is essential for identifying policy levers, avoiding unintended market distortions, and ensuring that both markets contribute effectively to emission reduction targets.

Building on this theoretical foundation, this section examines how synergistic mechanisms display across different regional contexts, highlighting their importance in promoting global energy transformation and emission reduction goals. First, electricity-carbon synergy can accelerate power sector decarbonization by providing economic incentives for reducing emissions and increasing renewable energy deployment. This is particularly crucial for high-energy-consuming industries [58], where market-based mechanisms can collaboratively increase carbon emission costs and improve renewable energy accessibility. In addition, such coupling contributes to optimizing resource allocation [59], improving market efficiency, and promoting technological innovation [60]. Ultimately, the synergistic development of electricity-carbon markets is essential for the green economic transformation, ensuring a

sustainable and resilient energy future. In this section, for a structured and systematic analysis, existing studies are categorized into three groups based on their geographic focus: Europe, Asia Pacific, and North America. In addition, tables featuring eleven critical evaluation indicators are provided under each category, allowing readers to gain a comparative understanding of electricity-carbon synergy across different regions.

4.1 Electricity-Carbon Synergy in Asia Pacific

This section explores the development and research progress on electricity-carbon synergy in the Asia Pacific region, focusing on China and Australia.

4.1.1 China

China's ETS started relatively late but is developing rapidly. Substantial efforts target electricity-carbon synergy to meet the “dual carbon” goals of carbon neutrality and carbon peaking [61]. Initiatives such as green electricity trading [62], green certificates [63], and the China Certified Emission Reduction Program [64] are designed to integrate renewable energy and incentivize carbon reduction. In reference [65], a two-stage type-2 fuzzy stochastic programming method is devised for planning clean energy production in Shanghai, indicating that integrating ETS and green certificates can significantly reduce CO_2 emissions. Study [66] assesses the impacts of China's national ETS on the economy, energy, and environment, suggesting a GDP reduction of 0.19% to 1.44%, a significant electricity price increase, and linear CO_2 emission reduction over time. Based on an analysis of the relationship between electricity, fossil fuel, and carbon market prices in Guangdong, literature [67] recommends implementing more stringent ETS benchmarks for allocating emissions allowances in the power sector. In literature [68], carbon emission quota prices and PV power revenue are linked for analysis, suggesting this can achieve grid parity for PV power by 2023, two years ahead of schedule. Moreover, work [69] evaluates the ETS's effectiveness in promoting renewable energy from 2004 to 2019, demonstrating a 2.326% increase in non-fossil energy power generation in pilot regions, especially for hydropower and PV power. References [70] and [71] utilize SD models to validate that coupling TGCs and ETS systems can optimize power supply and slow the growth rate of CO_2 emissions.

Moreover, in work [72], the effects of RPS and electricity market reforms on ETS are examined, showing that market reforms enhance ETS by increasing carbon emission rights demand and trading volume. Study [73] evaluates the carbon market's effects on energy intensity and carbon emission efficiency in 30 provinces from 2000 to 2017, indicating a 14.14% reduction in energy intensity and a 4.21% increase in carbon emission efficiency in pilot regions. Meanwhile, literature [74] reveals that China's rate-based ETS from 2015 to 2030 promotes power sector decarbonization and lowers carbon intensities of coal and gas power plants. Reference [75] examines the importance of optimizing energy trade-offs and interactions between China's carbon and electricity markets using a stochastic clearing model. In work [76], a spatial Durbin model is employed to verify that ETS can significantly promote renewable capacity and investment with spatial spillover effects. Besides, study [77] indicates that RPS and carbon trading policies together optimize the power supply and promote green certificate trading. Reference [78] predicts significant rises in carbon and electricity prices by 2025 due to the pass-through of carbon costs. Work [79] indicates that integrating provincial electricity markets can reduce abatement costs by 60% under a regional-market scenario. In work [80], a multi-stage stochastic programming model is utilized to verify that higher carbon prices promote shifts from coal to renewable energy, effectively reducing emissions.

Reference [81] suggests that a rolling horizon optimization strategy with initial carbon allowance allocation enhances carbon emission reductions by adjusting strategies and optimizing distribution. In work [82], the synergistic effects of ETS and TGC in China's electricity market are investigated, indicating that this coordinated mechanism enhances market efficiency, reduces emissions, and promotes renewable investments. In literature [83], how China's output-based ETS can facilitate the decarbonization of its power sector is evaluated, indicating it can peak CO_2 emissions before 2030 with a 13% reduction by 2035. Study [84] reveals that joint implementation of RPS and ETS mechanisms significantly enhances market efficiency and renewable energy investment while reducing emissions. Moreover, a bi-level optimization model is devised in reference [85] to validate that integrating electricity, ETS, and TGC markets can improve efficiency, promote renewable investments, and support carbon reduction targets. Reference [86] evaluates various output-based ETS configurations, indicating that China’s ETS accelerates emissions peak and adoption of carbon capture and storage with

minimal cost impact. Lastly, work [87] highlights the importance of coordinated electricity-carbon market mechanisms in reducing transaction costs, stimulating energy conservation, and promoting renewable energy investments.

4.1.2 Australia

Australia promotes electricity-carbon synergy through strategies like renewable energy targets, carbon pricing mechanisms, and emissions reduction funds [88]. In work [89], ETS scenarios on electricity prices, emissions, and economic impacts are analyzed, suggesting ETS can reduce emissions and promote renewables but raise electricity prices, requiring more balanced policies. Reference [90] explores the anti-correlation between emissions and spot prices in Australia's NEM. The research suggests that dynamic carbon pricing and market tariffs are necessary to align the operation of energy storage systems with emission reduction goals. Moreover, study [91] investigates the evolution of CO_2 emission intensities in Australia's NEM from 2009 to 2018. Based on a time-series regression model, the study examines the impact of electricity demand, changes in the generation mix, and carbon pricing mechanisms on emission intensities. The findings highlight that renewable energy deployment and the reduction of coal-fired generation are critical factors in decreasing emission intensities.

The reviewed studies in this section collectively demonstrate the complex interplay between carbon and electricity markets, emphasizing the need for integrated policy and market mechanisms to promote effective decarbonization. Table 1 provides a comprehensive analysis of the reviewed studies on electricity-carbon synergy across the Asia Pacific region.

4.2 Electricity-Carbon Synergy in Europe

This subsection investigates the studies on electricity-carbon synergy within Europe.

4.2.1 EU region

The EU region implemented ETS relatively early, providing the theoretical foundation and practical experience for research on electricity-carbon synergy. With the commencement of the EU ETS phase III, relevant research has gradually increased. Heinrichs et al. [92] demonstrate that integrating road transport into the EU ETS more efficiently reduces CO_2 emissions than technical measures, with minimal impact on electricity demand and CO_2 prices.

Table 1. Comparison of electricity-carbon synergy studies across the Asia Pacific region

Classification	Reference	Year	Geographic Scope	Covered sectors	Temporal Scope	Model	Methodology	Policy Implications	Emission reduction targets	Strengths	Limitations
China	Suo et al. [65]	2017	Shanghai	Electricity, Industry	2009-2015	Two-stage stochastic programming model	Two-stage type-2 fuzzy stochastic programming	Integration of ETS and TGC schemes	Local mitigation goals in Shanghai	Integrate multiple uncertainties and policy mechanisms	Limited broader applicability to other regions
	Lin et al. [66]	2019	China	Electricity	2017-2030	Dynamic recursive CGE model	CGE based policy and scenario analysis	Annual decline factor of 0.5% for carbon allowances	Peak CO_2 emissions by 2030	Incorporate economic, energy, and environmental impacts	Rely on assumptions and parameters of the CGE model
	Liu et al. [67]	2020	Guangdong Province	Electricity, Industry	2016-2019	Vector error correction model	Econometric analysis	Power sector liberalization; stricter benchmarks for ETS	China's 2030 “carbon peak” target	Comprehensive analysis of price interactions	Limited broader applicability to other regions
	Song et al. [68]	2020	China	Electricity	2020-2023	Carbon-electricity linkage model	Empirical analysis combining life cycle cost theory	Carbon-electricity linkage trading to promote PV grid parity	Not specifically quantified	Propose an innovative carbon-electricity linkage mechanism	Assume no free quota in carbon markets
	Liu et al. [69]	2021	China	Electricity	2004-2019	Difference-in-differences (DiD) model	Model-based policy evaluation	ETS can promote non-fossil energy development	Peak CO_2 emissions by 2030	Robustness tests using long-term panel data	Data limitations and assumptions
	Feng et al. [70]	2021	China	Electricity	2020-2026	SD model	Model-based policy synergy analysis	Joint implementation of TGC and ETS systems	Peak CO_2 emissions by 2030	Combine multiple market mechanisms and policy impacts	Potential policy redundancy between TGC and ETS
	Yu et al.	2021	China	Electricity	2018-2035	SD model	Model-based	Co-implementation	Peak CO_2 emissions	Comprehensive	Not distinguish the

[71]						scenario analysis	of TGC and ETS	by 2030	market integration and scenario analysis	investment between specific types of renewable energy
Ying et al. [72]	2021	China	Electricity	2020-2030	SD model	Model-based market synergy analysis	Coordinated policy implementation of ETS and RPS	Reduce CO_2 emission per unit of GDP by 60%-65% compared to 2005	Multiple policy scenarios and their impact on ETS	Assume certain policy implementation and market responses
Zhou et al. [73]	2022	30 provinces (excluding Hong Kong, Macao, Taiwan, and Tibet)	Electricity, Industry	2000-2017	DiD model	Super-epsilon-based measure method	Enhance government support, improve regional cooperation, and continue market reform	China's 2030 and 2060 “dual carbon” targets	Novel use of super-epsilon-based measure model for emission efficiency measurement	The time of data used in this study is short
Yu et al. [74]	2022	30 provinces (excluding Hong Kong, Macao, Taiwan, and Tibet)	Electricity	2015-2030	Multi-regional dynamic CGE model	CGE and benchmark method	Consider regional disparities and incorporate supportive measures accordingly	China's 2030 and 2060 “dual carbon” targets	Incorporation of different power generation technologies and their impacts	Lack of available data; modeling assumptions; ignore state-controlled price and power market reform
Jiang et al. [75]	2022	Jiangsu Province	Electricity	2020	Stochastic electricity market clearing model	Mixed-integer nonlinear programming and generalized benders decomposition	Dynamic carbon emission intensity considerations	Carbon emission intensity decreases annually	Integrate dynamic carbon emission intensity into the evaluation of energy trade-offs	The lag effect of policies is ignored
Zhang et al. [76]	2022	30 provinces in China	Electricity, Industry,	2006-2018	Spatial Durbin and mediation models	Spatial econometric and mediation	Optimize ETS design to enhance	Not specifically quantified	Identify spatial spillover effects of	Not all regional heterogeneities are

			Heat			analysis	regional coordination		ETS and key mediation paths	fully considered
Wang et al. [77]	2022	China	Electricity	2019-2020	Bi-level decision-making model,	Numerical experiment	Coordinated RPS and carbon trading policies	China's 2030 “carbon peak” target	Bi-level decision-making model to optimize power market strategies	Without extensive empirical validation
Wang et al. [78]	2023	China	Electricity	July-December, 2021	Threshold regression and SD models	Empirical and scenario analysis	Improve carbon cost pass-through mechanisms	China's 2030 “carbon peak” target	Evaluate the regional disparities and sector-specific impacts of ETS in the power sector	China's certified emission reduction program is not included
Song et al. [79]	2023	Five southern provinces in China	Electricity	2018	Partial equilibrium model	Model-based scenario analysis	Integrate provincial electricity markets can enhance the cost-effectiveness of carbon pricing	China's 2030 and 2060 “dual carbon” targets	Detailed assessment of the potential impacts of carbon market integration	Focus on specific regions
Huang et al. [80]	2023	China	Electricity	2020-2050	Uncertainty theory-based model	Model-based numerical simulation	Need for stable and predictable carbon pricing mechanisms	China's 2030 and 2060 “dual carbon” targets	More realistic assessment of policy impacts on investment decisions	Real-world dynamics are not fully considered
Feng et al. [81]	2023	China	Electricity	2020-2025	Stackelberg game based carbon allowance allocation model	Rolling optimization	Establish pre-carbon trading mechanisms and multiple performance periods	China’s 2060 “carbon neutrality” target	Effectively track enterprises' emission reductions and adjust allowance allocation	The data used are static to a certain extent
Chang et al. [82]	2023	China	Electricity	2020-2030	Interactive SD model	Dynamic equilibrium process	Integration of ETS and TGC	China's 2030 and 2060 “dual carbon”	Interaction analysis between multiple	Model assumptions make accurate

						analysis		targets	market mechanisms	predictions challenging
	Zhang et al. [83]	2023	China	Electricity	2020-2035	Renewable electricity planning and operation model	Model-based scenario analysis	Need for technology-specific benchmarks and free allocation adjustments	China's 2030 and 2060 “dual carbon” targets	Detailed consideration of regional distributional effects	Limited focus on fuel-switching away from coal
	Lei et al. [84]	2023	China	Electricity	2020-2030	SD model	Model-based scenarios and sensitivity analysis	Higher quotas and lower benchmark prices optimize the power structure	China's 2030 and 2060 “dual carbon” targets	Real-world data-based analysis of the interaction between RPS and ETS	Low market activity and trading frequency in the TGC market
	Li et al. [85]	2024	China	Electricity, Heat	2020-2030	CGE model	CGE based scenario analysis	Higher carbon prices and stringent benchmarks	China's 2030 and 2060 “dual carbon” targets	Detailed analysis of the impact of ETS and TGC coupling on the power sector	Market equilibrium analysis only considers a limited number of individuals
	Zhang et al. [86]	2024	China	Electricity, Heat	2020-2035	Renewable electricity planning and operation model	Econometric and scenario analysis	Need for a progressively stringent benchmark in the ETS system	China's 2030 “carbon peak” target	Analyze benchmark tightening effects on different power technologies and regions	Assume no allowance banking and ignore influence of electricity consumers
	Zhu et al. [87]	2024	China	Electricity	Not specified	Multi-agent behavioral decision-making model	Policy coordination analysis	Policies and incentives to promote electricity-carbon market trading efficiency	China's 2030 and 2060 “dual carbon” targets	Simulation and analysis of market coordination and policy impacts	Assume perfect compliance and participation across sectors
Australia	Meng et al.	2018	Australia	Electricity,	2020	Integrated CGE	Model-based	Design and	Reduce CO_2	Combine CGE and	Dynamic market

	[89]			Industry, Transport, Agriculture		and electricity model	sectoral and macroeconomic analysis	implementation of an ETS for the energy sector	emissions by 5% from 2000 levels	electricity models to assess the impact of an ETS	responses are not fully captured
	Bardwell et al. [90]	2023	Australia	Electricity	2013-2021	Least-cost dispatch model of NEM	NEM dispatch engine	Apply dynamic carbon incentives and market tariffs	Australia's net zero target	Detailed intra-day and inter-day analysis of emissions and price data	Not fully account for long-term changes in the electricity market
	Ming et al. [91]	2024	Australia	Electricity	2009-2018	Time-series regression model	Econometric analysis	Effectiveness of climate and energy policies in reducing emissions	Reduce CO_2 emissions by 26%-28% from 2000 levels	Capture short-term and long-term trends and policy impacts	Limited to the specific time frame

Meanwhile, reference [93] analyzes the price determinants of EU allowance (EUA) returns, highlighting exchange-specific effects across European electricity markets and the role of local markets in shaping carbon prices. Study [94] analyzes various electricity production scenarios, suggesting that high CO_2 prices alone can achieve power sector decarbonization without obligatory renewable energy targets, indicating a potential policy shift. References [95] and [96] explore the impact of EUA markets on stock returns and volatility of electricity companies, showing that carbon-intensive firms suffer while confirming significant volatility from energy to carbon markets. Furthermore, literature [97] adds that coal has the highest correlation with carbon prices. In work [98], it is verified that the impact of carbon markets on electricity markets weakens over time, suggesting higher carbon prices and dynamic allowance adjustments.

For regional focus, reference [99] investigates the impact of the EU ETS on the Southeast European regional electricity markets, suggesting expanding the EU ETS to neighboring countries to mitigate carbon leakage and improve efficacy. Studies [100] and [101] reveal that increases in carbon prices positively affect tradable green certificates (TGC) in the Swedish-Norwegian system, and Brent oil prices significantly influence carbon prices. Within the context of Germany's electricity sector, research [102] reveals that emission abatement under the EU ETS from 2005 to 2015 is positive but limited, suggesting the need for a unilateral flexible cap to ensure more consistent reduction. Focusing on the impact of EU ETS and renewable energy targets on windfall profits in the power sector, study [103] verifies that higher carbon prices and renewable energy penetration lead to significant windfall profits for power producers. Moreover, literature [104] compares the cost-effectiveness of renewable energy subsidy mechanisms in the EU power market by 2030, emphasizing that higher CO_2 prices can reduce cost differences between mechanisms. Study [105] examines the impact of coal phase-out policies on the EU ETS, indicating significant suppression of EUA prices. Reference [106], based on partial-equilibrium modeling, highlights that substantial CO_2 price increases are necessary to achieve an 80% emission reduction by 2050. This finding illustrates the crucial role of carbon pricing in long-term decarbonization of the European electricity system.

Study [107] finds that in the Greek market, carbon cost pass-through to electricity prices is about 60% when carbon prices are below 15 €/tCO_2e under EU ETS Phase III. Meanwhile,

reference [108] indicates that carbon prices will rise significantly with renewable energy expansion, enhancing economic feasibility and complementarity. Work [109] shows that tightening EU ETS targets accelerates power sector decarbonization, with renewable energy significantly contributing by 2030, despite moderate system cost increases. Reference [110] indicates that the EU ETS promotes short-term fuel switching but may hinder long-term renewable investments, suggesting the need for policy adjustments. In addition, study [111] explains varying results from different electricity market models due to differences in fuel switching, renewable investments, and power plant decommissioning. Besides, literature [112] identifies electricity demand and air temperature as significant predictors of emissions allowance prices, with non-linear relationships observed. In work [113], results show that EU ETS allowance banking smooths costs and pass-through to electricity prices from 2008 to 2018 is complete, especially in France. Study [114] suggests that short-term positive carbon market shocks benefit the renewable energy market in Europe, though this effect fades over time. Lastly, reference [115] finds that renewable energy exports reduce CO_2 emissions by replacing carbon-intensive generation in importing countries, stressing the need for coordinated renewable integration and effective carbon pricing.

4.2.2 UK

The UK is gradually reforming and localizing the UK ETS to align with its national climate goals while maintaining compatibility with the EU ETS for cross-border trade. Reference [116] investigates how generation costs, including gas prices, carbon prices, and exchange rates, are transferred to electricity wholesale prices in Great Britain from 2015 to 2018. The Brexit referendum and the EU ETS reform significantly impact electricity costs, with Brexit alone increasing annual household bills by £41. Moreover, study [117] investigates the effects of increasing interconnection between Great Britain and its European neighbors. It validates that by 2025 and 2030, the UK will shift from a net importer to a net exporter of electricity, influenced by carbon pricing and generation backgrounds. Work [118] explores the impact of the UK carbon price support, introduced in 2013, on carbon emissions in the power sector. Based on the synthetic control method, the study finds that carbon price support could lead to a significant reduction in CO_2 emissions, decreasing by 20.5% to 26% per year from 2013 to

2017. Literature [119] examines the dual impacts of renewable support schemes on consumers and the electricity sector in the UK, suggesting significant benefits by reducing fossil fuel imports and ETS emissions.

Although relatively few studies address the UK electricity-carbon market synergy, existing research emphasizes early adoption of carbon pricing through the UK ETS and the carbon price support mechanism [120]. These studies also highlight integration with the wholesale market and divergence from the EU ETS after Brexit. Carbon price volatility and renewable integration challenges remain central themes, suggesting that despite its mature policy framework, operational complexities persist. The UK power sector's carbon price signal directly affects the merit order, accelerating coal plant retirements and influencing interconnector flows with continental Europe [121]. Supplementary analysis of UK government reports and market data indicates that electricity-carbon coupling has contributed to a sustained decline in power sector emissions [121,122]. However, regional grid constraints and balancing costs require further examination in future research. To facilitate readers in making a comprehensive and intuitive comparison of various studies on electricity-carbon synergy in the European region, analysis results based on eleven critical evaluation indicators are tabulated in Table 2.

4.3 Electricity-Carbon Synergy in North America

This section investigates the research to enhance electricity-carbon synergy across the North American region, with a focus on the United States and Canada.

4.3.1 The United States

The United States promotes electricity-carbon synergy through initiatives like the RGGI and California's cap-and-trade program to reduce emissions and boost renewable energy. In literature [123], a regression analysis on California's real-time electricity market is conducted, indicating a significant and time-varying CO_2 premium that incentivizes renewable energy development. This suggests that the cap-and-trade program effectively internalizes CO_2 costs and promotes decarbonization in California's electricity market.

Table 2. Comparison of electricity-carbon synergy studies across the European region

Classification	Reference	Year	Geographic Scope	Covered sectors	Temporal Scope	Model	Methodology	Policy Implications	Emission reduction targets	Strengths	Limitations
EU region	Heinrichs et al. [92]	2014	Germany	Electricity, Transport	2010-2030	Coupled PERSEUS-EU and COMIT models	Policy scenario analysis	Support integration of transport into the EU ETS	Reduce CO_2 emissions by 25% between 2010 and 2030	Comprehensive analysis of integrating transport into the EU ETS	Volatile feed-in of renewable energies is simplified
	Boersen et al. [93]	2014	EU region	Electricity	2008-2012	Threshold GARCH model	Econometric analysis	Enhance market stability and reduce volatility in carbon prices	EU ETS Phase II target	Detailed econometric analysis considering multiple variables	The data set for validation is not complete
	Gawlik et al. [94]	2015	Poland	Electricity	2011-2050	TIMES-PL model	Energy system modeling analysis	Re-evaluate obligatory renewables targets if high CO_2 prices suffice	Reduce GHG emissions by 80-95% below 1990 levels	Diverse scenario analysis and robust mathematical modeling	Assumptions based on specific fuel price forecasts
	Tian et al. [95]	2016	EU region	Electricity, Industry	2005-2007, 2008-2012	DCC multivariate GARCH model	Ordinary least squares regression and time-series analysis	Incentive for green investments; proper allowance allocation	Reduce CO_2 emissions by 8% from 1990 levels	Analysis of stock return dynamics concerning carbon market impacts	Limited to historical data, which may not fully capture future market dynamics
	Balcilar et al. [96]	2016	EU region	Electricity, Industry	2008-2014	MS-DCC-GARCH model	Model-based empirical analysis	Carbon risk management and policy regulations	EU ETS Phase III and Kyoto Protocol targets	Comprehensive analysis of volatility spillovers and hedging strategies	Limited generalizability across different market conditions
	Zhang et al. [97]	2016	EU region	Electricity, Industry	2008-2014	DCC-GARCH and Baba, Engle, Kraft	Empirical analysis	Monitor volatility spillover effects to	EU ETS Phase III target	Advanced econometric models	Limited to a specific time frame

					and Kroner GARCH model		stabilize markets			
Zhu et al. [98]	2017	EU region	Electricity	2005-2016	Dynamic multiscale interactions model	Bivariate empirical mode decomposition	Raise carbon prices; implement dynamic emission allowance adjustments	EU ETS Phase I, II, and III targets	Multiscale analysis and robust empirical analysis	Complexity may limit generalizability
Višković et al. [99]	2017	South-East Europe	Electricity	2005-2016	22-node network market model	Bottom-up partial equilibrium framework	Consider carbon leakage in policy design	Reduce GHG emissions by 20% below 1990 levels	Quantify carbon leakage and impacts	Long-term capacity adjustments are not considered
Schusser et al. [100]	2018	Sweden-Norway and Nord Pool	Electricity	2005-2015	Vector Autoregressive (VAR) model	Multivariate VAR approach	Coordination between the carbon and green certificate markets	Reduce GHG emissions by 20% compared to 1990 levels	Provide empirical evidence on the interaction between multiple market-based instruments	Long-term effects and broader geographic applicability are not involved
Ji et al. [101]	2018	EU region	Electricity, Industry	2006-2017	VAR model	Rolling-windows method	Manage price and risk spillovers	EU ETS targets, aligning with commitment periods	Discuss static and dynamic connectedness in the energy-carbon system	Long-term impacts need further exploration
Schäfer et al. [102]	2019	Germany	Electricity	2005-2015	Linear regression model	Counterfactual scenario analysis	Intensity-based cap to address demand-side effects	EU ETS Phase III target	Precise estimation of ETS-induced emission reductions	Limited generalizability to other regions
Hobbie et al. [103]	2019	EU region	Electricity	2014-2024	Fundamental electricity transshipment model	Linear optimization	EU ETS reforms and adjustments to the auction-based system	EU ETS Phase III target	Insights into the structural factors affecting windfall profits	Ignore long-term investment responses

Özdemir et al. [104]	2020	EU region	Electricity	2030	Market equilibrium model	Model-based policy and scenario analysis	Balance use of capacity and energy subsidies	65% renewable energy electricity share by 2030	Highlight trade-offs between different subsidy mechanisms	Assume static capacities
Anke et al. [105]	2020	EU region	Electricity, Industry	2014-2030	Fundamental electricity transshipment model	Fundamental optimization model-based analysis	EUA cancellations to mitigate waterbed effects; flexible emission caps	EU 2030 target	Insights into the interplay between coal phase-outs and EUA prices	Sensitivity to EUA price assumptions
Müsgens et al. [106]	2020	EU region	Electricity	2020-2050	Two coupled partial equilibrium models	Partial equilibrium analysis	Renewable energy subsidies should continue alongside the EU ETS	Reduce CO_2 emissions by 80% from 1990 levels	Detailed comparison of ETS-only and subsidy-driven scenarios	Ignore short-term market fluctuations or political changes
Andrianesis et al. [107]	2021	Greece	Electricity	2013-2020	Day-ahead and mid-term scheduling model	Mixed integer linear programming	Combination of high carbon prices and low gas prices	EU ETS Phase III target	Quantitative analysis of emissions cost pass-through in a pool-based market	Limited generalizability to other regions
Anke et al. [108]	2021	EU region	Electricity	2030	European power market model	Model-based scenario analysis	Coordination between national and EU-wide policies	Reduce GHG emissions by 40% below 1990 levels	Scenario-based analysis of RES and EU ETS interactions	Model assumptions may ignore real-world complexities
Pietzcker et al. [109]	2021	EU region	Electricity, Transport, Heat	2018-2057	Long-term investment model for the electricity sector of Europe	Linear optimization analysis	Stricter EU ETS targets in line with the European Green Deal	Tightening from a 43% to a 63% emissions reduction by 2030	Integration of power sector and ETS dynamics for scenario analyses	Assume continuity and stability in policy and market conditions
Bersani et al. [110]	2022	EU region	Electricity, Industry	2020-2030	Market equilibrium model	Analytical analysis and numerical simulations	Highlight the potential weaknesses of ETS on renewable investments	EU 2030 target	Identify ETS's impact on energy-mix decisions and long-term	Model's assumptions and simplifications

										profitability	
	Ruhnau et al. [111]	2022	EU region	Electricity	2016-2030	Five numerical power sector models	Model comparison experiment	Need for model transparency and effective carbon pricing policies	Emissions reductions of 36-57% compared to 2016 levels	Reveal significant insights into model-induced uncertainties	Assumptions may neglect real-world complexities
	Eslahi et al. [112]	2023	EU region	Electricity	2005-2019	Extreme gradient boosting based modeling	Predictive modeling analysis	Enhance understanding of the structural determinants of carbon prices	Not specifically quantified	Examine how electricity demand and weather affect spot prices of EUA	Limited to specific weather variables and regions
	Bai et al. [113]	2023	EU region	Electricity, Industry, Heat	2008-2018	Theoretical dynamic model	Empirical analysis	Highlight the importance of policy mechanisms like the market stability reserve	EU ETS Phase II and III targets	New empirical strategy for estimating allowance cost pass-through	Potential biases due to unobserved technology markups
	Qiu et al. [114]	2023	EU region and UK	Electricity	2014-2021	Time varying parameter VAR model	Impulse response analysis	Stabilize and synergize these markets	EU targets for carbon neutrality by 2050	Dynamic analysis of market interactions	Not all types of renewable energy are covered, and potential spillover effects among them are ignored
	Romano et al. [115]	2024	EU region	Electricity	2018-2040	Antares generation dispatch model	Leave-one-out methodology	Coordinated renewable energy integration and carbon pricing	Net-zero CO_2 emissions by 2040 for the European electricity system	Assessment of cross-border impacts and interdependencies	Inaccuracy in battery storage capacity modeling
UK	Guo et al.	2019	Great Britain	Electricity	2015-2018	Vector error	Theoretical and	Coordinated carbon	Reduce GHG	Detailed	Market behavior

[116]					correction model and Cournot competition model	empirical analysis	pricing and political regulations on electricity costs	emissions by 40% below 1990 levels	consideration of significant political events	assumptions and exchange rate impacts
MacIver et al. [117]	2021	Great Britain, EU region	Electricity, Industry	2020, 2025, and 2030	ANTARES electricity market modeling tool	Scenario analysis	Harmonized carbon pricing across Europe	Reduce GHG emissions by 80-95% below 1990 levels	Comprehensive scenario-based analysis and robust market modeling	Ignore real-world complexities and future uncertainties
Leroutier et al. [118]	2022	UK, EU region	Electricity, Industry	2005-2017	Counterfactual analysis model	Synthetic control method	Apply effective carbon pricing to reduce emissions	2050 net-zero target	Robust empirical analysis and clear policy implications	Not estimate heterogeneous treatment effects across plants
Shao et al. [119]	2024	UK	Electricity, Industry	2006-2020	Techno-economic model	Comparative framework analysis	Distinguish between consumer and sectoral impacts in policy evaluations	Reduction in CO_2 emissions by 55% from 1990 levels	Account for both consumer costs and sectoral benefits	Not directly address economic costs or health impacts

Reference [124] investigates the impact of the RGGI within the Pennsylvania-New Jersey-Maryland electricity market using a DiD quasi-experimental design. The study finds that RGGI reduced CO_2 emissions by about 19.1% (equivalent to 6.22 million short tons per year), with reductions arising mainly from coal decline and emission leakage rather than genuine fuel switching. Reference [54] evaluates the impact of the RGGI program on fossil-fuel consumption and CO_2 emissions in the power sector. The study suggests that it significantly reduces coal and natural-gas consumption and cuts emissions by 1.3 million tons annually in participating states. Study [125] adopts a DiD approach with firm-level data (2009-2017), which reveals that RGGI reduces emissions in the electricity market by 13.43%, highlighting the need for broader participation to sustain emission reductions. Regarding New York's electricity market, the potential impacts of a carbon adder on it are validated using a CGE model [126], suggesting it provides strong incentives for renewable energy generation and effectively reduces CO_2 emissions. Study [127] analyzes New Jersey re-joining RGGI, indicating it significantly reduces CO_2 emissions and boosts economic growth, especially in the renewable energy sector. In work [128], the effectiveness of RGGI in reducing emissions is evaluated by comparing RGGI-regulated power plants with similar unregulated plants from 2008 to 2015, demonstrating significant CO_2 reductions and improved emission efficiency in RGGI plants.

4.3.2 Canada

Canada promotes electricity-carbon synergy through federal and provincial measures, including the federal carbon tax, provincial cap-and-trade systems, and significant renewable energy investments [129]. Study [130] investigates pathways to low-cost decarbonization of Canada's electricity sector using a linear programming optimization model. Results indicate that carbon prices must exceed \$50/tonne CO_2e to drive significant emissions reductions, recommending strategies like expanding wind power and enhancing inter-provincial transmission lines. In reference [131], the potential for emissions leakage under various carbon pricing scenarios and the impact of cross-border electricity trade with the United States are investigated. The study reveals that without leakage containment measures, Canadian emissions reduction could be offset by increased emissions from the United States. Moreover, literature [132] evaluates the impact of carbon management policies on Canada's electricity sector,

showing that current policies will reduce emissions by 38% by 2025 and 40% by 2030. In addition, work [133] develops a model to assess the environmental impacts of transitioning Canada's electricity system to low-carbon pathways, analyzing three policy scenarios with varying carbon tax levels and GHG emission targets. The findings indicate that higher carbon taxes can significantly reduce both direct and indirect emissions from the electricity sector. Finally, Table 3 provides readers with a critical comparison of various studies focused on electricity-carbon synergy in North America.

4.4 Comparative Analysis of Methods and Synergy Development

4.4.1 Modeling approaches and methodological insights

Building upon the preceding regional analysis, it is evident that electricity-carbon market studies not only vary by geographic and institutional context, but also by the modeling frameworks used to explore them. These differences in methodological design critically shape the scope, findings, and policy relevance of the research. To complement the thematic and regional assessment, this section compares and classifies the dominant methods employed in the reviewed literature, identifying their analytical roles, strengths, limitations, and implications for policy and system design.

Five main methodological types emerge across the review: econometric models, equilibrium-based models, techno-economic optimization frameworks, SD, and hybrid/integrated approaches. Table 4 summarizes their key characteristics and relevance. While some approaches emphasize causality and empirical inference, others are designed to capture macroeconomic spillovers, power system behavior, or policy feedback loops. A growing number of studies adopt integrated models that link multiple domains, aiming to produce more comprehensive and context-aware assessments of electricity-carbon market interactions. These methodological choices directly influence the types of insights generated. For instance, econometric models are well-suited for evaluating short-term policy impacts using historical data but are often limited in their ability to project long-term system transformation. In contrast, general equilibrium models provide a broad view of carbon pricing implications for economic structure and welfare but abstract away from operational constraints in electricity systems.

Table 3. Comparison of electricity-carbon synergy studies across the North American region

Classification	Reference	Year	Geographic Scope	Covered sectors	Temporal Scope	Model	Methodology	Policy Implications	Emission reduction targets	Strengths	Limitations
The United States	Woo et al. [123]	2018	California	Electricity	2011-2016	Full network model using real-time market data	Regression analysis	California's cap-and-trade program can internalize CO_2 costs and influence electricity prices	California's goal for reducing in-state CO_2 emissions	Robust evidence on the CO_2 cost pass-through using numerous market data	Not fully account for longer-term market dynamics
	Huang et al. [124]	2019	Northeastern United States	Electricity	2009-2013	Econometric model-based on DiD	Quasi-experimental analysis	RGGI reduces CO_2 mainly through coal decline and leakage	The goals of RGGI to stabilize and reduce CO_2 emissions	Strong causal design; robust evidence on ETS effects and leakage	Limited on long-term structural change; leakage concerns remain
	Yan [54]	2021	RGGI participating states	Electricity	2001-2018	DiD model	Econometric analysis	Need for a national cap-and-trade program	The goal of reducing CO_2 emissions within the participating states	State-level analysis over a long period	Not fully separate the impact of other concurrent policies and events
	Zhou et al. [125]	2021	RGGI participating states	Electricity, Heat	2009-2017	DiD model	DiD based analysis	Broader policy coordination to mitigate leakage	RGGI's goal to reduce CO_2 emissions in the power sector	Firm-level analysis capturing specific mechanisms of emission reductions	Endogeneity issues and the limitations of using static data
	Akın-Olçum et al. [126]	2021	New York	Electricity	2016-2029	CGE model	Model-based economic and environmental analysis	Provide carbon adders as incentives for RES generation and decarbonization	Reduce GHG emissions by 40% by 2030 and 80% by 2050	Analyze carbon adder's impacts on emissions, electricity prices, and welfare	Not capture long-term dynamic adjustments in the energy market
	Birur et al.	2022	New Jersey	Electricity,	2020-2030	Power system	Aurora electric	Emphasize the need	New Jersey's goals	Power system and	Simplify the

	[127]			Industry, Heat, Transport, Agriculture, Forestry		investment and dispatch model; CGE model	modeling software and CGE based analysis	for addressing emissions leakage	to reduce GHG emissions by 50% by 2030 and 80% by 2050	economic modeling to assess multi-dimensional impacts	complexity of regional power market interactions
	Cong et al. [128]	2022	Northeastern states in RGGI	Electricity	2008-2015	DiD model	Model-based covariance and comparative analysis	Empirical evidence of the superiority of mandatory carbon regulations	Reduce 2030 GHG emissions to 40% of the 1990 level	Robust comparison using matched plant pairs and rigorous statistical analysis	Costs are not observed; ignore possible spillover effects
Canada	Dolter et al. [130]	2018	Canada	Electricity	2025	Linear programming optimization model	Model-based analysis	Investments in wind power and new inter-provincial transmission lines	Reduce GHG emissions by 30% below 2005 levels by 2030	High geographic and temporal resolution of the model	Assume fixed electricity demand
	Bistline et al. [131]	2020	Canada and cross-border regions in the United States	Electricity	2020-2050	North American regional economy, greenhouse gas, and energy model	Integrated model analysis	Need for leakage containment measures	Net-zero emissions by 2050	Spatial and temporal analysis integrating cross-border trade dynamics	Not capture broader economic impacts
	Arjmand et al. [132]	2022	Canada	Electricity	2018-2050	Multi-period optimization-based capacity expansion model	Canadian opportunities for planning and production of electricity resources	Higher carbon taxes and additional policies to achieve deep decarbonization	Canada's targets of 40-45% reduction below 2005 levels by 2030 and net-zero emissions by 2050	High spatial and temporal resolution with comprehensive policy assessment	Parameter uncertainties affect planning model results
	Chen et al. [133]	2023	Canada	Electricity, Economic	2020-2050	Stochastic optimization-driven input-output model	Factorial analysis; environmentally-extended input-output analysis	Higher carbon taxes and avoid carbon leakage	40-45% reduction below 2005 levels by 2030 and net-zero emissions by 2050	Assessment of both direct and indirect environmental impacts	Sectoral aggregation uncertainty

Table 4. Methodological typology of electricity-carbon synergy studies

Method type	Core features	Common applications	Strengths	Limitations	Policy relevance
Econometric/ empirical models [54,69,73,91,100-102,114, 124,125]	DiD, panel data models, regression, VAR	ETS impact, carbon price pass-through, policy evaluation	Empirical causality; interpretable; real data	Require exogeneity assumptions; weak system interaction modeling	Short-term impact of ETS/policy; carbon price elasticity
General/partial equilibrium models [66,74,85,89,126,127]	CGE based models	Carbon tax and ETS macro effects	Captures sectoral trade-offs, economy-wide feedback	Rigid structure; lack real-world constraints	Carbon leakage, cost-benefit, welfare effects
Optimization &simulation models [80,90,110,115,127, 132]	Dispatch, expansion planning, market-clearing simulation	System operation under carbon cost; investment path optimization	Realistic techno-economic modeling; captures grid behavior	Static behavior; underestimate policy adaptation	Generation mix, system cost, RES integration
SD Models [70-72,78,82,84]	Feedback loops, delays, dynamic complexity	Long-term transition dynamics; policy feedback analysis	Captures time-lag, inertia, unintended consequences	Low empirical precision; difficult to validate	Long-run adaptability, policy design stability
Hybrid or integrated approaches [92,97,106,111,116, 131]	Coupling of models or databases across domains	Cross-level policy analysis; scenario building	Comprehensive scope; balances realism and causal insight	Complex to implement; high data and computation needs	Multi-dimensional planning and resilience evaluation

Optimization and simulation tools are effective in representing power dispatch, generation mix, and investment planning under carbon constraints but may lack responsiveness to behavioral or institutional dynamics. Meanwhile, SD models offer an alternative lens to capture non-linear feedback, path dependencies, and policy lock-ins, despite their relatively limited application in this domain. These differences also have implications for interpreting the results of the reviewed literature. Studies using econometric models may overemphasize short-term or retrospective policy effects, while those based on equilibrium or simulation approaches could understate institutional frictions or behavioral inertia. Consequently, model selection should align with the specific research or policy question and be complemented by robustness checks and transparent assumptions. As electricity and carbon markets become more integrated, future research would benefit from hybrid methodological strategies that combine empirical validation, scenario-based planning, and system feedback analysis. This integrative modeling perspective is crucial to informing policies that are not only cost-effective but also adaptive, equitable, and resilient under future uncertainties. Beyond policy implications, these methodological insights also point to priorities for academic inquiry. Key areas include advancing interoperability

between economic, engineering, and policy models and conducting comparative assessments across markets with different maturity levels to validate the generalizability of findings. Another priority is improving the transparency and accessibility of cross-regional datasets, which is essential for enhancing reproducibility and supporting collaborative research.

4.4.2 Regional synergy assessment

Beyond modeling approaches, how different regions are positioned along the electricity-carbon synergy is critical for contextualizing both technical modeling outcomes and policy recommendations. Building on the aforementioned literature analyses and recent developments, this study divides electricity-carbon market synergies into four progressive stages. At the lowest level, no synergy describes a situation where carbon pricing and electricity markets function independently. In this case, no observable influence occurs on pricing, dispatch, or investment patterns. Weak synergy emerges when some linkages are present, but carbon price signals are only partially and inconsistently reflected in electricity market operations or investment decisions. Static synergy refers to a more established connection in which the two markets are formally integrated. However, the transmission of carbon price signals into operational and investment decisions remains limited or delayed, and feedback mechanisms function with reduced intensity. Dynamic synergy represents the highest level of integration. At this stage, carbon pricing signals are fully internalized within electricity market operations. They actively influence dispatch schedules, shape investment portfolios, and foster cross-sectoral coordination under mature institutional arrangements and well-functioning feedback loops.

Classification of regions into these stages is based on evidence from Sections 3 to 4.3. It is corroborated by official market data and policy evaluations from authoritative institutions, including the IEA [2,4,8,29,30,44,47,56], World Bank [17], and International Carbon Action Partnership [134]. The assessment considers four main aspects. First, the degree to which carbon costs are transmitted to electricity prices. Second, the extent and stability of regulatory alignment between the two markets. Third, the maturity and liquidity of trading platforms. Fourth, the strength of policy frameworks in providing consistent investment signals. Applying these criteria to each jurisdiction ensures that the resulting stage assignments are not subjective but rather supported by measurable indicators and documented in multiple independent sources.

The European Union stands out as the most advanced example, having reached the stage of dynamic synergy. In this context, the EU ETS enables carbon price signals to be fully internalized within electricity markets [135]. Power producers adjust dispatch and investment decisions accordingly, with green electricity gaining implicit value through carbon cost pass-through [136]. This is supported by relatively mature market rules, high liquidity, and forward-looking regulatory designs. Modeling studies from Europe in this review typically adopt CGE or hybrid simulation frameworks, which effectively capture cross-sectoral interactions and feedback loops. Moreover, policy adaptability and investment signaling are strong, though full integration with sectors like transport and buildings is still evolving.

North America, by contrast, remains in a state of static synergy. While regional carbon markets such as the RGGI and California's cap-and-trade exist, their interaction with electricity markets is often constrained by jurisdictional fragmentation and limited real-time price adjustment [137]. DiD-based empirical studies dominate, reflecting the region’s focus on evaluating historical policy interventions. Despite some progress, the feedback mechanism between carbon and electricity prices remains weak, and long-term investment signals vary significantly across states and provinces [138].

China is currently in a weak synergy stage, with a national ETS under development and early-stage reforms in electricity market liberalization [139]. The carbon costs have not yet been fully incorporated into electricity pricing. Instead, administrative pricing dominates, and carbon signals are not systematically reflected in generation dispatch or investment behavior [140]. Optimization and simulation-based models are commonly used to test policy scenarios, but further institutional reform is needed to build robust carbon-electricity linkages. Table 5 summarizes these findings by presenting a cross-regional comparison of synergy stages and key indicators related to policy adaptability, investment incentives, and cross-sectoral coordination. It is noted that the feedback mechanism in Table 5 reflects the degree to which carbon pricing signals (e.g., allowance costs) are transmitted to the electricity market.

Despite the expansion of ETS worldwide, the global carbon market remains highly fragmented, with limited interlinkages across jurisdictions. Variations in carbon price levels, allocation methods, measurement, reporting, and verification (MRV) standards, and sectoral coverage create substantial barriers to integration [141]. The EU’s Carbon Border Adjustment

Mechanism (CBAM) exemplifies both the opportunities and tensions arising from this weak connectivity. By aligning the carbon cost of imports with the EU ETS, CBAM aims to prevent carbon leakage and protect domestic industry competitiveness, yet its unilateral design risks reinforcing market segmentation [142]. Exporters to the EU without comparable carbon pricing face higher effective costs, potentially incentivizing the creation of parallel schemes or bilateral equivalence agreements, but also sparking disputes over trade fairness and WTO compatibility.

Current CBAM's impact on global carbon market convergence will depend on its role as either a bridge or a barrier. On one hand, it could stimulate harmonization by encouraging trading partners to adopt ETSs compatible with the EU's system [143], thereby expanding the global carbon pricing network. On the other hand, its administrative complexity, data requirements, and exclusion of certain sectors may lock in asymmetries between linked and non-linked markets [142]. Without broader coordination, such as mutual recognition of allowances or standardized MRV protocols, CBAM's influence may remain regional rather than global, leaving the carbon market as a patchwork of isolated systems. To mitigate these risks, future efforts should focus on fostering multilateral dialogue to align carbon pricing principles. In addition, interoperable MRV and allowance recognition frameworks should be explored. Over time, such measures could transform CBAM from a unilateral trade instrument into a stepping stone for broader carbon market integration.

Table 5. Regional electricity-carbon synergy stages with characteristics

Region	Synergy stage	Supporting characteristics	Feedback mechanism	Policy adaptability	Cross-sectoral coordination	Investment signal
EU	Dynamic	Cross-border electricity-carbon integration; mature ETS with feedback loops; coordinated electricity-carbon policy design	Strong	High	Moderate to High	Strong
North America	Static	Mature but fragmented ETS; limited coordination with electricity markets; lack of integrated design	Weak	Moderate	Low-Moderate	Moderate
China	Weak	ETS under construction; electricity market reform incomplete; minimal linkage between carbon and electricity systems	Weak	Emerging	Low	Weak

5. SWOT Analysis and Outlooks

5.1 SWOT analysis

To complement the descriptive and comparative findings, a SWOT analysis [144] is applied to investigate key internal and external factors influencing the integration of electricity and carbon markets. The method is appropriate because electricity-carbon synergy is shaped not only by technical modeling outcomes but also by institutional, policy, and market dynamics. These dimensions require a holistic assessment framework. In this review, the SWOT process follows a structured, evidence-based approach.

First, strengths and weaknesses (internal factors) are identified from the peer-reviewed studies retained through the PRISMA-based screening process, focusing on inherent attributes of systems or policies, such as regulatory structures, technological capacity, and market maturity. Second, opportunities and threats (external factors) are derived from broader political, socio-economic, and environmental drivers or constraints. These are captured through global policy documents, statistical datasets, and reports from institutions such as the IEA, the World Bank, and the International Carbon Action Partnership. All candidate factors are collected from the literature and supporting reports, then categorized into the four SWOT elements based on explicit inclusion criteria: (i) direct relevance to electricity-carbon market coupling; (ii) empirical or modeled evidence; and (iii) clear link to policy or market implications. Cross-checking across multiple sources ensures that no quadrant is dominated by single-study findings. This systematic process ensures the robustness of the SWOT results and their direct link to the strategic recommendations in Section 6. Figure 5 visualizes the resulting SWOT matrix based on the above procedure.

Strengths are evident in the increasing political commitment and institutional support from major economies. For instance, the EU ETS achieved a record emissions drop in 2023, led by the power sector's shift to wind, solar, and gas. By early 2024, emissions had fallen 47.6% below 2005 levels, putting the EU ETS well on track to meet its 2030 target of a 62% reduction [135]. Technological progress in grid digitalization and storage systems has also enhanced power system flexibility, facilitating the integration of intermittent renewables. However,

weaknesses persist. Several developing countries lack fully operational carbon markets or robust carbon accounting systems. Moreover, electricity price formation in many regions remains administratively controlled, limiting the pass-through of carbon costs to end-users and distorting market incentives for decarbonization. Infrastructure bottlenecks, particularly in aging grid systems, further constrain renewable energy penetration in high-demand regions. On the opportunity side, global carbon market coverage is expanding rapidly. As of January 2025, 38 ETSs are in force globally, with 20 more under development or consideration, covering 19% of global GHG emissions [135]. Innovation-driven market expansion, combined with increasing green finance flows and international cooperation, opens new prospects for scalable, cross-border emissions trading frameworks.

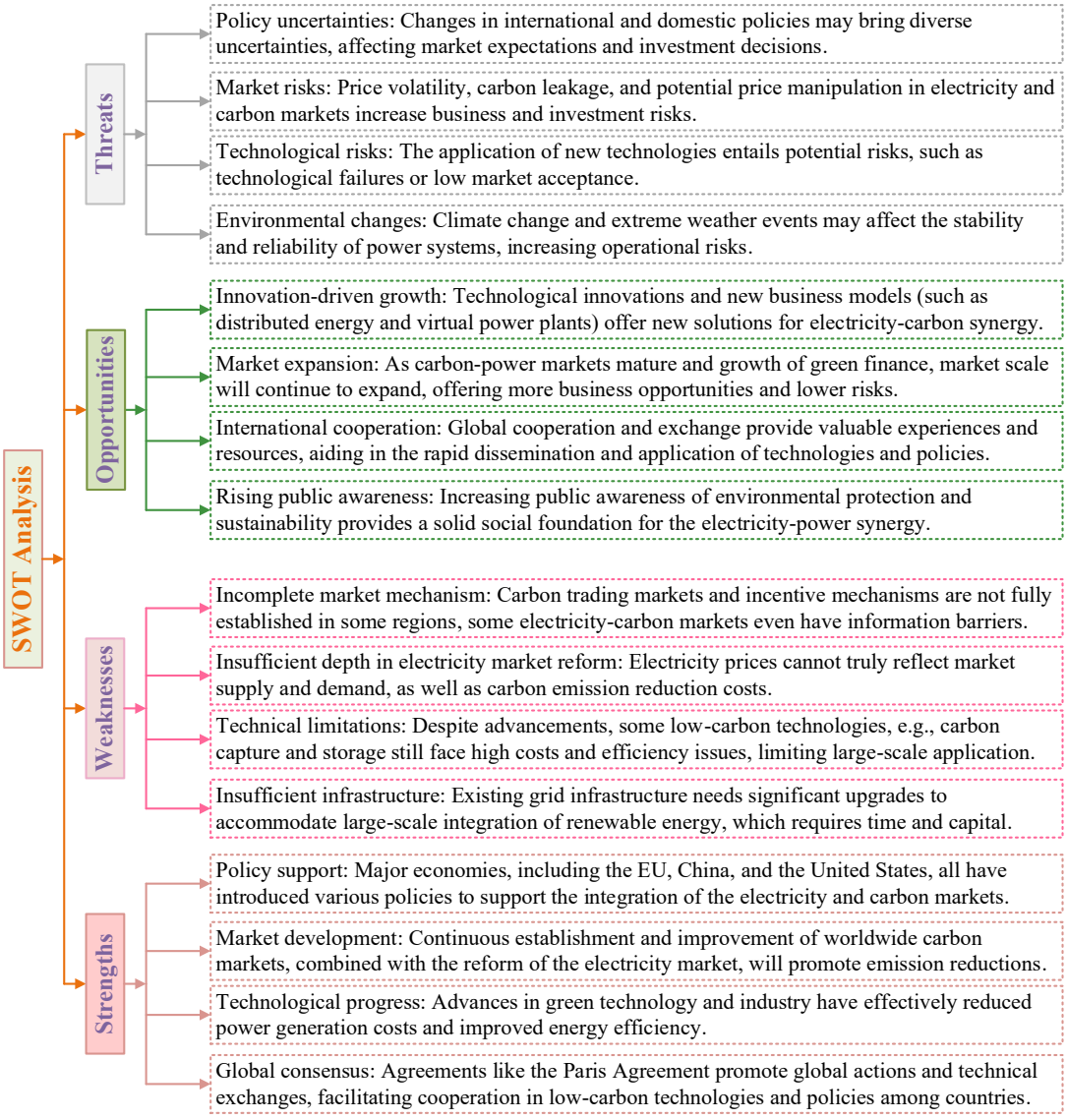

Fig. 5. SWOT analysis regarding electricity-carbon synergy.

Nonetheless, threats must be managed. Policy volatility, especially with shifts in political leadership, can reverse climate pledges, while extreme climate events and market price fluctuations threaten power system stability and investment confidence. New technologies (e.g., hydrogen-ready infrastructure, carbon capture) also introduce operational and market risks, particularly in regions with limited regulatory preparedness or financial capacity. Beyond these external and technological uncertainties, market failure risks remain a critical concern for sustaining electricity-carbon market synergies. Carbon leakage undermines both the environmental integrity and the competitiveness rationale of ETSs [145]. It occurs through relocation of emissions-intensive production to weaker jurisdictions, re-routing of intermediate goods trade, or diversion of low-carbon investment to unregulated regions. Such leakage not only dilutes global mitigation gains but also creates political pressure to weaken domestic carbon prices, thereby weakening the price signals transmitted to electricity markets [146]. Similarly, price manipulation risks, which display as strategic hoarding of allowances, speculative trading in low-liquidity markets, or deliberate distortion of auction outcomes, can decouple carbon prices from underlying abatement costs [147]. In the electricity-carbon context, such distortions reduce the credibility and predictability of carbon-cost pass-through, impairing both operational dispatch and long-term investment planning.

Mitigating these risks requires a multi-pronged approach: strengthening anti-manipulation and position-limit rules in allowance trading; enhancing market transparency through real-time disclosure of transaction volumes, ownership concentration, and cross-market linkages; and fostering international coordination on MRV standards and carbon pricing benchmarks to limit leakage incentives. Without such safeguards, even well-designed market coupling frameworks risk being undermined by structural vulnerabilities in carbon trading systems.

5.2 Outlooks

The strategies proposed here align with the SWOT findings. They aim to leverage internal strengths and external opportunities while addressing weaknesses and mitigating potential threats across technology, market design, policy frameworks, and international cooperation. In addition to practical recommendations for policymakers and market stakeholders, the findings

also point to clear academic research priorities obtained from the literature review and comparative analyses in Sections 4 and 5. These include expanding cross-regional comparative modeling under harmonized carbon-electricity price datasets, integrating emerging technologies such as blockchain-based carbon tracking and artificial intelligence (AI)-enabled forecasting into synergy modeling frameworks, and developing scenario-based evaluations that couple power sector decarbonization pathways with evolving carbon market mechanisms. Addressing these priorities requires improving methodological interoperability across disciplines, deepening empirical validation under different market maturity levels, and enhancing data transparency to ensure reproducibility in cross-border market analysis.

To enhance operability, specific solutions and future development suggestions are proposed from four perspectives, as follows:

(1) Technology and Renewable Energy

- Technological innovation and infrastructure enhancement: Increase investment in advanced renewable energy technologies, low-carbon techniques, and smart grid research. Pilot projects can be implemented to test and demonstrate new technologies and business models, paving the way for large-scale deployment. Grid infrastructure should be upgraded and modernized to accommodate large-scale renewable integration, including flexibility, resilience, and capacity improvements through smart grid technologies and advanced transmission systems. Powerful tools such as AI and the Internet of Things (IoT) can be applied to enhance grid management, predictive maintenance, and demand response. In parallel, investing in climate-resilient infrastructure, distributed energy resources, and advanced weather forecasting capabilities is essential to safeguard the grid against the potential impacts of climate change and extreme weather. Against the broader backdrop of digital transformation, emerging technologies offer strong potential to strengthen the coupling between carbon and power markets. In particular, blockchain for carbon tracking and AI for tariff forecasting can enhance measurement accuracy, transparency, and operational responsiveness. On the carbon-tracking side, blockchain offers features that directly address long-standing MRV challenges in carbon markets. The decentralized and immutable ledger structure safeguards transaction records. In addition, smart contracts can automate compliance processes, thereby reducing administrative costs and preventing the double-counting of emissions allowances [148]. Through lowering

intermediation barriers, blockchain systems can broaden market participation, particularly for small and medium-sized enterprises. This expansion enhances overall liquidity and strengthens trust in carbon credit transactions [148]. When integrated with IoT infrastructure, blockchain can also support real-time emissions tracking across facilities and supply chains. This combination enables the accurate differentiation of low- and high-carbon electricity and provides auditable data accessible to regulators, market operators, and participants. It also facilitates the automated issuance and retirement of carbon credits in near real time [149]. Such capabilities shorten the feedback loop between actual operational emissions and market signals, allowing carbon costs to be more effectively internalized into electricity pricing. AI, particularly in tariff forecasting, supports more adaptive and responsive electricity-carbon price interactions. AI models trained on multi-source datasets, including wholesale electricity prices, carbon allowance prices, weather forecasts, and demand patterns, can generate high-resolution price forecasts [150,151]. These forecasts enable operators and participants to optimize dispatch, bidding strategies, and investment planning in line with carbon-reduction targets. For example, AI-driven predictive analytics can anticipate carbon price fluctuations under varying policy and demand scenarios [150], allowing power producers to dynamically adjust generation portfolios to minimize emissions costs;

- Promote renewable energy: Enhance market roles to reduce power system transformation costs. Given regional differences in renewable resources, power load, and grid structures, support measures should guide market participation at all stages of renewable energy development. Such measures can help establish a dynamic adjustment mechanism for renewable energy deployment and power system optimization. Grid integration should facilitate mechanisms for various market participants to share clean energy consumption responsibilities through multi-energy complementarity, searching for the most cost-effective capacity reserves and regulation services. In addition, both carbon and electricity markets should prioritize renewable energy as the main power source. The carbon market can play a key role by amplifying the positive externalities of renewables while reducing the negative externalities of fossil fuels. This process ultimately enhances the market competitiveness of renewable energy.

(2) Market Design

- Expansion and upgrading of carbon markets: Expand and connect carbon markets to create larger, more liquid markets, thereby reducing emission reduction costs and improving the efficiency and effectiveness of carbon trading systems. The scope of industries covered by carbon trading mechanisms should be broadened to increase both market depth and width. This expansion requires refining quota accounting and allocation principles to generate effective carbon price signals, since the allocation method has a significant impact on carbon pricing. Furthermore, it is essential to tighten the total carbon quota based on properly determining the full-process carbon emissions of key emitting units. The aim is to achieve uniform marginal carbon reduction costs across industries and to prevent the worsening of "carbon leakage" between sectors;
- Deepen power marketization: Power market reforms should be further advanced, with a particular focus on electricity pricing. This will help ensure that prices accurately reflect both market supply-demand conditions and carbon reduction costs. Moreover, green electricity market trading mechanisms can be introduced and improved by separating renewable energy electricity from traditional fossil fuel electricity, allowing it to be traded as an independent commodity. This differentiation promotes renewable energy development and utilization through market forces. Furthermore, the integration of power generation companies into the carbon market requires further expanding the range of electricity price fluctuations. This enables electricity prices to fully transmit carbon costs downstream, achieving a positive interaction between electricity and carbon prices, with carbon prices guiding companies in energy conservation and emission reduction.

(3) Policy and Regulatory Frameworks

- Governments should enhance and maintain consistent policy support for renewable energy and decarbonization initiatives. This includes clear long-term targets, stable financial incentives, and coherent regulatory frameworks to attract investment. Carbon pricing mechanisms such as carbon taxes and cap-and-trade systems need to be further strengthened to raise carbon prices and incentivize deeper reductions. Adaptive policies should evolve alongside technological and market developments, while harmonized carbon pricing and emissions reporting standards would enhance transparency and comparability across jurisdictions;
- Regulatory frameworks must also address the structural risks already discussed in Section

5.1, such as carbon leakage and price manipulation. Instead of restating technical measures, the emphasis here is on ensuring that governance systems remain credible, transparent, and enforceable, so that carbon cost signals can reliably guide electricity market operations and long-term investment decisions. Furthermore, policy designs should guarantee that carbon costs are consistently embedded in electricity price formation, avoiding distortions from rigid administrative controls. Stability mechanisms such as allowance reserves or price corridors may also be necessary to reduce uncertainty for investors, while robust enforcement and credible penalties for non-compliance can reinforce market trust.

(4) International Cooperation

- International cooperation is critical for mitigating carbon leakage and ensuring global market alignment. The EU CBAM provides a concrete illustration of how cross-border carbon pricing can strengthen electricity-carbon market synergies. By mitigating carbon leakage and aligning trade flows with carbon cost internalization, CBAM reinforces price coupling between electricity and carbon markets. Evidence from multi-model analyses [141-143] indicates that its implementation can reduce average carbon leakage rates from around 12% to 6%, and narrow disparities in GDP losses between regulated and unregulated regions. Moreover, modeling results indicate that CBAM can narrow the disparity in GDP losses between "coalition" and "non-coalition" countries from a ratio of 3:1 to roughly 1:1, highlighting its role in stabilizing investment signals for decarbonization in the power sector. The mechanism has also triggered "policy convergence" effects, with some trading partners accelerating domestic ETS development to maintain competitiveness and avoid CBAM liabilities. Such responses enhance cross-border institutional coupling between electricity and carbon markets. Macroeconomic impacts are generally modest. However, sectoral effects are more pronounced, especially in electricity and energy-intensive industries, where the carbon price signal is significantly enhanced. Overall, the current evidence suggests that CBAM, when designed with comprehensive coverage, verifiable accounting, and robust governance, tends to promote electricity-carbon synergies by reinforcing carbon price signals, reducing leakage, and inducing policy alignment. However, the magnitude of these benefits is highly sensitive to policy design, administrative feasibility, and the level of international cooperation achieved.

6. Conclusions

Electricity-carbon synergy essentially refers to the effective coordination and integration of electricity and carbon markets in terms of environmental rights accounting, data interoperability, and unified certification. This study highlights the importance of electricity-carbon synergy by critically reviewing existing research in this field. The findings emphasize their collective effectiveness in promoting significant emission reductions and supporting clean energy applications. This review explores the current status of global electricity-carbon markets and discusses the connotation, implementation path, current challenges, and future trends of electricity-carbon market synergy. The main contributions and findings of this work are outlined as follows:

- An in-depth overview of the worldwide electricity and carbon markets is undertaken, emphasizing the diversity of market designs and regulatory frameworks across different regions, which is essential for understanding regional challenges and opportunities in market integration;
- The existing studies regarding the electricity-carbon synergy are classified into three general categories based on their geographic focus, i.e., Europe, Asia Pacific, and North America. Then, a structured literature analysis framework is carried out from a global perspective based on eleven crucial evaluation indicators, including geographic scope, covered sectors, model, methodology, policy implications, pros and cons, etc. This multi-regional analysis highlights the need for tailored strategies considering regional economic, technical, and policy contexts. Following this, a SWOT analysis is carried out to identify strengths, weaknesses, opportunities, and threats within a broader techno-socio-economic-political context;
- Strategic recommendations and future development pathways are proposed to mitigate threats and address challenges. These insights provide practical guidance for industry professionals, stakeholders, and policymakers to make informed decisions that advance effective electricity-carbon synergy. This is crucial for achieving net-zero emissions and facilitating the global energy transition towards green and low-carbon directions;
- The electricity-carbon synergy fosters a collective effort towards a green and low-carbon

transition by establishing a price transmission mechanism between electricity and carbon prices. However, the path to effectively integrating the electricity and carbon markets faces challenges and difficulties, such as market volatility, imperfect mechanisms, policy uncertainty, technological barriers, and insufficient infrastructure. To address these challenges, future development requires continuous technological innovation, more stable and coherent policy frameworks, substantial investment in infrastructure, more complete and in-depth market-oriented reforms, and strengthened international cooperation. By focusing on these areas, stakeholders can more effectively navigate the complexities of integrating electricity and carbon markets, ultimately progressing towards a sustainable net-zero future.

Despite the strategic insights of this review, several limitations should be noted and addressed in future research. First, the distribution of literature across regions is uneven. For instance, abundant peer-reviewed studies exist for the EU, China, and North America, but relatively fewer focus on the UK, limiting the depth of analysis for this region. In addition, this review focuses primarily on Asia Pacific, Europe, and North America, as these regions contribute the largest share of relevant studies that examine carbon-electricity synergy. Other regions with emerging or less mature carbon markets (e.g., Latin America, Africa, and the Middle East) are not included due to the scarcity of peer-reviewed research on this topic. These limitations may restrict the comprehensiveness of cross-regional comparisons and understate region-specific challenges and opportunities. Future studies should therefore expand empirical coverage both in underrepresented regions like the UK and in currently excluded regions to strengthen global comparative analyses of electricity-carbon market synergies. Second, as electricity-carbon synergy research is still in exploratory and early development stages for most regions, rapid technological advancements, market expansion, and policy changes may bring new challenges. This could affect the relevance and applicability of some conclusions, necessitating future adjustments to ensure the research remains up-to-date and relevant for stakeholders and policymakers.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (62263014), Yunnan Provincial Basic Research Project (202401AT070344, 202301AT070443).

References

[1] F. P. Colelli, J. Emmerling, G. Marangoni, M. N. Mistry, and E. De Cian, “Increased energy use for adaptation significantly impacts mitigation pathways,” *Nature Communications*, vol. 13, no. 1, p. 4964, Aug. 2022.

[2] International Energy Agency, "Net zero by 2050," International Energy Agency, Paris, France, License: CC BY 4.0, May 2021.

[3] Intergovernmental Panel on Climate Change, “Summary for Policymakers,” in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2021, pp. 3-32, Doi: 10.1017/9781009157896.001.

[4] International Energy Agency, "Electricity 2024," International Energy Agency, Paris, France, License: CC BY 4.0, Jan. 2024.

[5] B. Yu, D. Fang, K. Xiao, and Y. Pan, “Drivers of renewable energy penetration and its role in power sector's deep decarbonization towards carbon peak,” *Renewable and Sustainable Energy Reviews*, vol. 178, p. 113247, May 2023.

[6] K. Peng, K. Feng, B. Chen, Y. Shan, N. Zhang, P. Wang, K. Fang, Y. Bai, X. Zou, W. Wei, X. Geng, Y. Zhang, and J. Li, “The global power sector’s low-carbon transition may enhance sustainable development goal achievement,” *Nature Communications*, vol. 14, no. 1, p. 3144, May 2023.

[7] P. A. Østergaard, N. Duic, Y. Noorollahi, and S. Kalogirou, “Advances in renewable energy for sustainable development,” *Renewable Energy*, vol. 219, p. 119377, Dec. 2023.

[8] International Energy Agency, "Renewables 2023," International Energy Agency, Paris, France, License: CC BY 4.0, Jan. 2024.

[9] S. Molla, O. Farrok, and M. J. Alam, “Electrical energy and the environment: Prospects and upcoming challenges of the World's top leading countries,” *Renewable and Sustainable Energy Reviews*, vol. 191, p. 114177, Mar. 2024.

[10] E. Graham, N. Fulghum, and K. Altieri. “Global electricity review 2025”. Ember. Retrieved from https://ember-energy.org/insights/research/global-electricity-review-2025. Apr. 2025.

[11] Ember & Energy Institute-with major processing by Our World in Data, “Statistical review of world energy,” May 2025, Ember and Energy Institute [Online]. Available: https://ourworldindata.org/grapher/per-capita-electricity-source-stacked.

[12] Ember and Energy Institute-with major processing by Our World in Data, “Carbon intensity of electricity generation,” Jun. 2024, Ember and Energy Institute [Online]. Available: https://ourworldindata.org/grapher/carbon-intensity-electricity.

[13] M. Jang, S. Yoon, S. Jung, and B. Min, “Simulating and assessing carbon markets: Application to the Korean and the EU ETSs,” *Renewable and Sustainable Energy Reviews*, vol. 195, p. 114346, May 2024.

[14] B. Matthias, M.-F. Kranz, T. Steger, and J. Schäfer, “Accelerating decarbonization digitally: status quo and potentials of greenhouse gas emission tracking and trading,” *Journal of Cleaner Production*, vol. 469, p. 143125, Sep. 2024.

[15] P. Li, W. Wang, and X. Xia, “Assessing the effectiveness of carbon cap-and-trade and hybrid subsidy policies: The perspective of production, environment, and consumer,” *Journal of Cleaner Production*, vol. 468, p. 143074, Aug. 2024.

[16] International Carbon Action Partnership, "Emissions trading worldwide: Status report 2024," International Carbon Action Partnership, Berlin, Germany, Apr. 2024.

[17] World Bank, "State and Trends of Carbon Pricing 2024," World Bank, Washington, DC, USA, License: Creative Commons Attribution CC BY 3.0 IGO, May 2024.

[18] J. P. Sasse and E. Trutnevyte, “A low-carbon electricity sector in Europe risks sustaining regional inequalities in benefits and vulnerabilities,” *Nature Communications*, vol. 14, no. 1, p. 2205, Apr. 2023.

[19] W. Liu, B. He, Y. Xue, J. Huang, J. Zhao, and F. Wen, “A comprehensive modeling framework for coupled electricity and carbon markets,” *Energy Conversion and Economics*, vol. 5, no. 1, pp. 1-14, Feb. 2024.

[20] W. Chen, Y. Ma, and C. Bai, “The impact of carbon emission quota allocation regulations on the investment of low-carbon technology in electric power industry under peak-valley price policy,” *IEEE Transactions on Engineering Management*, vol. 71, pp. 374-391, Nov. 2021.

[21] Y. Wang, H. Xie, X. Sun, L. Tang, and Z. Bie, “A cross-chain enabled day-ahead collaborative power-carbon-TGC market,” *Energy*, vol. 258, p. 124881, Nov. 2022.

[22] A. Triyanti, H. Du, D. L. Hegger, P. P. Driessen, H. F. van Rijswick, M. Scown, and H. K. Gilissen, “Clarifying and strengthening the role of law and governance in climate scenario frameworks,” *Earth System Governance*, vol. 18, p. 100199, Dec. 2023.

[23] M. Shahnazari, A. McHugh, B. Maybee, and J. Whale, “Overlapping carbon pricing and renewable support schemes under political uncertainty: Global lessons from an Australian case study,” *Applied Energy*, vol. 200, pp. 237-248, Aug. 2017.

[24] J. H. Keppler, S. Quemin, and M. Saguan, “Why the sustainable provision of low-carbon electricity needs hybrid markets,” *Energy Policy*, vol. 171, p. 113273, Dec. 2022.

[25] M. Mehling, *Good Spillover, Bad Spillover: Industrial Policy, Trade, and the Political Economy of Decarbonization*. MIT Center for Energy and Environmental Policy Research, Jan. 2025.

[26] C. Lyu and B. Scholtens, “Integration of the international carbon market: A time-varying analysis,” *Renewable and Sustainable Energy Reviews*, vol. 191, p. 114102, Mar. 2024.

[27] M. J. Page, J. E. McKenzie, P. M. Bossuyt, I. Boutron, T. C. Hoffmann, C. D. Mulrow, L. Shamseer, J. M. Tetzlaff, and D. Moher, “Updating guidance for reporting systematic reviews: development of the PRISMA 2020 statement,” *Journal of Clinical Epidemiology*, vol. 134, pp. 103-112, Jul. 2021.

[28] R. Sarkis-Onofre, F. Catalá-López, E. Aromataris, and C. Lockwood, “How to properly use the PRISMA statement,” *Systematic Reviews*, vol. 10, no. 1, p. 117, Apr. 2021.

[29] International Energy Agency, "Steering Electricity Markets towards a Rapid Decarbonisation," International Energy Agency, Paris, France, License: CC BY 4.0, Jun. 2022.

[30] International Energy Agency, "Electricity Market Report 2023," International Energy Agency, Paris, France, License: CC BY 4.0, Feb. 2022.

[31] J. Tian, S. Zhou, and Y. Wang, “Assessing the technical and economic potential of wind and solar energy in China-A provincial-scale analysis,” *Environmental Impact Assessment Review*, vol. 102, p. 107161, Sep. 2023.

[32] D. Liu, Y. Jiang, C. Peng, J. Jian, and J. Zheng, “Can green certificates substitute for renewable electricity subsidies? A Chinese experience,” *Renewable Energy*, vol. 222, p. 119861, Feb. 2024.

[33] C. Allen, A. Biddulph, T. Wiedmann, M. Pedercini, and S. Malekpour, “Modeling six sustainable development transformations in Australia and their accelerators, impediments, enablers, and interlinkages,” *Nature Communications*, vol. 15, no. 1, p. 594, Jan. 2024.

[34] R. Faia, F. Lezama, J. Soares, T. Pinto, and Z. Vale, “Local electricity markets: A review on benefits, barriers, current trends and future perspectives,” *Renewable and Sustainable Energy Reviews*, vol. 190, p. 114006, Feb. 2024.

[35] F. Shayan, H. Harsij, and D. Badulescu, “Regional institutions’ contribution to energy market integration in the middle East,” *Energy Strategy Reviews*, vol. 51, p. 101266, Jan. 2024.

[36] M. Tutak and J. Brodny, “Renewable energy consumption in economic sectors in the EU-27. The impact on economics, environment and conventional energy sources. A 20-year perspective,” *Journal of Cleaner Production*, vol. 345, p. 131076, Apr. 2022.

[37] E. Ricciolini, A. Tiralti, L. Paolotti, L. Rocchi, and A. Boggia, “Sustainable development according to 2030 agenda in European Union countries: Evidence of the enlargement policy,” *Sustainable Development*, vol. 32, no. 3, pp. 1894–1912, Jun. 2024.

[38] V. M. Charitopoulos, M. Fajardy, C. K. Chyong, and D. M. Reiner, “The impact of 100% electrification of domestic heat in Great Britain,” *iScience*, vol. 26, no. 11, Nov. 2023.

[39] J. L. Castle and D. F. Hendry, “Five sensitive intervention points to achieve climate neutrality by 2050, illustrated by the UK,” *Renewable Energy*, vol. 226, p. 120445, May. 2024.

[40] P. R. Brown and A. Botterud, “The value of inter-regional coordination and transmission in decarbonizing the US electricity system,” *Joule*, vol. 5, no. 1, pp. 115-134, Jan. 2021.

[41] J. W. Moraski, N. D. Popovich, and A. A. Phadke, “Leveraging rail-based mobile energy storage to increase grid reliability in

the face of climate uncertainty," *Nature Energy*, vol. 8, no. 7, pp. 736-746, Jun. 2023.

[42] M. Saffari, M. McPherson, and A. Rowe, "Evaluation of flexibility provided by cascading hydroelectric assets for variable renewable energy integration," *Renewable Energy*, vol. 211, pp. 55-63, Jul. 2023.

[43] A. Azarpour, O. Mohammadzadeh, N. Rezaei, and S. Zendehboudi, "Current status and future prospects of renewable and sustainable energy in North America: Progress and challenges," *Energy Conversion and Management*, vol. 269, p. 115945, Oct. 2022.

[44] International Energy Agency, "Enhancing China's ETS for Carbon Neutrality: Focus on Power Sector," International Energy Agency, Paris, France, License: CC BY 4.0, May 2022.

[45] S. Byrom, G. D. Bongers, P. Dargusch, A. Garnett, and A. Boston, "A case study of Australia's emissions reduction policies-An electricity planner's perspective," *Journal of Environmental Management*, vol. 276, p. 111323, Dec. 2020.

[46] H. Choo, Y. G. Kim, and D. Kim, "Power sector carbon reduction review for South Korea in 2030," *Renewable and Sustainable Energy Reviews*, vol. 196, p. 114348, May 2024.

[47] International Energy Agency, "Reforming Korea's Electricity Market for Net Zero," International Energy Agency, Paris, France, License: CC BY 4.0, Dec. 2021.

[48] M. J. Presno, M. Landajo, and P. F. González, "GHG emissions in the EU-28. A multilevel club convergence study of the emission trading system and effort sharing decision mechanisms," *Sustainable Production and Consumption*, vol. 27, pp. 998-1009, Jul. 2021.

[49] Y. Lovcha, A. Perez-Laborda, and I. Sikora, "The determinants of CO_2 prices in the EU emission trading system," *Applied Energy*, vol. 305, p. 117903, Jan. 2022.

[50] *EU ETS Handbook*, Climate Action, European Commission, Brussels**,** Belgium, 2015, pp. 16-17.

[51] J. Sitarz, M. Pahle, S. Osorio, G. Luderer, and R. Pietzcker, "EU carbon prices signal high policy credibility and farsighted actors," *Nature Energy*, pp. 1-12, May 2024.

[52] J. Shao, J. Li, and G. Liu, "The impacts of consumer-funded renewable support schemes in the UK: From the perspective of consumers or the electricity sector?," *Renewable and Sustainable Energy Reviews*, vol. 183, p. 113498, Sep. 2023.

[53] H. Jung and C. K. Song, "Effects of emission trading scheme (ETS) on change rate of carbon emission," *Scientific Reports*, vol. 13, no. 1, p. 912, Jan. 2023.

[54] J. Yan, "The impact of climate policy on fossil fuel consumption: Evidence from the regional greenhouse gas initiative (RGGI)," *Energy Economics*, vol. 100, p. 105333, Aug. 2021.

[55] S. U. Pauer, "Including electricity imports in California's cap-and-trade program: A case study of a border carbon adjustment in practice," *The Electricity Journal*, vol. 31, no. 10, pp. 39-45, Dec. 2018.

[56] International Energy Agency, *United States 2024*, IEA, Paris https://www.iea.org/reports/united-states-2024, Licence: CC BY 4.0, Jul. 2024.

[57] T. J. Rennie, B. B. Grant, R. J. Gordon, W. N. Smith, and A. C. VanderZaag, "Regional climate influences manure temperature and methane emissions-a pan-Canadian modeling assessment," *Science of The Total Environment*, vol. 750, p. 142278, Jan. 2021.

[58] L. Wang, C. Yang, Z. Xu, G. Yuan, L. Tang, Y. Bai, and X. Wang, "Analysis of carbon electricity coupled market modeling method based on carbon credit trading mechanism," *International Journal of Electrical Power & Energy Systems*, vol. 156, p. 109707, Feb. 2024.

[59] A. He, Q. Xue, R. Zhao, and D. Wang, "Renewable energy technological innovation, market forces, and carbon emission efficiency," *Science of the Total Environment*, vol. 796, p. 148908, Nov. 2021.

[60] W. Zhang, G. Li, and F. Guo, "Does carbon emissions trading promote green technology innovation in China?," *Applied Energy*, vol. 315, p. 119012, Jun. 2022.

[61] X. Jia, Y. Zhang, R. R. Tan, Z. Li, S. Wang, F. Wang, and K. Fang, "Multi-objective energy planning for China's dual carbon goals," *Sustainable Production and Consumption*, vol. 34, pp. 552-564, Nov. 2022.

[62] X. Wang, R. Long, H. Chen, Y. Wang, Y. Shi, S. Yang, and M. Wu, “How to promote the trading in China's green electricity market? Based on environmental perceptions, renewable portfolio standard and subsidies,” *Renewable Energy*, vol. 222, p. 119784, Feb. 2024.

[63] H. Guo, Q. Chen, Q. Xia, and C. Kang, “Modeling strategic behaviors of renewable energy with joint consideration on energy and tradable green certificate markets,” *IEEE Transactions on Power Systems*, vol. 35, no. 3, pp. 1898-1910, May 2020.

[64] C. Zhang and B. Lin, “Impact of introducing Chinese certified emission reduction scheme to the carbon market: Promoting renewable energy,” *Renewable Energy*, vol. 222, p. 119887, Feb. 2024.

[65] C. Suo, Y. P. Li, S. W. Jin, J. Liu, Y. F. Li, and R. F. Feng, “Identifying optimal clean-production pattern for energy systems under uncertainty through introducing carbon emission trading and green certificate schemes,” *Journal of Cleaner Production*, vol. 161, pp. 299-316, Sep. 2017.

[66] B. Lin and Z. Jia, “What will China's carbon emission trading market affect with only electricity sector involvement? A CGE based study,” *Energy Economics*, vol. 78, pp. 301-311, Feb. 2019.

[67] X. Liu and Z. Jin, “An analysis of the interactions between electricity, fossil fuel and carbon market prices in Guangdong, China,” *Energy for Sustainable Development*, vol. 55, pp. 82-94, Apr. 2020.

[68] Y. Song, T. Liu, B. Ye, and Y. Li, “Linking carbon market and electricity market for promoting the grid parity of photovoltaic electricity in China,” *Energy*, vol. 211, p. 118924, Nov. 2020.

[69] J. Y. Liu and Y. J. Zhang, “Has carbon emissions trading system promoted non-fossil energy development in China?,” *Applied Energy*, vol. 302, p. 117613, Nov. 2021.

[70] T. Feng, R. Li, H. Zhang, X. Gong, and Y. Yang, “Induction mechanism and optimization of tradable green certificates and carbon emission trading acting on electricity market in China,” *Resources, Conservation and Recycling*, vol. 169, p. 105487, Jun. 2021.

[71] X. Yu, Z. Dong, D. Zhou, X. Sang, C. Chang, and X. Huang, “Integration of tradable green certificates trading and carbon emissions trading: how will Chinese power industry do?,” *Journal of Cleaner Production*, vol. 279, p. 123485, Jan. 2021.

[72] Z. Ying and X. Zhang, “The impact of Renewable Portfolio Standards on carbon emission trading under the background of China’s electricity marketization reform,” *Energy*, vol. 226, p. 120322, Jul. 2021.

[73] A. Zhou, X. Lin, and J. Li, “Assessing the impact of the carbon market on the improvement of China's energy and carbon emission performance,” *Energy*, vol. 258, p. 124789, Nov. 2022.

[74] Z. Yu, Y. Geng, A. Calzadilla, and R. Bleischwitz, “China's unconventional carbon emissions trading market: the impact of a rate-based cap in the power generation sector,” *Energy*, vol. 255, p. 124581, Sep. 2022.

[75] K. Jiang, X. Yan, N. Liu, and P. Wang, “Energy trade-offs in coupled ICM and electricity market under dynamic carbon emission intensity,” *Energy*, vol. 260, p. 125077, Dec. 2022.

[76] M. Zhang, Y. Ge, L. Liu, and D. Zhou, “Impacts of carbon emission trading schemes on the development of renewable energy in China: Spatial spillover and mediation paths,” *Sustainable Production and Consumption*, vol. 32, pp. 306-317, Jul. 2022.

[77] L. Wang and K. Li, “Research on renewable energy consumption and emission reduction in power market based on bi-level decision making in China,” *Energy*, vol. 260, p. 125119, Dec. 2022.

[78] H. R. Wang, T. T. Feng, and C. Zhong, “Effectiveness of CO_2 cost pass-through to electricity prices under 'electricity-carbon' market coupling in China,” *Energy*, vol. 266, p. 126387, Mar. 2023.

[79] J. Cui, F. Song, and Z. Jiang, “Efficiency vs. equity as China's national carbon market meets provincial electricity markets,” *China Economic Review*, vol. 78, p. 101915, Apr. 2023.

[80] X. Huang, J. S. Kim, K. R. Hong, and N. H. Kim, “How do carbon trading price and carbon tax rate affect power project portfolio investment and carbon emission: an analysis based on uncertainty theory,” *Journal of Environmental Management*, vol. 345, p. 118768, Nov. 2023.

[81] H. Feng, Y. J. Hu, C. Li, and H. Wang, “Rolling horizon optimisation strategy and initial carbon allowance allocation model to reduce carbon emissions in the power industry: case of China,” *Energy*, vol. 277, p. 127659, Aug. 2023.

[82] X. Chang, Z. Wu, J. Wang, X. Zhang, M. Zhou, T. Yu, and Y. Wang, "The coupling effect of carbon emission trading and tradable green certificates under electricity marketization in China," *Renewable and Sustainable Energy Reviews*, vol. 187, p. 113750, Nov. 2023.

[83] H. Zhang, D. Zhang, and X. Zhang, "The role of output-based emission trading system in the decarbonization of China's power sector," *Renewable and Sustainable Energy Reviews*, vol. 173, p. 113080, Mar. 2023.

[84] X. Lei and X.-g. Zhang, "The synergistic effect between Renewable Portfolio Standards and carbon emission trading system: a perspective of China," *Renewable Energy*, vol. 211, pp. 1010-1023, Jul. 2023.

[85] J. Li, Y. Hu, Y. Chi, D. Liu, S. Yang, Z. Gao, and Y. Chen, "Analysis on the synergy between markets of electricity, carbon, and tradable green certificates in China," *Energy*, vol. 302, p. 131808, Sep. 2024.

[86] H. Zhang, D. Zhang, S. Guo, and X. Zhang, "Impact of benchmark tightening design under output-based ETS on China's power sector," *Energy*, vol. 288, p. 129832, Feb. 2024.

[87] S. Zhu, J. Ji, Q. Huang, S. Li, J. Ren, D. He, and Y. Yang, "Optimal scheduling and trading in joint electricity and carbon markets," *Energy Strategy Reviews*, vol. 54, p. 101426, Jul. 2024.

[88] W. Qian, A. W. Suryani, and K. Xing, "Does carbon performance matter to market returns during climate policy changes? Evidence from Australia," *Journal of Cleaner Production*, vol. 259, p. 121040, Jun. 2020.

[89] S. Meng, M. Siriwardana, J. McNeill, and T. Nelson, "The impact of an ETS on the Australian energy sector: An integrated CGE and electricity modeling approach," *Energy Economics*, vol. 69, pp. 213-224, Jan. 2018.

[90] L. Bardwell, L. Blackhall, and M. Shaw, "Emissions and prices are anticorrelated in Australia's electricity grid, undermining the potential of energy storage to support decarbonisation," *Energy Policy*, vol. 173, p. 113409, Feb. 2023.

[91] W. Ming, F. Nazifi, and S. Trück, "Emission intensities in the Australian National Electricity Market-An econometric analysis," *Energy Economics*, vol. 129, p. 107184, Jan. 2024.

[92] H. Heinrichs, P. Jochem, and W. Fichtner, "Including road transport in the EU ETS (European Emissions Trading System): A model-based analysis of the German electricity and transport sector," *Energy*, vol. 69, pp. 708-720, May 2014.

[93] A. Boersen and B. Scholtens, "The relationship between European electricity markets and emission allowance futures prices in phase II of the EU (European Union) emission trading scheme," *Energy*, vol. 74, pp. 585-594, Sep. 2014.

[94] L. Gawlik, A. Szurlej, and A. Wyrwa, "The impact of the long-term EU target for renewables on the structure of electricity production in Poland," *Energy*, vol. 92, pp. 172-178, Dec. 2015.

[95] Y. Tian, A. Akimov, E. Roca, and V. Wong, "Does the carbon market help or hurt the stock price of electricity companies? Further evidence from the European context," *Journal of Cleaner Production*, vol. 112, pp. 1619-1626, Jan. 2016.

[96] M. Balcilar, R. Demirer, S. Hammoudeh, and D. K. Nguyen, "Risk spillovers across the energy and carbon markets and hedging strategies for carbon risk," *Energy Economics*, vol. 54, pp. 159-172, Feb. 2016.

[97] Y. J. Zhang and Y. F. Sun, "The dynamic volatility spillover between European carbon trading market and fossil energy market," *Journal of Cleaner Production*, vol. 112, pp. 2654-2663, Jan. 2016.

[98] B. Zhu, D. Han, J. Chevallier, and Y. M. Wei, "Dynamic multiscale interactions between European carbon and electricity markets during 2005–2016," *Energy Policy*, vol. 107, pp. 309-322, Aug. 2017.

[99] V. Višković, Y. Chen, and A. S. Siddiqui, "Implications of the EU emissions trading system for the South-East Europe regional electricity market," *Energy Economics*, vol. 65, pp. 251-261, Jun. 2017.

[100] S. Schusser and J. Jaraitė, "Explaining the interplay of three markets: Green certificates, carbon emissions and electricity," *Energy Economics*, vol. 71, pp. 1-13, Mar. 2018.

[101] Q. Ji, D. Zhang, and J. B. Geng, "Information linkage, dynamic spillovers in prices and volatility between the carbon and energy markets," *Journal of Cleaner Production*, vol. 198, pp. 972-978, Oct. 2018.

[102] S. Schäfer, "Decoupling the EU ETS from subsidized renewables and other demand side effects: lessons from the impact of the EU ETS on CO_2 emissions in the German electricity sector," *Energy Policy*, vol. 133, p. 110858, Oct. 2019.

[103] H. Hobbie, M. Schmidt, and D. Möst, "Windfall profits in the power sector during phase III of the EU ETS: Interplay and

effects of renewables and carbon prices," *Journal of Cleaner Production*, vol. 240, p. 118066, Dec. 2019.

[104] Ö. Özdemir, B. F. Hobbs, M. van Hout, and P. R. Koutstaal, "Capacity vs energy subsidies for promoting renewable investment: Benefits and costs for the EU power market," *Energy Policy*, vol. 137, p. 111166, Feb. 2020.

[105] C. P. Anke, H. Hobbie, S. Schreiber, and D. Möst, "Coal phase-outs and carbon prices: Interactions between EU emission trading and national carbon mitigation policies," *Energy Policy*, vol. 144, p. 111647, Sep. 2020.

[106] F. Müsgens, "Equilibrium prices and investment in electricity systems with CO_2-emission trading and high shares of renewable energies," *Energy Economics*, vol. 86, p. 104107, Feb. 2020.

[107] P. Andrianesis, P. Biskas, and G. Liberopoulos, "Evaluating the cost of emissions in a pool-based electricity market," *Applied Energy*, vol. 298, p. 117253, Sep. 2021.

[108] C. P. Anke and D. Möst, "The expansion of RES and the EU ETS-valuable addition or conflicting instruments?," *Energy Policy*, vol. 150, p. 112125, Mar. 2021.

[109] R. C. Pietzcker, S. Osorio, and R. Rodrigues, "Tightening EU ETS targets in line with the European Green Deal: Impacts on the decarbonization of the EU power sector," *Applied Energy*, vol. 293, p. 116914, Jul. 2021.

[110] A. M. Bersani, P. Falbo, and L. Mastroeni, "Is the ETS an effective environmental policy? Undesired interaction between energy-mix, fuel-switch and electricity prices," *Energy Economics*, vol. 110, p. 105981, Jun. 2022.

[111] O. Ruhnau, M. Bucksteeg, D. Ritter, R. Schmitz, D. Böttger, M. Koch, A. Pöstges, M. Wiedmann, and L. Hirth, "Why electricity market models yield different results: Carbon pricing in a model-comparison experiment," *Renewable and Sustainable Energy Reviews*, vol. 153, p. 111701, Jan. 2022.

[112] M. Eslahi and P. Mazza, "Can weather variables and electricity demand predict carbon emissions allowances prices? Evidence from the first three phases of the EU ETS," *Ecological Economics*, vol. 214, p. 107985, Dec. 2023.

[113] Y. Bai and S. J. Okullo, "Drivers and pass-through of the EU ETS price: Evidence from the power sector," *Energy Economics*, vol. 123, p. 106698, Jul. 2023.

[114] L. Qiu, L. Chu, R. Zhou, H. Xu, and S. Yuan, "How do carbon, stock, and renewable energy markets interact: Evidence from Europe," *Journal of Cleaner Production*, vol. 407, p. 137106, Jun. 2023.

[115] E. Romano, R. Mutschler, P. Hollmuller, M. Sulzer, K. Orehounig, and M. Rüdisüli, "Spatial carbon and price spillovers among EU countries on their pathway toward net-zero electricity supply," *Energy Economics*, vol. 131, p. 107349, Mar. 2024.

[116] B. Guo and G. C. Gissey, "Cost pass-through in the British wholesale electricity market," *Energy Economics*, vol. 102, p. 105497, Oct. 2021.

[117] C. MacIver, W. Bukhsh, and K. R. Bell, "The impact of interconnectors on the GB electricity sector and European carbon emissions," *Energy Policy*, vol. 151, p. 112170, Apr. 2021.

[118] M. Leroutier, "Carbon pricing and power sector decarbonization: Evidence from the UK," *Journal of Environmental Economics and Management*, vol. 111, p. 102580, Jan. 2022.

[119] J. Shao, J. Li, and G. Liu, "The impacts of consumer-funded renewable support schemes in the UK: From the perspective of consumers or the electricity sector?," *Renewable and Sustainable Energy Reviews*, vol. 183, p. 113498, Sep. 2023.

[120] D. Hirst and M. Keep, "Carbon Price Floor (CPF) and the price support mechanism," House of Commons Library Briefing Paper, no. 20, pp. 1-26, 2018.

[121] World Bank, International Energy Agency, and International Carbon Action Partnership, "Carbon pricing in the power sector: Role and design for transitioning toward net-zero carbon development," World Bank Group, Washington, DC, 2024. [Online]. Available: http://hdl.handle.net/10986/42091. [Accessed: Aug. 11, 2025]. License: CC BY-NC 3.0 IGO.

[122] Vivid Economics, "The future of carbon pricing in the UK," Report prepared for the Committee on Climate Change, Aug. 2019. [Online]. Available: https://www.theccc.org.uk/publication/the-future-of-carbon-pricing-in-the-uk-vivid-economics/.

[123] C. K. Woo, Y. Chen, J. Zarnikau, A. Olson, J. Moore, and T. Ho, "Carbon trading's impact on California's real-time electricity market prices," *Energy*, vol. 159, pp. 579-587, Sep. 2018.

[124] L. Huang and Y. Zhou, "Carbon prices and fuel switching: A quasi-experiment in electricity markets," *Environmental and*

Resource Economics, vol. 74, no. 1, pp. 53-98, Jan. 2019.

[125] Y. Zhou and L. Huang, "How regional policies reduce carbon emissions in electricity markets: Fuel switching or emission leakage," *Energy Economics*, vol. 97, p. 105209, May 2021.

[126] G. Akın-Olçum, C. Böhringer, T. Rutherford, and A. Schreiber, "Economic and environmental impacts of a proposed 'Carbon adder' on New York's energy market," *Climate Policy*, vol. 21, no. 6, pp. 823-842, May 2021.

[127] D. Birur, P. Lal, T. Levin, Z. Zhou, B. Wolde, T. Wieczerak, and P. Thimmapuram, "Fostering green economy in New Jersey under the aegis of regional greenhouse gas Initiative," Presented at the 25th Annual Conference on Global Economic Analysis, June 8-10, 2022, Virtual Conf. [Online]. Available: https://ageconsearch.umn.edu/record/333434.

[128] Y. Cong, M. Freedman, J. D. Park, and A. J. Stagliano, "Carbon emission regulation of electric utility generating plants: new evidence on differential outcomes from mandated versus voluntary CO_2 reduction initiatives," *Energy Efficiency*, vol. 15, no. 8, p. 71, Dec. 2022.

[129] S. Mascher, "Striving for equivalency across the Alberta, British Columbia, Ontario and Québec carbon pricing systems: the Pan-Canadian carbon pricing benchmark," *Climate Policy*, vol.18, no. 8, pp.1012-1027, May 2018.

[130] B. Dolter and N. Rivers, "The cost of decarbonizing the Canadian electricity system," *Energy Policy*, vol. 113, pp. 135-148, Feb. 2018.

[131] J. E. Bistline, J. Merrick, and V. Niemeyer, "Estimating power sector leakage risks and provincial impacts of Canadian carbon pricing," *Environmental and Resource Economics*, vol. 76, no. 1, pp. 91-118, Apr. 2020.

[132] R. Arjmand and M. McPherson, "Canada's electricity system transition under alternative policy scenarios," *Energy Policy*, vol. 163, p. 112844, Apr. 2022.

[133] L. Chen, G. Huang, B. Luo, and L. Liu, "Unveiling environmental implications of Canadian electricity system's low-carbon transitions: A multi-regional stochastic optimization-driven input-output model," *Journal of Cleaner Production*, vol. 420, p. 138363, Sep. 2023.

[134] International Carbon Action Partnership, "Emissions trading worldwide: Status report 2025," International Carbon Action Partnership, Berlin, Germany, Apr. 2025.

[135] O. Ruhnau, M. Bucksteeg, D. Ritter, R. Schmitz, D. Böttger, M. Koch, A. Pöstges, M. Wiedmannan, and L. Hirth, "Why electricity market models yield different results: Carbon pricing in a model-comparison experiment," *Renewable and Sustainable Energy Reviews*, vol. 153, p. 111701, Jan. 2022.

[136] W. Acworth, M. M. De Oca, A. Boute, C. Piantieri, and F. C. Matthes, "Emissions trading in regulated electricity markets," *Climate Policy*, vol. 20, no. 1, pp. 60-70, Nov. 2019.

[137] N. W. Chan and J. W. Morrow, "Unintended consequences of cap-and-trade? Evidence from the Regional Greenhouse Gas Initiative," *Energy Economics*, vol. 80, pp. 411-422, May 2019.

[138] E. Narassimhan, S. Koester, and K. S. Gallagher, "Carbon pricing in the US: examining state-level policy support and federal resistance," *Politics and Governance*, vol. 10, no. 1, pp. 275-289, Mar. 2022.

[139] Y. Y. Chi, H. Zhao, Y. Hu, Y. K. Yuan, and Y. X. Pang, "The impact of allocation methods on carbon emission trading under electricity marketization reform in China: A system dynamics analysis," *Energy*, vol. 259, p. 125034, Nov. 2022.

[140] H. R. Wang, T. T. Feng, and C. Zhong, "Effectiveness of CO_2 cost pass-through to electricity prices under 'electricity-carbon' market coupling in China," *Energy*, vol. 266, p. 126387, Mar. 2023.

[141] J. Zhong and J. Pei, "Carbon border adjustment mechanism: A systematic literature review of the latest developments," *Climate Policy*, vol. 24, no. 2, pp. 228-242, Mar. 2024.

[142] E. Erdogdu, "The carbon border adjustment mechanism: Opportunities and challenges for non-EU countries," *Wiley Interdisciplinary Reviews: Energy and Environment*, vol. 14, no. 1, p. e70000, Mar. 2025.

[143] G. Magacho, E. Espagne, and A. Godin, "Impacts of the CBAM on EU trade partners: Consequences for developing countries," *Climate Policy*, vol. 24, no. 2, pp. 243-259, 2024.

[144] M. A. Benzaghta, A. Elwalda, M. M. Mousa, I. Erkan, and M. Rahman, "SWOT analysis applications: An integrative

literature review," *Journal of Global Business Insights*, vol. 6, no. 1, pp. 54-72, Mar. 2021.

[145] T. Nielsen, N. Baumert, A. Kander, M. Jiborn, and V. Kulionis, "The risk of carbon leakage in global climate agreements," *International Environmental Agreements: Politics, Law and Economics*, vol. 21, no. 2, pp. 147-163, Jun. 2021.

[146] M. Jakob, "Why carbon leakage matters and what can be done against it," *One Earth*, vol. 4, no. 5, pp. 609-614, May 2021.

[147] R. Betz, A. Michaelowa, P. Castro, R. Kotsch, M. Mehling, K. Michaelowa, and A. Baranzini, *The Carbon Market Challenge: Preventing Abuse through Effective Governance*. Cambridge, United Kingdom: Cambridge University Press, 2022.

[148] T. P. Abiodun, N. Nwulu, and P. Olukanmi, "Application of blockchain technology in carbon trading market: A systematic review," *IEEE Access*, vol. 13, pp. 5446-5470, 2025.

[149] S. Tripathy, A. Rawat, M. R. Lenka, and A. R. Swain, "Towards a sustainable future: Blockchain in carbon emission tracking and reduction," in *2025 International Conference on Emerging Systems and Intelligent Computing (ESIC)*, Bhubaneswar, India, Feb. 8-9, 2025, pp. 338-343.

[150] J. O. Ojadi, C. S. Odionu, E. C. Onukwulu, and O. A. Owulade, "AI-enabled smart grid systems for energy efficiency and carbon footprint reduction in urban energy networks," *International Journal of Multidisciplinary Research and Growth Evaluation*, vol. 5, no. 1, pp. 1549-1566, 2024.

[151] H. Ma, K. McAreavey, R. McConville, and W. Liu, "Explainable AI for non-experts: Energy tariff forecasting," in *2022 27th International Conference on Automation and Computing (ICAC)*, Bristol, United Kingdom, Sep. 1-3, 2022, pp. 1-6.