GLOBAL PROGRESS IN CARBON PRICING AND TRADING MECHANISMS: MARKET TOOLS FOR ECOLOGICAL AND ENVIRONMENTAL INTEGRATION

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Abstract. Greenhouse gas (GHG) emissions severely challenge ecology, economic growth, and human health, significantly affecting global climate change. Hence, effective control of carbon emissions and global low-carbon transformation has become a focus of governmental strategies and research studies, which are briefly surveyed in this paper. Although the efficiency of carbon emission reduction can be improved by financially encouraging enterprises, the available market-oriented policy tools—carbon pricing and carbon trading—have not yet been optimized due to significant differences in pricing mechanisms, market stability, and economic benefits across countries. To this end, available studies on GHG, carbon emission, carbon trading, and carbon pricing were analyzed and reviewed in this paper according to the gradual deepening principle, taking into account the accuracy, credibility, and reliability of the surveyed data. Global applications of carbon trading and carbon pricing, pricing modes, and future trends were discussed in detail. Carbon trading strategies were analyzed, and the feasibility of the global carbon emission reduction via carbon market tools was explored, providing references for policymaking and academic research.
Keywords: *greenhouse gas (GHG), carbon pricing, carbon trading, carbon emissions, carbon credit*

Introduction

Due to global industrialization and urbanization, greenhouse gas (GHG) emissions have rapidly increased over the past years. Hence, GHG emissions have become a key factor influencing global climate change. Xie et al. (2023) reported that Global GHG emissions increased by 60% (from 27 $GtCO_2e$ in 1970 to 43 $GtCO_2e$ in 2020), with an annual growth rate of 1.8%, resulting in severe global warming. According to the data released by the World Meteorological Organization, the global average temperature has increased by 0.8°C (between 13.9°C and 14.7°C), with ~70% of this rise occurring post 1980 (Baccini et al., 2017; WMO, 2023). Approximately half of the temperature rise occurred between the end of the 20th century and the beginning of the 21st century (Zhang et al., 2022). As a result, the incidence of extreme weather events, including heat waves, droughts, floods, and storms, has increased significantly (IPCC, 2021). Climate change challenges agriculture, water resources, and energy security, as well as biodiversity and ecosystems (Stern, 2007; Narassimhan et al., 2018). As a result, governments, organizations, and enterprises have tried to develop effective carbon emission reduction

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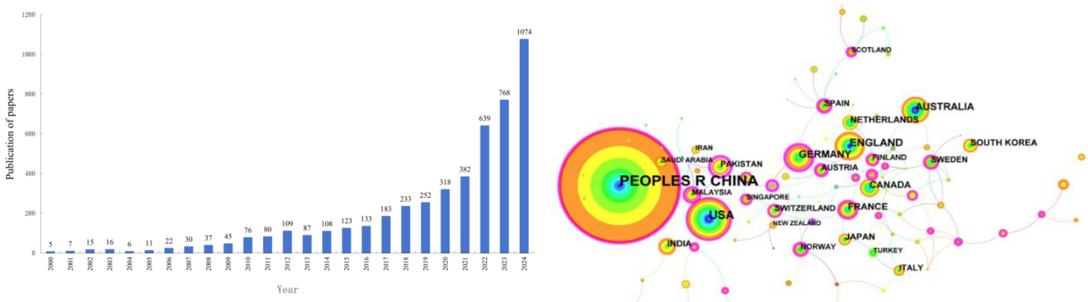
strategies to mitigate the economic and ecological hazards of carbon emissions using various scientifically substantiated approaches (IEA, 2023). This study used a systematic bibliometric analysis of academic publications on carbon market mechanisms throughout April 2025. Use of CiteSpace software with the whole-counting method, we extracted high-frequency keywords (co-occurrence frequency 10) to map research trends. Data were obtained from the Web of Science Core Collection using the search question: TS=(("Carbon trading" OR "Carbon pricing" OR "Carbon market" OR "Carbon emission") AND ("Greenhouse gas" OR "Climate change" OR "GHG")) with the publication of the years 2000–2025. From the first pool of 7,590 publications, research domain-based rigorous screening, journal credibility, and abstract relevance were excluded from the databases, with the remaining 2,470 duplicates and non-conforming records. The knowledge graph was constructed by the final corpus of 5,120 publications. A 9-fold increase is shown by the annual publication volume, as illustrated in *Fig. 1a*, which shows that there is an exponential growth from less than 100 articles annually (2010) to more than 1000 annually (2024). We identified dominant research borders and emerging trajectories in carbon emission governance and market-based mitigation mechanisms by quantitative analysis of important metrics (including citation networks, co-citation clusters, and collaborative linkages).



(a) (b)

Figure 1. *Annual volumes of publications on carbon trading (a) and their breakdown by countries and regions (b)*

It has been demonstrated that carbon trading and pricing, which are market-oriented approaches, are key policy tools for addressing climate change. As shown in *Fig. 1b*, the largest number of studies on carbon trading and carbon pricing have been reported by researchers from China, the USA, Australia, Germany, Japan, and France.

Research highlight analysis by CiteSpace revealed that recent studies of carbon pricing strategies focused on environmental science, economics, computer engineering, agriculture, geography, and management science (see *Fig. 2*), especially carbon trading, carbon pricing, supply chain, trading market, and trading rules (see *Fig. 3*). Herein, carbon trading depends on “Cap-and-Trade”: upper limits of total emission are set by governments, and enterprises trading of carbon emission allowances by enterprises is allowed to optimize the carbon emission reduction costs. Meanwhile, carbon pricing can encourage enterprises and consumers to reduce the consumption of high-carbon products by increasing carbon emission costs via Carbon Tax or Carbon Credit systems.

Figure 3 shows the co-citation network in carbon pricing developed using CiteSpace based on the Web of Science (WoS) Database. Herein, studies in different years are denoted by different colors. Key topics include carbon trading, trade regulation, carbon

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pricing, supply chain, carbon market, and carbon price prediction. Node size and connection intensity reflect the impacts and topic relevance of the publication, respectively. Research highlights include government policy, market mechanism, environmental strategy, and carbon emission, implying interdisciplinary integration and future trends in this field.

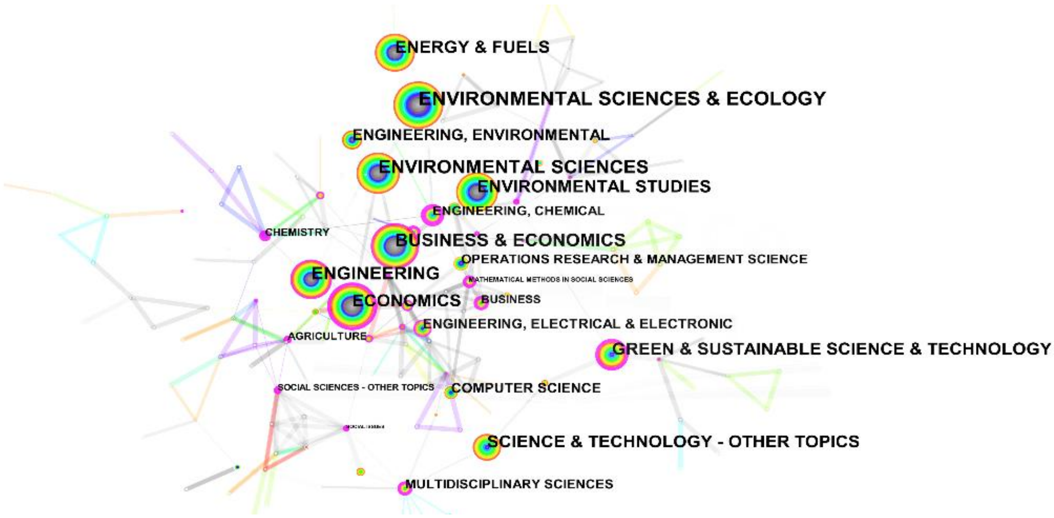

Figure 2. *Popularity and correlations of carbon trading and carbon pricing in different fields*

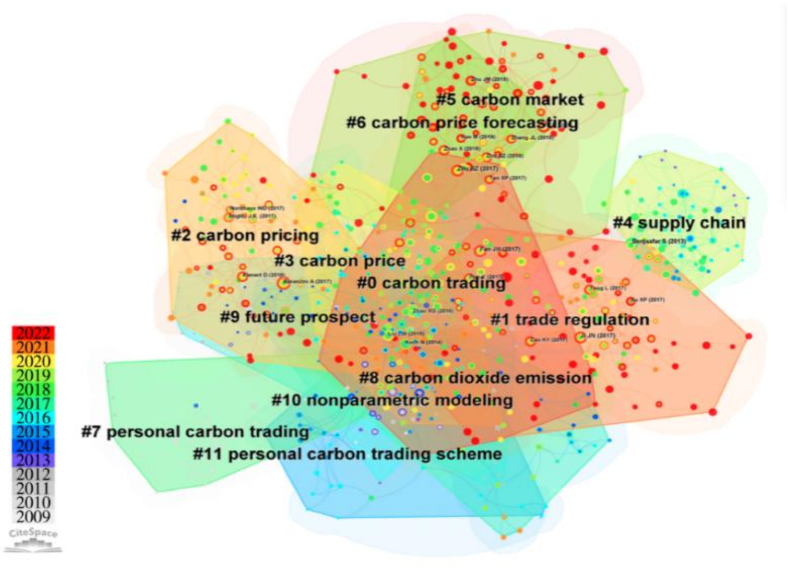

Figure 3. *Schematic of co-cited literature in carbon pricing based on Web of Science database*

As a result, the purpose of this study is to methodically examine and evaluate the current status of carbon trading and pricing mechanisms, challenges, as well as global strategies and environmental and ecological effects.

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GHG emission and carbon pricing strategies

Due to rapid global industrialization, GHG emissions have been significantly increasing, becoming one of the dominant driving factors of global warming (Huisingh et al., 2015). Indeed, energy consumption, industrial production, and land use change are major sources of GHG emissions, and the oil and gas industry dominates, especially in major emission entities such as China (Howard, 2017; Lazarus et al., 2018). Control of carbon emissions by the oil and gas industry, including carbon capture and storage (CCS), energy structure optimization, and intelligent management systems, has attracted increasing attention globally (Dubey and Arora, 2022; Patel et al., 2022). Additionally, the energy utilization of agricultural waste is a key measure in reducing carbon emissions.

For instance, replacing fuel with straw as bioenergy has expanded significantly (Lee et al., 2021; Zhang, 2022), with global bioenergy production from agricultural residues reaching 15.5 EJ (exajoules) in 2023—a 25% increase since 2018—offsetting 1.8 billion tons of CO_2 emissions annually (IEA, 2023). In the EU alone, straw-based bioenergy use grew by 40% (2018-2023), displacing 12% of coal in heat generation (Bioenergy Europe, 2023). Meanwhile, advances in renewable energy (e.g., wind and solar energy) promote global carbon emission reduction (Taylor et al., 2023). Global wind and solar capacity surged to 2,300 GW in 2023, up from 1,200 GW in 2020. This generated 4,500 TWh of clean electricity—12% of global supply—avoiding 4.3 billion tons of CO_2 emissions in 2023 (IEA, 2023; IRENA, 2024). Solar PV installations alone grew by 35% YoY in 2023, with China accounting for 60% of new additions (BNEF, 2024). Therefore, investigations of characteristics and paths of carbon emissions in different fields are significant to low-carbon development and provide references for policymaking (Jiang, 2023; Yang et al., 2023).

At the policy level, economic measures are widely regarded as effective carbon emission regulation tools, and the carbon trading market and carbon pricing mechanism are extremely important (Johnson and Lee, 2023). Carbon Tax has made great achievements in various countries and regions. As of 2021, there were 61 carbon pricing mechanisms, covering 22% of global emissions. Among them, 30 countries used carbon taxes and 31 countries used carbon trading systems. The carbon price in Sweden and Switzerland exceeds 100 US dollars per ton, while the carbon price in the European Union is 50 US dollars per ton in the trading system. Furthermore, among OECD countries, France, India, South Korea, Mexico and the United Kingdom have reduced the carbon pricing gap (OECD, 2023). Carbon Tax encourages enterprises to reduce carbon emissions and invest in clean energy by taxing carbon emissions (Meng, 2024). An efficient carbon market mechanism can also optimize carbon emission resource allocation and enhance economic incentives for low-carbon transformation (Jiang, 2023). Taxation on GHG emissions (Carbon Tax) can effectively encourage enterprises and individuals to reduce carbon emissions and develop/apply clean energy, thereby achieving global climate governance. Carbon Tax has been launched in various countries and regions to reduce GHG emissions and promote a low-carbon economy. Taxation on carbon emissions can encourage enterprises and individuals to reduce carbon emissions and enhance awareness of carbon emission reduction. Previous studies have demonstrated that GHG emission has become one of the most severe global challenges (Wang, 2024). For GHG emissions in different industries (e.g., oil and gas, agriculture), the carbon emission reduction goals can be achieved by optimizing energy structure, accelerating technology innovation, and establishing a carbon market and pricing mechanism. These

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studies provide references for policymaking in carbon emission reduction and sustainable development (Huisingh et al., 2015).

The direct carbon pricing tools include "compliance" tools and a "Carbon credits system" in that carbon pricing mechanism. The "compliance" tools, including the Carbon Tax and emission trading system (ETS), are compulsory and require entities to pay for their GHG emission. The Carbon Credits system is voluntary, and the participants can acquire "Carbon Credits" (credits) with quantified and verified carbon emission reduction or carbon removal activities. Herein, the core part is the internalization of the externalities of GHG emissions by market-oriented approaches, which encourages enterprises to reduce carbon emissions. Indirect carbon pricing refers to tools that can change the prices of products related to carbon emission, and it is not proportional to the relative carbon emission of these products. For instance, fuel excise taxes on the fuel (e.g., gasoline and diesel) are based on consumed quantity, indirectly achieving carbon emission pricing by fuel combustion. Additionally, some emerging measures have been proposed to tax (carbon price) on imported or exported high-emission products via the carbon border adjustment mechanism (CBAM) to guarantee that the carbon costs of imported and local products are consistent. In this way, carbon leakage can be prevented, and competition fairness can be maintained.

Carbon Tax

Carbon Tax is a market-based environmental policy tool, and its core part is to reduce GHG emissions and promote low-carbon economic development by taxing carbon emissions and increasing the consumption cost of fossil energy (Nordhaus, 2019). Governments encourage enterprises to reduce GHG emissions by charging carbon emissions. Under the Carbon Tax scheme, governments set emission prices (i.e., tax rate), and the influences on carbon emission reduction depend on the enterprises' attitude on the price (Baranzini and Carattini, 2017). It has been demonstrated that Carbon Tax can effectively reduce carbon emissions without causing severe negative impacts on economic growth (Fischer and Fox, 2012). For instance, the GHG emission by manufacturing factories in British Columbia, Canada, has decreased by 4% since the launch of the Carbon Tax in 2008; this can be attributed to the fact that manufacturing factories tend to reduce energy consumption to minimum Carbon Tax (Murray and Rivers, 2015). Additionally, revenue from carbon tax can be used to compensate taxpayers and communities and minimize its negative influences on the economy (Metcalf, 2019).

Basic principles of Carbon Tax

The basic principles of Carbon Tax are as follows: enterprise behaviors are guided by tuning the carbon price so that enterprises with high carbon emissions face additional financial costs, which stimulates these enterprises to reduce carbon emissions (Parry and Williams, 2012). In practice, Carbon Tax is typically levied based on the carbon content of fuel or the amount of CO_2 produced by its combustion. For instance, carbon pricing mechanisms (e.g., Carbon Tax and ETS) have been applied in over 70 countries and regions by 2023 (World Bank, 2023). Carbon Tax can reduce carbon emissions and generate additional public revenue. According to statistics (IMF, 2019), 50 USD/t global Carbon Tax can create a tax revenue of 1.5 trillion USD, which is 1.5% of global GDP. Nevertheless, the Carbon Tax is practical performance depends on the tax rate, the scope

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of application in the specific industry, and government regulation (Metcalf, 2019). Specifically, low tax rates can barely generate effective price signals, while over-high tax rates lead to increased operation costs of enterprises, resulting in degraded international competitive advantages. Therefore, the Carbon Tax rate shall be set to achieve a balance of carbon emission reduction and economic feasibility.

Pricing mechanism of Carbon Tax

The government directly levies the Carbon Tax rate on carbon emissions, and governments determine the Carbon Tax rate. Carbon Tax aims to achieve carbon emission reduction by increasing the carbon emission cost (Metcalf and Weisbach, 2009). The Carbon Tax rates are determined based on social cost, carbon emission reduction goals, and economic affordability. Indeed, governments may set the Carbon Tax rate based on the Social Cost of Carbon (SCC), which refers to damages caused by carbon emissions to the ecology and society (Nordhaus, 2017). SCC reflects the long-term influences of carbon emissions on climate change, human health, and the ecosystem. To achieve specific carbon emission reduction goals, governments would set an appropriate Carbon Tax rate so that enterprises are financially motivated to reduce carbon emissions. Herein, the Carbon Tax rate is proportional to the urgency and difficulty of the carbon emission reduction goal. Also, the Carbon Tax shall be set with the economic affordability of enterprises taken into consideration to avoid excessive impacts on the competitive advantage of enterprises and economic growth. Therefore, Carbon Tax is typically accompanied by tax refunds and/or subsidies to balance economic growth and environmental protection (Aldy and Stavins, 2012).

Carbon Tax in different countries and regions

Carbon Tax has been launched in various countries and regions, while the tax rate, scope of application, and ultimate performance may vary (World Bank, 2024). The results illustrated in *Fig. 4* prove that the design of Carbon Tax varies significantly among different countries, which can be attributed to differences in economic level, energy structure, and political environment.

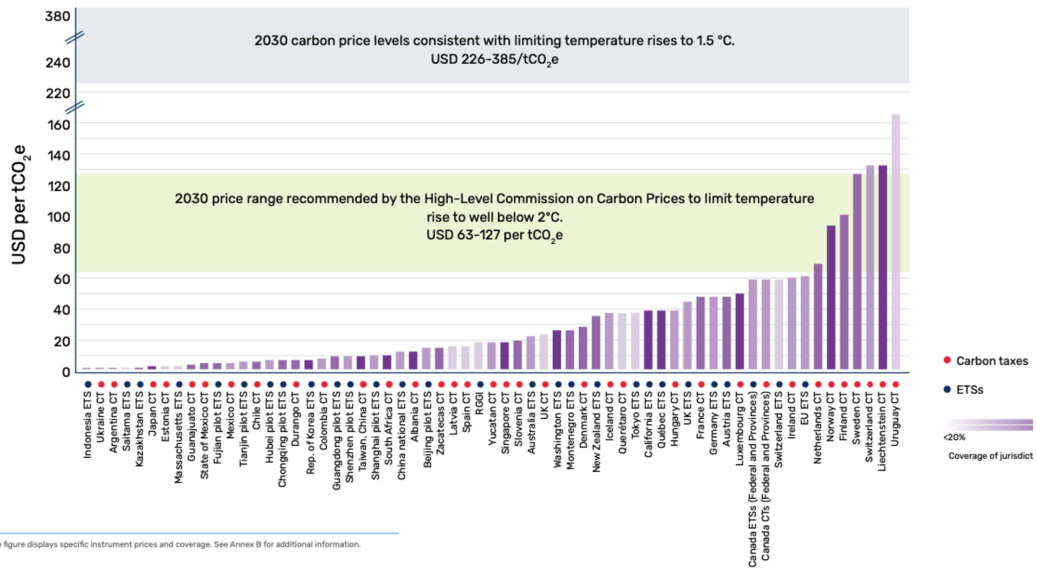

Figure 4. *Carbon Tax rates in different countries and regions (World Bank, 2023)*

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In *Fig. 4*, red bars refer to the carbon price. For instance, the Carbon Tax in Uruguay has reached 165 USD/t. Meanwhile, either Carbon Tax (red) or ETS (blue) can dominate, while both Carbon Tax and ETS can be present in some countries and regions. Sweden is one of the earliest countries to launch a Carbon Tax. A Carbon Tax system has been applied in Sweden since 1991, and the tax rate increased from 27 USD/t in 1991 to 130 USD/t in 2024, which is one of the highest tax rates in the world; the Carbon Tax system in Sweden covers various fields, including energy, industry, and transportation. As a result, the carbon emission in Sweden fell by 30% (from 55 $MtCO_2e$ in 1990 to 38 $MtCO_2e$ in 2023) while GDP grew 60% (OECD, 2023). The Swedish government supports renewable energy and energy efficiency technology using the revenue from the Carbon Tax, resulting in a low-carbon transition in its economy. In Canada, the federal government sets a minimum tax rate, while the provincial governments can set a specific rate; alternatively, the provincial governments can choose to participate in the carbon market (Government of Canada, 2023). In 2023, the minimum Carbon Tax rate set by the federal government of Canada was 65 CAD/t (~50 USD/t), and it would be elevated to 170 CAD/t (~130 USD/t) in 2030 (SMSE, 2023). In 2021, the Carbon Tax in Canada generated revenue of 6 billion CAD, 90% of which was used to compensate the communities, especially low-income families (Government of Canada, 2023). In Singapore, Carbon Tax was launched in 2019, with an initial rate of 5 SGD/t (~3.7 USD/t), and the tax rate would be increased to 50-80 SGD/t (~37-60 USD/t) in 2026 (Singapore Ministry of Sustainability and the Environment, 2023). Despite the absence of a nationwide Carbon Tax, China has launched the largest ETS, which covers the power industry and would be expanded to other industries with high carbon emissions, including steel, building materials, and petrochemicals (Ministry of Ecology and Environment of China, 2023). Currently, the Chinese government regards Carbon Tax as a complementary policy: The Carbon Tax in China shall be 50-100 RMB/t (~7-14 USD/t) and 200 RMB/t (~28 USD/t) by 2030 and 2060, respectively (Tsinghua University, 2023). In the UK, the carbon tax was launched in 1993, and a carbon price-supporting mechanism was established in 2013 (Carbon Price Support, CPS); an additional carbon tax is applied to enterprises in the power industry (UK Government, 2023). Currently, the Carbon Tax rate in the UK is 18 GBP/t (~23 USD/t) for coal- and gas-based power plants. In France, Carbon Tax has been launched since 2014, with an initial rate of 7 EUR/t (~7.5 USD/t); the Carbon Tax reached 44.6 EUR/t (~48 USD/t) in 2018 (French Ministry for the Ecological Transition, 2023). In Russia, no national Carbon Tax has been launched. At the same time, a carbon trading pilot is conducted in Sakhalin Oblast, and a nationwide Carbon Tax is on the way (Russian Ministry of Economic Development, 2023). Russia is the fourth largest carbon emission entity, and its economy is highly dependent on oil and natural gas exports, making it resistant to Carbon Tax. Fortunately, the Russian government intends to launch a low-rate Carbon Tax owing to the EU's carbon border adjustment mechanism (CBAM) to avoid the influences of a high Carbon Tax on its exports.

Carbon emission trading system

Generally, the carbon price in ETS emission trading system (ETS) is determined by the supply and demand of allowances in the market. Examples are the "cap-and-trade" and "rate-based" approaches (Dissou and Karnizova, 2016). ETS has been demonstrated to effectively reduce GHG emissions without significantly impacting economic growth

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(Xie et al., 2023). For instance, carbon emissions have decreased continuously since the launch of EU ETS in 2005 (Ellerman et al., 2016). Additionally, ETS encourages enterprises to reduce carbon emissions and develop a competitive edge by achieving technology innovation and enhancing energy efficiency (Ellerman et al., 2008). Cap-and-trade is a market-based economic tool for environmental regulation, wherein an upper limit is set for the total carbon emission (one allowance refers to 1 ton of CO_2 equivalent, tCO_2e), and the emission allowances are attributed to enterprises or other emission entities. If practical carbon emission by enterprises is lower than the emission allowance, enterprises can sell excess emission allowances to other enterprises; if practical carbon emission by enterprises is higher than the emission allowance, enterprises must purchase additional emission allowances from other enterprises. In other words, allowances can be traded among controlled entities and/or other traders. In this way, enterprises are encouraged by the market to achieve carbon emission reduction based on cost-effectiveness so that the carbon emission reduction goal (lowest total cost) can be ultimately realized (Ellerman et al., 2008; Stavins, 2008). Ellerman et al. (2008) reported that economic efficiency and flexibility are the most significant advantages of the carbon emission allowance trading systems. When the trading of emission allowances is allowed, enterprises are motivated to reduce carbon emissions based on cost optimization. Additionally, this system can facilitate the development of new technologies and clean energy, thereby providing financial support for environmental protection (Stavins, 2008). Recent studies have demonstrated that carbon trading systems have effectively reduced emission costs and promoted green technology innovations globally (Green, 2021). Also, the maturity of a carbon market is positively related to its performance in carbon emission reduction (Böhm et al, 2012; Hepburn et al., 2020).

Main carbon trading systems

The application of Carbon Tax has expanded globally. According to statistics (World Bank, 2024), carbon pricing mechanisms have been launched in over 75 countries and regions by 2024; Carbon Tax and ETS have been launched in 36 and 39 of them, respectively, as shown in *Fig. 5*. Herein, countries and regions with both Carbon Tax and carbon trading (purple), carbon trading (blue), or Carbon Tax (red), and countries and regions having the intention to launch Carbon Tax or carbon trading (light purple) are differentiated by colors.

European Union Emission Trading System (EU ETS)

As the first ETS, EU ETS is currently one of the largest and most successful carbon trading systems. By 2020, the EU ETS has covered approximately 11,000 facilities, and total GHG emissions by the European Union account for over 40% of global GHG emissions (European Commission, 2015). Since its launching in 2005, EU ETS has covered 27 EU members and some countries in the European Economic Area (European Commission, 2023). In EU ETS, “Cap-and-Trade” was applied, and the upper limit of carbon emission was continuously reduced. The carbon price in the EU ETS reached 50 (Koch et al., 2021) and 90 EUR/t (~97 USD/t), respectively, making EU ETS one of the carbon markets with the highest carbon prices (World Bank, 2023). Since 2005, carbon emissions by industries covered by the EU ETS have decreased by 43% from 1.9 $GtCO_2e$ in 2005 to 1.1 $GtCO_2e$ in 2021 (European Commission, 2021). Recent studies reveal that the EU ETS plays a key role in developing renewable energy and trans-industry cooperation in carbon emission reduction (Teixidó et al., 2019).

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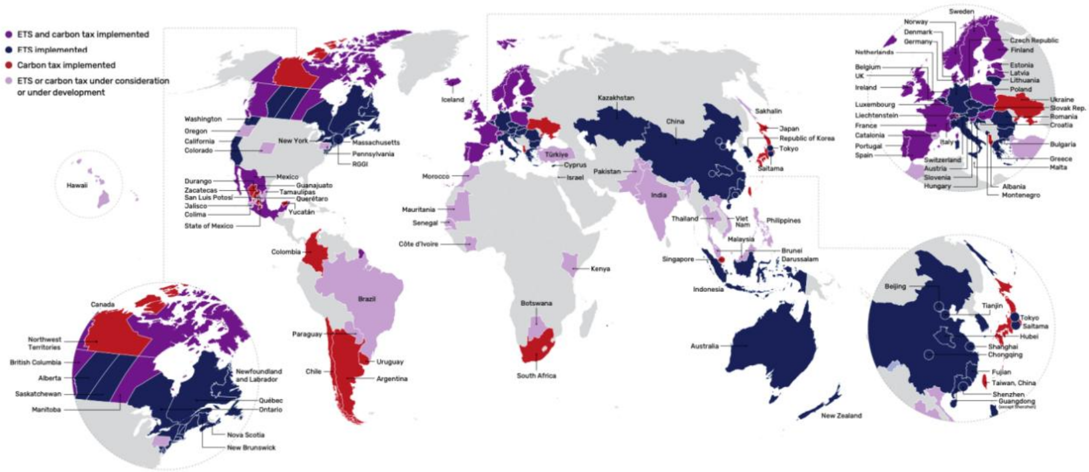

Figure 5. *Participations of different countries and regions in carbon trading (World Bank, 2024)*

Carbon market in China

In China, a national carbon emission allowance exchange was launched in 2017 and has become the largest single carbon market. In 2021, the total trading volume of the carbon market in China reached 410 million tCO_2e, with a transaction amount exceeding 1 billion RMB, i.e. ~140 million USD (Xie et al., 2023). The carbon market in China covers over 2000 power plants and involves carbon emission allowances of 4 billion tons (Wang and Li, 2021). Zhang et al. (2022) claimed that China's carbon market significantly impacts enterprises' environmental management and clean energy development. Nevertheless, China's carbon market faces various issues, including market reversal, data bias, and inadequate standardization. Although China has not yet formally implemented a nationwide carbon tax, academic and governmental studies propose initial rates ranging from 10 to 20 RMB/tCO_2 e, with long-term targets of 30-50 RMB/tCO_2 e (averaging -36 RMB/tCO_2 e). This aligns closely with the average carbon market price of 34.7 RMB/tCO_2 e observed during the same period.

Carbon market in North America

No national carbon trading market has been established in the USA, while regional carbon markets have been established in some states. For instance, the California Cap-and-Trade Program is one of the strictest carbon trading systems and has covered energy, power, industry, and transportation; the carbon allowance supply would be further reduced (California Air Resources Board, 2023). Additionally, the Regional Greenhouse Gas Initiative (RGGI) in the northeastern part of the USA has covered 11 states, and a combinatorial auction is employed to enhance the transparency of the carbon market (RGGI, 2024). The carbon markets in North America include carbon trading systems in California (i.e., the California Cap-and-Trade Program) and New England, and the RGGI; the California Cap-and-Trade Program was launched in 2013, and the accumulated transaction volume has exceeded 1 billion tCO_2e by 2020, with an annual transaction amount over 5 billion USD (Cushing et al., 2018). RGGI was launched in 2009, and its accumulated carbon emission reduction has reached 150 million t; the revenue has been used to apply clean energy and improve energy efficiency (Cosbey et al., 2019). Cushing

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et al. (2018) reported that these systems can facilitate carbon emission and promote economic growth and environmental protection integration. Nevertheless, regional carbon markets in North America are limited by low compliance and constraint performance. Recent studies have demonstrated that California's carbon market positively impacts the environmental welfare of social equity and low-income communities while achieving environmental protection goals (Rabe, 2022).

In 2019, a federal "backstop" set a national price on carbon throughout Canada, merging a fuel levy on most fossil fuels with the Output-Based Pricing System (OBPS) for large industrial sites, which mandates yearly decarbonization targets and generates emissions credits. Provinces and territories are free to design their own plans provided that they meet or exceed the federal floor (in effect, price of CAD$20/tonne) and slated to increase CAD$15 per tonne per year till CAD$170/tonne in 2030. Linked to California's cap-and-trade market since 2014, Québec's cap-and-trade scheme has embraced almost 80% of the province's emissions from electricity, manufacturing, and transport sectors. Before the start of the fourth year of auctions in early 2024, around CAD $9.9 billion was collected in province coffers, and over 11.4 million tons of CO_2 equivalent were traded in the 2020 compliance year alone (Government of Canada, 2025).

Mexico rolled out a pilot emissions-trading system in 2020, targeting power plants and factories that release at least 100 000 t CO_2 annually. Allowances have so far been handed out free, and officials have not yet published verified figures on volumes or market values for 2020–2021 (ICAP, 2025).

Carbon market of other countries

In 2021, a carbon trading system (UK ETS), which is highly consistent with the EU ETS, was established in the UK; free carbon allowances would be reduced gradually in the UK ETS (UK Government, 2023). In 2023, the carbon price in the UK ETS was approximately 60 GBP/t (~76 USD/t), which is one of the highest carbon prices globally. Additionally, South Korea, Japan, and Russia plan to introduce pilots of the carbon trading market. Matekele et al. (2024) investigated the application of carbon trading mechanisms in sub-Saharan African countries, especially Tanzania. Although carbon trading is an emerging field in Africa, the intention of local communities to adopt carbon trading is affected by multiple factors, including attitude, subjective norms, perceived costs, benefits, and education.

Pricing mechanism of ETS

ETS is a market-based carbon pricing mechanism wherein the governments set an upper limit of total emission (Cap), and carbon emission allowances are allocated to enterprises or auctioned (Ellerman et al., 2010). Enterprises are allowed to trade the allowances in the market, resulting in a carbon price. Indeed, pricing in ETS is mainly affected by supply and demand, policy regulation, and economic factors (Convery, 2009). Also, energy prices, technological progress, and the macroeconomic situation may affect the carbon price. For instance, increased fossil energy prices may lead to increased production costs for enterprises, thereby affecting the demand and price of carbon allowance (Newell et al., 2003). The carbon price in ETS is determined by supply and demand: at a fixed allowance supply, increased demand for allowance by enterprises would cause increases in the carbon price, and vice versa (Pietzcker et al., 2021). For instance, economic growth increases manufacturing activities, carbon allowance demand, and carbon prices (Zhang and Chen, 2022). On the other hand, governments can regulate

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the carbon price by tuning the total allowances to achieve market stabilization (e.g., upper and lower limits of carbon price). For instance, the market stability reserve (MSR) was introduced into the EU ETS to counteract allowance redundancy and carbon price fluctuation (European Commission, 2020). Khaqqi et al. (2018) proposed a blockchain-based ETS, which involves the reputation of both sellers and buyers to enhance the efficiency and reliability of emission trade. The block-based credit emission trading scheme (BCRB), a novel ETS model with blockchain as the frame and credit trading system as the transaction mechanism, was established. *Figure 6* shows the ETS method and its correlation with elements in the ETS policy. Herein, the shaded area refers to elements in the BCRB model. Blockchain and smart devices are employed to support one element (i.e., monitoring, verification, and reporting) of the ETS. Meanwhile, blockchain and smart devices can support credit systems as fundamental credit trading systems. The credit trading system comprises market segmentation and prior value order mechanisms. In this way, fraud issues in conventional ETS can be avoided due to the high transparency and traceability of blocks, and participants are encouraged to fulfill the carbon emission reduction obligations by the credit system, thereby optimizing pricing and trading of carbon allowance.

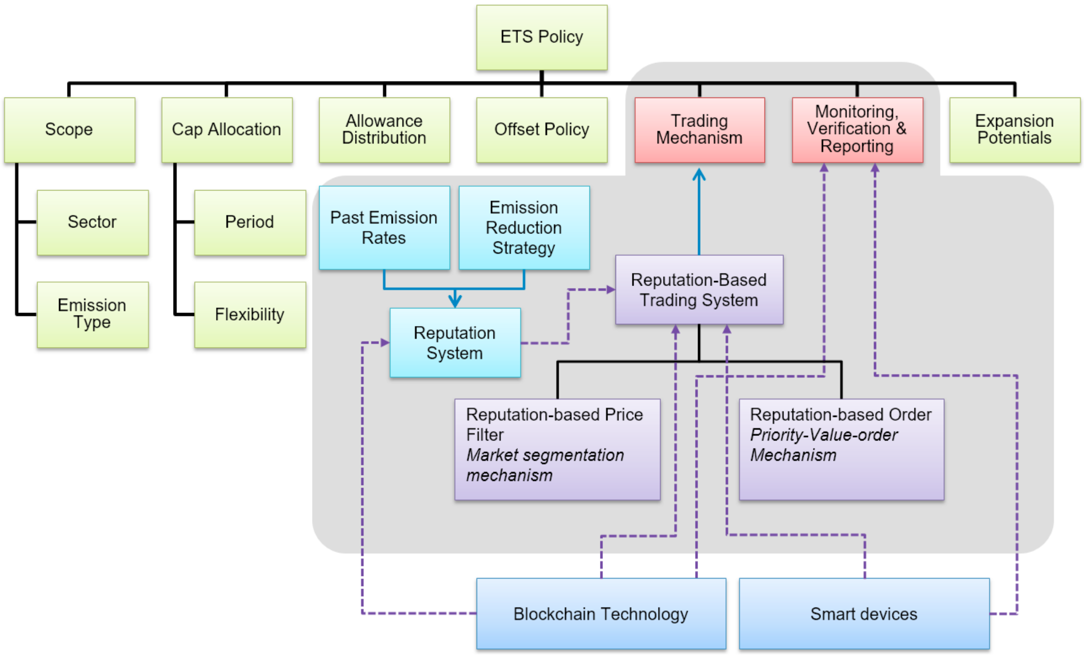

Figure 6. *ETS policy's elements and the approach of the proposed model (Khaqqi et al., 2018)*

Carbon Emission Allowance Options (CEAO) is an ETS-derived tool depending on the price of carbon emission allowances set by the ETS (Liu, 2023). It provides a hedging tool for price fluctuations via the options mechanism, wherein the holders are given the right to buy and sell the carbon emission allowances at a predetermined price within a specific period in the future (Chevallier, 2011). The CEAO aims to provide a flexible carbon pricing mechanism to minimize transaction risks and optimize carbon emission reduction costs (Jiang and Shao, 2023). The Black-Scholes (B-S) model, which is based on the no-arbitrage hypothesis and can provide references for market pricing, was the first model used for pricing carbon emission allowance options (Black and Scholes, 1973).

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Despite its wide applications in financial markets, the BSM model shows limited applicability in the carbon market owing to the non-linear fluctuation of the carbon price and policy influences. Therefore, the BSM model has been improved.

As the carbon price tends to show long-term memory and auto-correlation, the fractional Brownian motion (FBM) model has been introduced to improve the BSM model. The FBM model assumes that carbon price complies with a random process with the Hurst exponent to effectively reflect long-term trends of the carbon markets (Ahirwal and Maiti, 2022). Owing to fluctuations in the carbon markets, the generalized autoregressive conditional heteroskedasticity (GARCH) model is typically employed to describe fluctuations in carbon price. The GARCH model dynamically adjusts volatility parameters to reflect accurate market fluctuations (Lo, 2016). Also, the regime-switching jump-diffusion model (RSJM) has been introduced to enhance model applicability further. In the RSJM model, the options price can be dynamically tuned based on the market conditions (Li et al., 2023). The jump-diffusion model (JDM) can effectively describe the jumping of market prices and enhance pricing sensitivity (Böhm et al., 2012). Recent studies have demonstrated that nonparametric methods integrating RBF neural networks can further enhance model robustness and prediction accuracy (Han and Liu, 2023).

Pricing of carbon emission allowance options is a hot topic in studies of the carbon market. Despite reasonable applicability, conventional BSM models show limitations in carbon pricing under high uncertainty of the carbon market and policy risks. Artificial intelligence (AI) and machine learning (ML) have recently been widely applied in financial pricing. Improved models (e.g., FBM, GARCH, and RSJM) show enhanced market adaptability, and AI methods further increase their prediction capabilities. Recently, approaches based on the radial basis function network (RBF) model, the long- and short-term memory (LSTM) model, and the LSTM/GARCH-SVR decomposition integration model have been introduced to studies of pricing of carbon emission allowance options to enhance the prediction accuracy (Dong et al., 2023). First, the RBF model can handle non-linear data and be used for carbon pricing. It has been demonstrated that the RBF model showed improved prediction accuracy compared with conventional BSM models, especially in the capture of non-linear features of the carbon price (Lo, 2016). Then, the LSTM model is a deep learning model specific for processing time-series data, and it can effectively identify long- and short-term dependencies in data. The LSTM model has been widely applied to analyze and predict carbon price fluctuation for carbon price prediction. For instance, Wang (2024) reported a model integrating LSTM and a broad learning system (BLS), which was then used for the prediction of carbon emission allowance prices in Hubei, China. The results showed that this model exhibited great advantages in predicting accuracy and efficiency. Liu (2022) predicted the carbon emission allowance transaction price using the LSTM/GARCH-SVR decomposition integration model, aiming to facilitate rational asset management and optimization of resource allocation and achieve sustainable development of carbon trading markets. Overall, the LSTM model shows great advantages in the process of complicated and non-linear features in carbon price prediction. The LSTM model can identify potential trend changes based on historical data, providing valuable references to investors and policymakers. In the future, pricing approaches combining multivariate analysis, machine learning, and market dynamics will attract great attention in pricing carbon emission allowance options.

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Carbon Credits system

Carbon Credits system is a market-oriented tool based on voluntary carbon emission reduction activities. Herein, enterprises or individuals can acquire tradable Carbon Credits by conducting activities that comply with the carbon emission reduction protocol, wherein each Carbon Credit refers to a reduction of 1 tCO_2e. Carbon Credits can be acquired by reducing carbon emissions (e.g., methane capture in landfills) or removing GHG (e.g., carbon fixation by afforestation). The Carbon Credits can be sold to enterprises or governments to compensate carbon emissions, wherein possible capita sources include compliant markets (e.g., ETS or Carbon Tax with carbon offset allowable), fulfillment of Nationally Determined Contributions (NDCs) goals, voluntary carbon offset of enterprises, and outcome-based climate financing (Kreibich and Hermwille, 2021). The Carbon Credits system provides flexibility to enterprises that can barely achieve carbon emission reduction by themselves and provides financial support to organizations aiming to achieve carbon emission reduction (Kollmuss et al., 2008). Nevertheless, such a mechanism faces great challenges, such as verification of authenticity and additionality of Carbon Credits (Cames et al., 2016).

Additionally, some emerging measures have been applied to charge imported/exported high-emission products regarding carbon price via the border carbon adjustment (BCA) to guarantee that the carbon costs of imported and local products are consistent. In this way, carbon leakage can be prevented, and competition fairness can be maintained. Nevertheless, BCA has not yet been widely incorporated into current carbon pricing systems (Mehling et al., 2019). EU has been trying to launch the CBAM, which requires payment of additional carbon costs for high-emission products exported to the EU. As a result, countries and regions that are business partners of the EU intend to launch Carbon Tax to avoid export degradation. Indeed, BCA may affect international trade, especially exports from developing countries (Böhringer et al., 2016). Therefore, the application of BCA shall consider its potential influences on global trading and the economy (Cosbey et al., 2019).

Overall, Carbon Tax shall be designed and applied based on the local economy, energy structure, and social development. Some countries and regions (e.g., Canada, Singapore, UK) increase the tax rate gradually, while others (e.g., Sweden and France) set high initial tax rates (Torres et al., 2022). Both international pressure and economic conditions may affect decisions by countries and regions with no Carbon Tax yet (e.g., China and Russia). Due to exacerbating global climate changes, countries and regions have been exploring carbon pricing strategies suitable for their specific situations to promote a green economy while inhibiting carbon emissions.

Integration of carbon market into ecology and environmental science

Role of the carbon market in biodiversity protection

The carbon market has been playing an increasingly important role in bio-diversity protection, especially with the synergy of mechanisms such as REDD+, which aims to reduce carbon emissions caused by deforestation and forest degradation. Specifically, REDD+ provides economic incentives to developing countries to facilitate forest protection and recovery, reduce carbon emissions, and protect biodiversity (Angelsen et al., 2018). Indeed, appropriate carbon offset plans can effectively protect tropical forest, which has unparalleled influences on global bio-diversity (Griscom et al., 2020). For

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instance, REDD+ in Amazon has protected over 35 million hectares of tropical forest, reducing carbon emission by 1 billion t (Hou et al., 2024). Nevertheless, this mechanism faces challenges in long-term performance and sustainability: (1) how to guarantee permanent effects of protective measures; (2) how to address/eradicate the fundamental driving factors of forest degradation (Rosenbloom et al., 2020). Additionally, the carbon market and bio-diversity credit systems shall be integrated. For instance, encouraging enterprises and governments to invest in bio-diversity protection and allow carbon offset trading may be a more comprehensive ecological protection strategy (Murray et al., 2015).

Role of ecological compensation mechanisms in the carbon market system

The ecological compensation mechanisms play a key role in the carbon market system, and methods based on natural carbon sequestration (e.g., forest recovery and wetland restoration) can achieve both carbon emission reduction and ecosystem recovery (Were, 2019). For instance, wetland carbon sequestration can realize significant carbon storage and provide key ecosystem services (e.g., water purification and flood control). In the USA, approximately 50 million tons of Carbon Credits, mainly from forest and wetland restoration in northern California, have been registered in California's forest carbon offset project (CARB, 2022). In the EU, the Natural Restoration Law came into force in 2023, and it requires the recovery of at least 20% of damaged ecosystems by 2030; forest and wetland Carbon Credits trading markets have been established (European Commission, 2023). In China, the ecological compensation fund has exceeded 20 billion RMB under the "ecology for economy" scheme, and some forest and agriculture carbon sinks have been involved in the national carbon market (Zhang et al., 2022). Additionally, these mechanisms are consistent with Payments for Ecosystem Services (PES), wherein land owners receive financial compensation for maintaining and/or improving ecological functions, thereby facilitating thorough integration of carbon finance and ecological protection strategies (Salzman et al., 2018). The "blue carbon" market (i.e., marine ecosystem carbon sinks such as mangrove forests and seagrass beds) has been introduced to carbon trading systems. For instance, blue carbon-based Carbon Credits systems are launching in Australia and the UAE (Howard et al., 2017).

Contributions of different carbon trading modes to ecosystem service and sustainable development goals (SDGs)

Different carbon trading systems show differences in the integration level of ecosystem service and SDGs (Dong et al., 2022). For instance, EU ETS previously focused on carbon trading of industrial emissions and has expanded to land use and forest carbon sink compensation (European Commission, 2021). In the China carbon market, carbon sink trade in agriculture and forest have been introduced to the pilot projects, and they exhibit improved ecological adaptability and great potential for sustainable development (Zhang et al., 2022). The carbon market in California has involved carbon sinks of forest and agriculture, and the transaction volume in 2022 exceeded 560 million tons of CO_2, wherein the forest projects accounted for 14% of the total transaction (CARB, 2022). In South Korea, carbon emission reduction allowances were set for enterprises, and the Carbon Credits auction mechanism was introduced to the carbon trading market in 2023; the carbon price exceeded 40 USD/t (Wu et al., 2019). In Canada, a national carbon pricing mechanism was applied, and the carbon price is 65 CAD/t; the revenue has been partially invested in a green fund that provides financial support to

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ecological rehabilitation (Government of Canada, 2023). Integrating the carbon market and SDGs is significant to sustainable development. The carbon pricing mechanism can directly facilitate SDG 13 (climate action), thereby promoting carbon emission reduction by market incentives; it indirectly facilitates SDG 15 (terrestrial animals), thereby promoting forest protection and land restoration (United Nations, 2021). Nevertheless, the application of the carbon market faces issues in ecology. For instance, large carbon sequestration projects may induce the expansion of single plants (e.g., planted forests for carbon sink), which achieves carbon storage at the cost of degradation of habitat diversity (Koh and Ghazoul, 2010). Therefore, future carbon finance policies shall prioritize multifunctional land use strategies to achieve the balance of carbon emission reduction goals and ecological integrity.

Challenges and prospects

The carbon pricing mechanism plays a key role in global climate policymaking. We face challenges such as low carbon prices, low policy coverage, and uneven development.

Challenges

Low global carbon price

Currently, only 5% of carbon prices of GHG emissions covered by carbon pricing have reached the level required to achieve the goals of the Paris Agreement. For instance, the average carbon price in the EU ETS was 25 EUR/t in 2020, while the carbon price must reach 100 EUR/t to achieve carbon neutrality by 2050 (European Commission, 2020). Over-low carbon prices can barely generate sufficient economic incentives for enterprises to reduce carbon emissions (Ellerman et al., 2010).

Limited policy coverage

Despite expanding the range of global carbon pricing mechanisms,carbon pricing will only cover 23% of global carbon emissions (vs. >50% needed for Paris alignment), omitting aviation (2.5% global emissions) and shipping (3%) by 2023 (Metcalf and Weisbach, 2009; IEA, 2023). The carbon market remains absent in many countries and regions, especially developing countries, resulting in limited global carbon emission reduction performance (Zhang et al., 2022). Additionally, the coverage of the carbon market remains low in some industries (e.g., aviation, shipping, and agriculture) (Pietzcker et al., 2021).

Uneven development

Currently, the carbon pricing mechanism is mainly applied in developed countries, including the EU, China, the USA, and Canada, while the carbon market in developing countries is still in its infancy. As a result, the fairness of the carbon market in international trade is doubted. More importantly, carbon leakage (high-emission enterprises shift production to countries and regions with low or no carbon prices) may be triggered, resulting in global degradation of carbon emission reduction performance (Nordhaus, 2017).

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Social acceptance and political resistance

Carbon Tax and ETS may cause increases in energy prices, which will negatively effect low-income communities as a result, as demonstrated by France's 2018 “Yellow Vest” that were started by fuel tax rises (Aldy and Stavins, 2012; World Bank, 2023). Furthermore, particular markets and sectors commonly get exemptions that lower policy efficacy. For example, while South Korea exempts export-dependent enterprises from the EU, EU grants free ETS allowances to the energy-related sectors such as the production of steel and cement, whereas the EU exempts the exports of these sectors. Similar to this, Germany grants shipping tax concessions and the British Columbia of Canada's carbon levy on the aviation and agricultural industries (IEA, 2023).

Future prospects

Besides serving as a key tool of environmental governance, a carbon trading mechanism can help to achieve the carbon emission reduction goal at the macroscopic level. Analysis of policies during the application of the carbon trading mechanism reveals that effective policy implementation depends on the active participation of all entities and the optimization of market rules. Therefore, governments, enterprises, and social communities shall participate to guarantee the efficient operation of carbon trading markets. Du (2022) investigated the practical experiences of the EU and found that the advantages of EU ETS in economy, environmental protection, and technology innovation provide valuable references to China. The results also demonstrated that the EU promotes a green economy, facilitates the development and applications of clean technology, and enhances enterprises’ environmental responsibility awareness using a carbon pricing mechanism. Jiang and Shao (2023) emphasized the significance of international collaboration in carbon markets by exploring possible paths of international trading of carbon emission allowance. In the context of globalization, the synergy of regional markets favors handling global climate issues. Indeed, by promoting international collaboration and knowledge sharing, different countries and regions can learn from each other, share resources, and deepen collaboration and optimization in carbon trading to achieve the global carbon emission reduction goal.

Increasing carbon price

To achieve the goals in the Paris Agreement, the carbon price shall be increased gradually to reflect the environmental costs of carbon emission and enhance market incentives for carbon emission reduction (Nordhaus, 2017). For instance, the EU plans to increase the carbon price to 100 EUR/t by 2030 (European Commission, 2020). Also, a dynamic adjustment mechanism for Carbon Tax is suggested, wherein the tax rate is adjusted regularly based on inflation and technological innovations to guarantee good long-term carbon emission reduction performance.

Expanding policy coverage

Countries and regions should try to establish and optimize the carbon pricing mechanisms and expand their range of industries and emission sources covered by the carbon pricing mechanism (Chevallier, 2011). Especially, ETS and/or Carbon Tax shall be introduced to industries with no mature carbon markets (e.g., aerospace and agriculture) (Parry, 2020). Carbon markets’ full connection and integration will also be a future trend. For instance, the integration of EU ETS with the carbon markets in

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Switzerland and the UK to develop a large carbon trading system is underway (Zhang and Wen, 2022).

Enhancing international collaboration

Countries and regions shall deepen coordination and collaboration in carbon pricing to develop Cross-Border Carbon Trading Agreements and minimize price distortion among regional carbon markets, thereby improving market efficiency. Meanwhile, countries and regions shall be devoted to establishing a universal or mutually recognized Global Carbon Credit System, wherein enterprises in different countries and regions can recognize each other's carbon emission reduction credit to enhance the credit liquidity in carbon markets (Metcalf and Weisbach, 2009). Additionally, countries and regions shall apply CBAM on imported high-carbon products to prevent carbon leakage (European Commission, 2020). In the future, such a mechanism can encourage more countries and regions to participate in carbon markets, resulting in universal carbon pricing standards (Ellerman et al., 2010).

Developing carbon finance market

Owing to great advances in carbon markets, carbon finance products (e.g., carbon options, carbon futures, carbon index funds) are believed to play more important roles in the future (Lee et al., 2021). A future trend is the securitization transaction of carbon emission reduction projects and/or Carbon Credits of enterprises, which can increase capital liquidity in carbon markets. Meanwhile, more accurate carbon options pricing models shall be developed by integrating financial markets and environmental economics to tackle market fluctuation and policy changes (Li et al., 2023). The Carbon Credits market shall also be integrated with a green financial system to provide more financing channels to low carbon projects. Development and optimization of the carbon finance market can make several contributions: (1) improving participation willingness of enterprises and investors; (2) providing risk management tools to enterprises to minimize financial uncertainty induced by carbon price fluctuations; (3) facilitating green investment, to guide capital to renewable energy and low carbon technology (Fan et al., 2020).

Integration with AI and Blockchain

In the future, AI and blockchain will play key roles in carbon trading and carbon market regulation (Lee et al., 2021). AI tools can be used to predict the future trend of carbon prices, thereby enhancing the efficiency of ETS and trading of carbon finance products (Zhang et al., 2019). Blockchain can enhance the transparency of carbon trading, thereby preventing fraud in Carbon Credits and improving market trust (Chevallier, 2011).

Policymakers shall make efforts to promote fairness, sustainability, and transparency in carbon pricing mechanisms to achieve global climate goals. Researchers may focus on the synergy of technology innovation and policymaking to promote low-carbon technology and sustainable economic growth. Technological innovation is a key driving force in solving carbon emission issues (Smith et al., 2022) Researchers and policymakers shall work together to promote the development and application of low-carbon technology, thereby achieving carbon emission reduction goals and facilitating sustainable economic development. Future studies shall also involve empirical studies,

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trans-regional comparison, and synergy of technology innovation and policy making, and provide more effective methods and strategies for climate change and sustainable economic development by overcoming limitations and challenges of previous studies.

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