PLANT SCIENCE TODAY
Vol 12(sp1): 01–13
https://doi.org/10.14719/pst.9175

eISSN 2348-1900

REVIEW ARTICLE

Carbon trading across borders: A comparative review of global trading mechanisms

M Nithya Priya[1], C Velavan[1*], T Samsai[2], R Premavathi[3] & S Senthilnathan[4]

[1]Department of Agricultural and Rural Management, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[2]Directorate of Planning and Monitoring, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[3]Department of Agricultural Extension and Rural Sociology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[4]Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Correspondence email - velavanc@tnau.ac.in

Received: 28 April 2025; Accepted: 03 July 2025; Available online: Version 1.0: 09 September 2025; Version 2.0: 29 September 2025

Cite this article: Nithya Priya M, Velavan C, Samsai, Premavathi R, Senthilnathan S. Carbon trading across borders: A comparative review of global trading mechanisms. Plant Science Today. 2025;12(sp1):01–13. https:/doi.org/10.14719/pst.9175

Abstract

The intensifying effects of global warming have pushed countries globally to adopt measures to reduce greenhouse gas (GHG) emissions. Collective national and international measures are necessary, as unbridled carbon emissions continue to exacerbate global warming, extreme weather, sea-level rise and to decline agricultural productivity, posing serious threats to food security, economic stability and public health. Developing countries are particularly vulnerable, with estimated annual climate-related changes exceeding USD 1.7 trillion due to their limited adaptive capacity. Addressing these causes, Carbon Trading presents a market-oriented solution, aspiring to mitigate GHGs by facilitating the buying and selling of emission permits. Under the Paris Agreement, a strongly regulated and tailored carbon market tailored to specific conditions can incentivize cost-effective mitigation, encourage green innovation and promote clean energy and net-zero efforts. A lack of a strong carbon market can lead to significant economic losses, with estimates suggesting that the potential reduction in GDP for developing countries could be as high as 2.8 % by 2050. However, significant challenges remain in price stability, carbon leakage avoidance and coordination with wider policy frameworks This review takes up carbon trading systems across six jurisdictions, *viz.* the European Union, China, New Zealand, Switzerland, South Africa and India, assessing their structure, problems of implementation, economic efficiency and environmental efficacy within the environments of both developing and developed economies. The reviewed literature reveals notable differences in market maturity, sectoral coverage and price management mechanisms, highlighting significant variations in these areas along with specific challenges.

Keywords: carbon markets; carbon quota allocation; challenges faced; emission reduction; sectoral coverage

Introduction

Climate change remains one of the most urgent global challenges, primarily driven by the rise in greenhouse gas (GHG) emissions. Since pre-industrial times, the global average temperature has increased by approximately 1.1 °C, leading to more frequent and intense climate-related disasters, biodiversity loss and environmental degradation. To address this crisis, the international community has committed to a 45 % reduction in GHG emissions by 2030 and achieving net-zero emissions by 2050, aiming to limit global warming to well below 2 °C, preferably 1.5 °C. However, delayed climate action may push the world toward an "Emissions cliff edge", where catastrophic and irreversible consequences become unavoidable. Inaction also amplifies the difficulty, cost and severity of future mitigation, especially the rising food demand, fossil fuel dependence and land degradation exemplified by China's significant contribution of 15.93 Gt CO_2-eq (Fig. 1).

The Emission Trading System (ETS), or Carbon Trading, is a market-based approach to reducing GHG emissions by imposing a monetary value on carbon. Under this system, a governing body sets an emission cap and entities trade allowances, promoting cost-effective mitigation. The concept of ETS emerged from global climate efforts under the United Nations Framework Convention on Climate Change (UNFCCC), particularly through the 1997 Kyoto Protocol, which introduced flexible mechanisms, namely Emissions Trading, the Clean Development Mechanism (CDM) and Joint Implementation (JI), to enable cost-effective emissions reduction. ETS has evolved as a central climate policy instrument, implemented across both developed and developing countries. The European Union Emission Trading System (EUETS), launched in 2005 as the largest carbon market, has inspired the establishment of similar systems in nations such as New Zealand, South Korea, China and Switzerland. As a key instrument for emission reduction, innovation and low-carbon investment across both developed and developing countries. However, policy gaps, institutional limits and economic constraints hinder its adoption in some regions. Despite these barriers, carbon markets continue to struggle with price volatility, inconsistent regulation and the risk of carbon leakage.

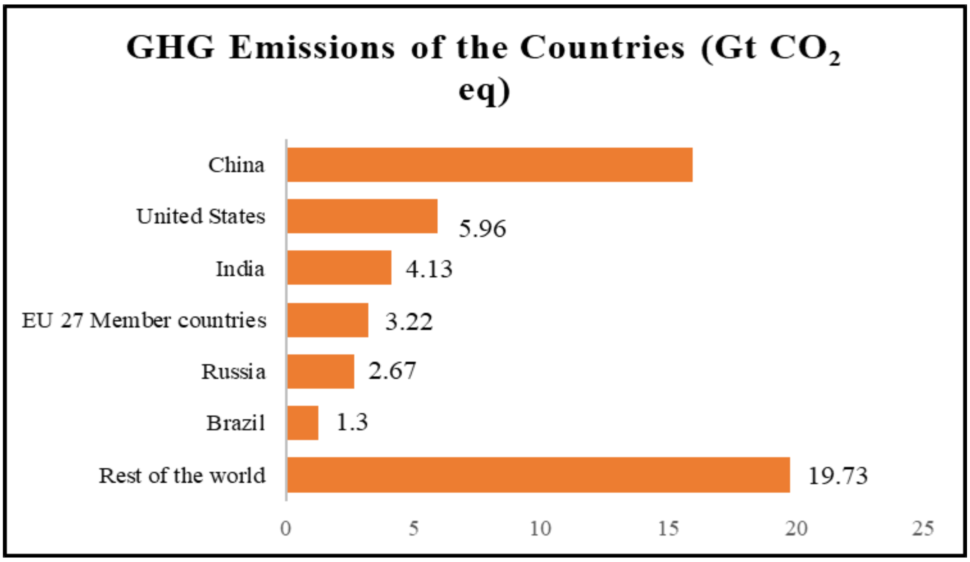

Fig. 1. GHG emissions of the countries in Gt (Gigatons) CO_2 eq.

COP 29, the 29th United Nations Climate Change Conference, was held in November 2024 in the capital city of Azerbaijan, Baku. The "Finance COP" moniker highlights its focus on pressing the need for climate finance with major investments and a new financing target to drive developing countries forward in addressing climate change. COP29 plans to mobilize $300 billion annually to developing countries by 2035, with the long-term vision of achieving $1.3 trillion per annum through combined public and private funding.

This review paper discusses six selected jurisdictions based on economic status: high-income nations (European Union, Switzerland and New Zealand), upper-middle-income nations (China and South Africa) and a lower-middle-income nation (India) to enable a comparative understanding of ETS across economic tiers illustrated in Fig. 2 and in Table 1. The European Union is chosen for its pioneering and integrated carbon market, which serves as a global benchmark. New Zealand is notable for its unique inclusion of the forestry sector, incorporating carbon sequestration, offering a model for land-based mitigation strategies. Switzerland, despite its small scale, demonstrates regulatory innovation, a comprehensive sectoral coverage and successful cross-border market integration linked with the EU ETS. As the major global emitters and fast-growing economies, China and India play a critical role in shaping global climate outcomes and represent emerging market approaches to ETS. South Africa is chosen because it is a resource-intensive economy where carbon tax has been implemented, providing insights from the African continent. These countries were selected for their distinct policy approaches, environmental significance and availability of reliable data.

Carbon trading mechanisms: Country-wise analysis

European Union ETS

EU ETS, which came into operation on January 1, 2005, set binding CO_2 emission limits on energy and metal production industries to lower GHG emissions by 8 % below 1990 levels between 2008 and 2012 (6). Fig. 3 presents the GHG emissions across the country. The EU ETS has evolved through four phases and market regulations have led to improved emissions reductions, greater market stability and increased policy effectiveness (7). In its first phase (2005-2007), the EU ETS was

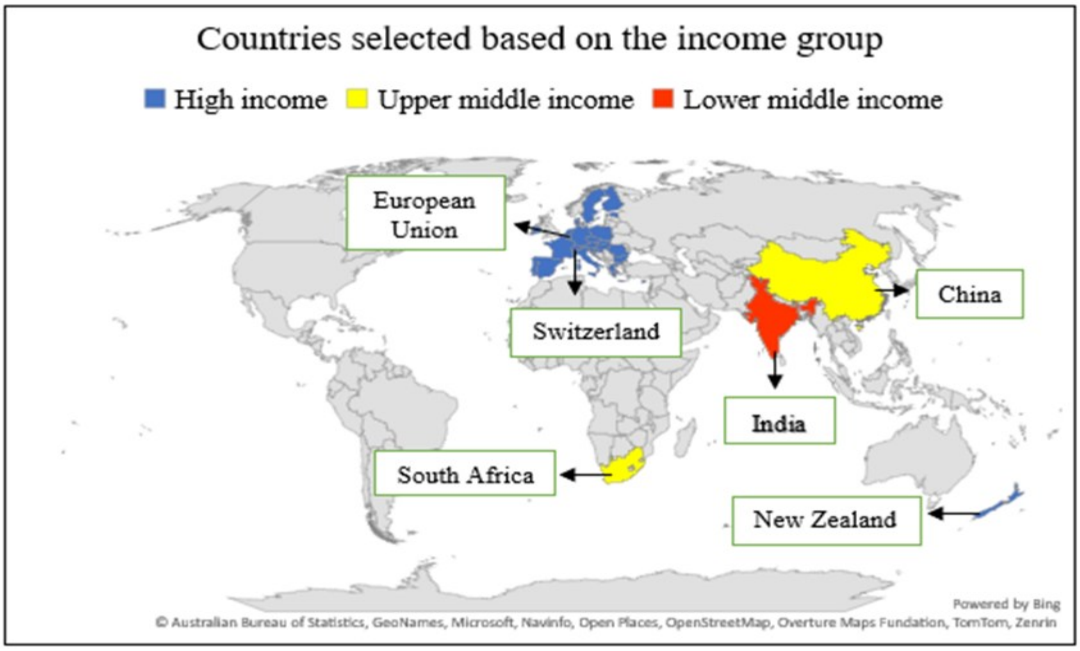

Fig. 2. Countries selected based on the income group.

Table 1. Comparative framework of the carbon trading of selected countries

Jurisdiction	Year	Allocation method	Sectoral coverage	Price per unit	Gas covered	Government revenue	Coverage threshold
European Union ETS	2005	Auctioning, Free allocation, Trading-Secondary market	Electricity & heat, Industry, Mining and aviation	USD 12.57	CO_2, N_2O, PFCs, SO_2	USD 47.1 billion (2023)	20 MW
Switzerland ETS	2008	Free allocation, Auctions	Electricity & heat, Industry, Mining and aviation	USD 87.67	CO_2, N_2O, SO_2	USD 38.8 million (2023)	20 MW
Switzerland Carbon Tax	2008	Set price	Electricity & heat, Industry, Mining, Buildings and Agriculture	USD 132.12	CO_2	USD 1617 million (2022)	NA
New Zealand ETS	2008	Free allocation	Electricity & heat, Industry, Mining, Buildings, Aviation, Agriculture, Transport, Forestry, fishing fuel use	USD 35.11	CO_2, N_2O, CH_4, SF_6	USD 21.3 million (2023)	25000 tCO_2 -e
New Zealand Carbon Tax	2008	Set price	No covered sectors	NA	All	NA	NA
South Africa	2019	Set price	Electricity & heat, Industry, Mining, Buildings, Aviation, Agriculture, Forestry, fishing fuel use, Waste	USD 10.09	CO_2, N_2O, CH_4, SF_6	USD 115 million (2022) (R1,689 million)	10 MW

Source Ref. (29, 54).

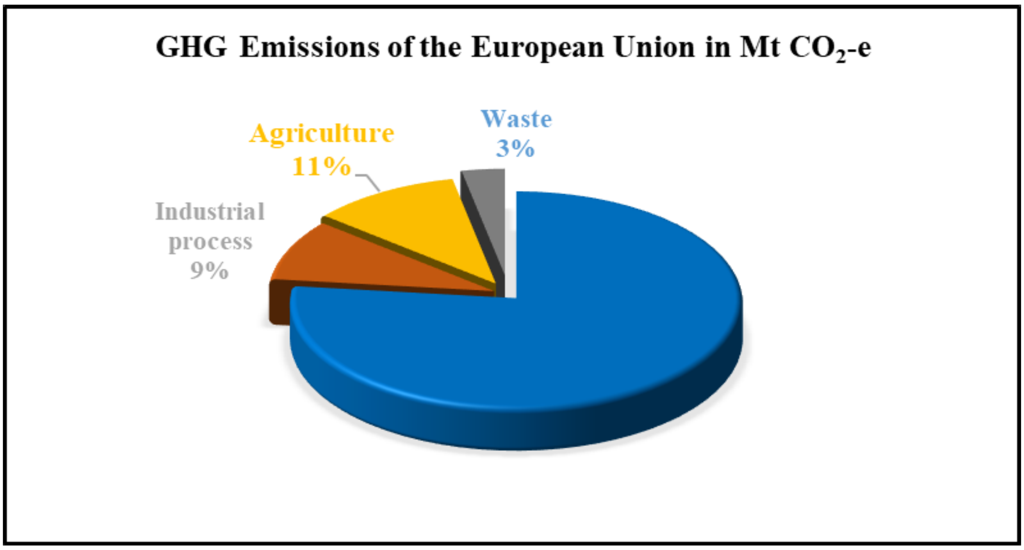

Fig. 3. GHG Emissions of the European Union in Mt CO_2 -e.

subject to the energy market but exerted a minimal overall effect (8). A study conducted in 2006 affirmed that the EU-ETS applies to over 11500 installations and captures around 45 % of the EU's CO_2 emissions. The trading participants and the regulating bodies of the European Energy Exchange are illustrated in Fig. 4. However, it did not cover non-CO_2 greenhouse gases, which accounted for 20 % of total emissions, reflecting its limited scope (9). Phase 1 (2005-2007) was a "learning by doing" phase that enhanced emissions data and encouraged the CDM and JI, shaping company choices in the power sector. Phase 2 (2008-2012) aligned with the Kyoto Protocol, expanded sectoral coverage, improved allocation methods and achieved further emission reductions despite the shortcomings experienced during Phase 1 (10). Phase 3 (2013-2020) improved distribution and new entrant reserves, enhancing market stability and reducing emissions by 40-80

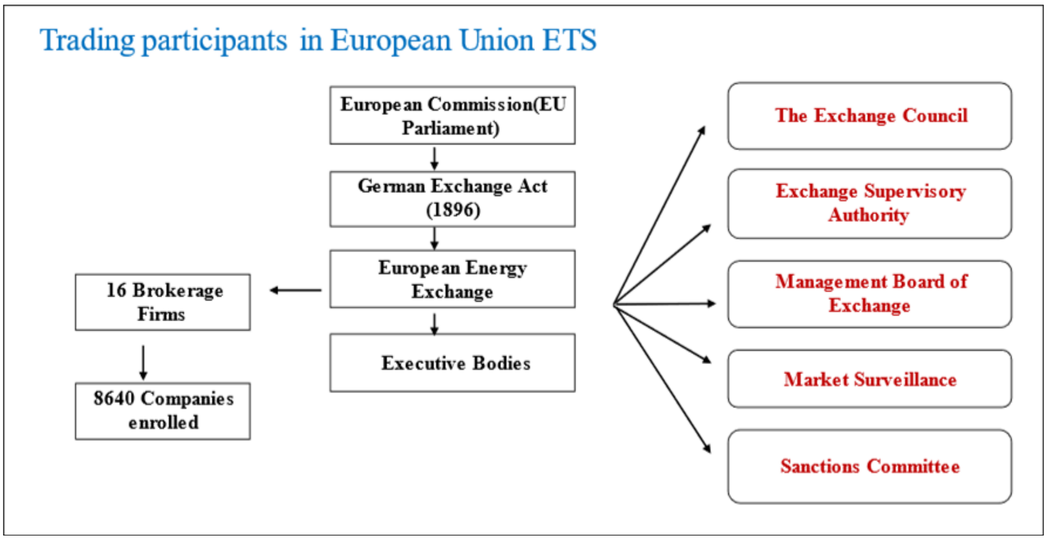

Fig. 4. Trading participants in European Union ETS. Source Ref. (24).

million tons annually (11). Phase 4 (2021-2030) introduced the Market Stability Reserve to stabilize supply and price, while global issues such as COVID-19 and the European Green Deal have affected allowance prices and targets (12).

The aviation industry relied on allowances from other EU ETS sectors and cheap Kyoto credits and its limited demand had a minimal impact on carbon prices. Airlines passed the prices to consumers and had a bigger effect on leisure travellers than business travellers because they were not price-conscious (13). Between 2005 and 2012, most EU ETS emission allowances were allocated for free, reducing the effectiveness of the cap-and-trade system in incentivizing emissions reductions. Consequently, trading activity was low, close to 0 % in 2005-2007 and only increased to 2.6-5.7 % between 2008 and 2012, providing little incentive for firms to reduce emissions (14). The EU countries' CO_2 emissions reduced overall, led by Greece falling 29 %, Norway 1.1 % and the Czech Republic 13.3 %, with Iceland and Latvia experiencing an increase (15). Outside the EU ETS, Turkey experienced a sharp 42.8 % increase, which diverged from the direction of the EU. The European Union Allowance (EUA) prices in the EU ETS dropped from nearly €30 in mid-2008 to below €5 by mid-2013, primarily due to the economic downturn, increased deployment of renewable energy sources (RES) and reliance on international credits like CERs (16). The increased deployment of wind and solar power significantly played a role, where a strong negative correlation was identified between RES deployment and European Union Allowance (EUA) prices. The EU ETS has a limit on overall emissions through transferable credits, which allows for measured cuts. It aligns with the EU's broader objective of reducing emissions by at least 40 % by 2030 (17). The effectiveness of the ETS varies across countries and is influenced by institutional factors such as the strength of green political parties and prevailing public opinion. Sweden and Denmark reduced emissions more than Greece and Portugal due to stronger policies. Increased ETS prices promoted renewables in the energy mix, as Lithuania's proportion rose from 3 % in 2000 to 74.7 % in 2022.

The "Fit for 55" package, which came into force in 2021, aims to meet the European Climate Law's objectives of achieving climate neutrality by 2050 and a net reduction of 55 % in GHG emissions by 2030 compared to 1990 levels. It includes six key reforms: enhancing the EU ETS, reinforcing the Market Stability Reserve, covering aviation and shipping emissions, creating a Social Climate Fund for buildings, roads and small industries and implementing the Carbon Border Adjustment Mechanism (CBAM). CBAM prevents carbon leakage by imposing CO_2 pricing on imports, supporting local industries and encouraging innovation. The package imposes stricter CO_2 targets, with a 55 % reduction for new cars and a 50 % reduction for vans by 2034, aiming to achieve 100 % by 2035, thereby boosting the adoption of electric and hydrogen vehicles.

Market stability reserves of the European ETS: The Market Stability Reserve (MSR) was launched in the EU Emissions Trading System in 2019 to limit excess allowances and enhance market stability by stabilizing carbon prices. It encouraged low-carbon investments, even amidst shocks such as the COVID-19 pandemic (18). MSR could increase carbon prices in the short to mid-term, reduce excess allowances and encourage earlier emissions reductions (19). However, it may raise overall costs by limiting returns on allowances and prove less effective at absorbing external shocks, thereby reducing its capacity to manage future uncertainties. While MSRs likely encouraged speculative banking and returns, the chances of realizing huge gains were minimal (20). The Market Stability Reserves cancelled 2.16 billion allowances, along with an additional 0.28 billion during the pandemic, to balance the 2020 emissions decline (21). This highlights its role in stabilizing CO_2 prices, underpinning recovery and lowering emissions for a beneficial climate impact. The EU is advancing to EU ETS2, an expansion of its original scheme, to include road transport, buildings and more industrial sectors by 2027. This shift aims to strengthen carbon pricing and supports the EU's path toward net-zero by 2050, reinforcing its role as a global leader in carbon market development.

Constraints in the EU ETS : The EU ETS is a fundamental climate policy instrument based on a cap-and-trade mechanism to lower GHG emissions. The 2008 economic crisis was the primary driver of emission reductions during the early phases of the EU ETS, rather than the policy itself. The impact of the EU ETS on companies has been mixed, while some studies have reported no significant effects on turnover, employment, or profits and even noted growth in the electricity sector, others reported declines in productivity indicators such as labor productivity and total factor productivity (22, 23). The EU ETS had a minor effect on competitiveness, jobs, or revenue in the cement and steel sectors (24). However, the power sector saw rising material costs and revenue due to regulatory pressures (25). The EU ETS has been subjected to regulatory pressures, particularly in high-emitting sectors such as Electricity, Metal Ore and Transport, which exhibit the highest CO_2 intensity and price influences. Carbon restrictions resulted in a 0.1 %–5 % rise in energy-intensive industry prices, particularly in aluminium and steel. In Phase IV, companies boosted research and development efforts, which enhanced output and competitiveness; however, overall employment levels declined.

Switzerland ETS

Switzerland employs a hybrid approach to reduce its GHG emissions, combining a carbon tax (CO_2 tax) that covers 51 % of emissions with an ETS that accounts for 33 %, as illustrated in Fig. 5 (26). The Swiss ETS came under the European Union ETS 2008, along with New Zealand (27). In the first ETS phase (2008-2012), membership was voluntary for firms that wanted to be exempted from the CO_2 charge. Voluntary membership was open to energy-intensive sectors and they were given free allowances depending on their emission reduction potential. Switzerland excludes energy-intensive industries from its carbon tax to protect employment and competitiveness, but the scheme cost CHF 1.3 billion (2008-2018) with uncertain benefits. Emission reductions were no more effective than the regular tax and job effects are uncertain. Extending it would raise costs and transfer the burden to households and small businesses. These industries should pay for climate policy (28). The Swiss parliament is discussing the extension of carbon pricing to the transport sector, which is responsible for one-third of the nation's GHG emissions. The highest emitters are cement plants, followed by the chemical, refining, district heat, metal and paper industries. In Switzerland, aviation is the major climate polluter, with non-CO_2 effects tripling its

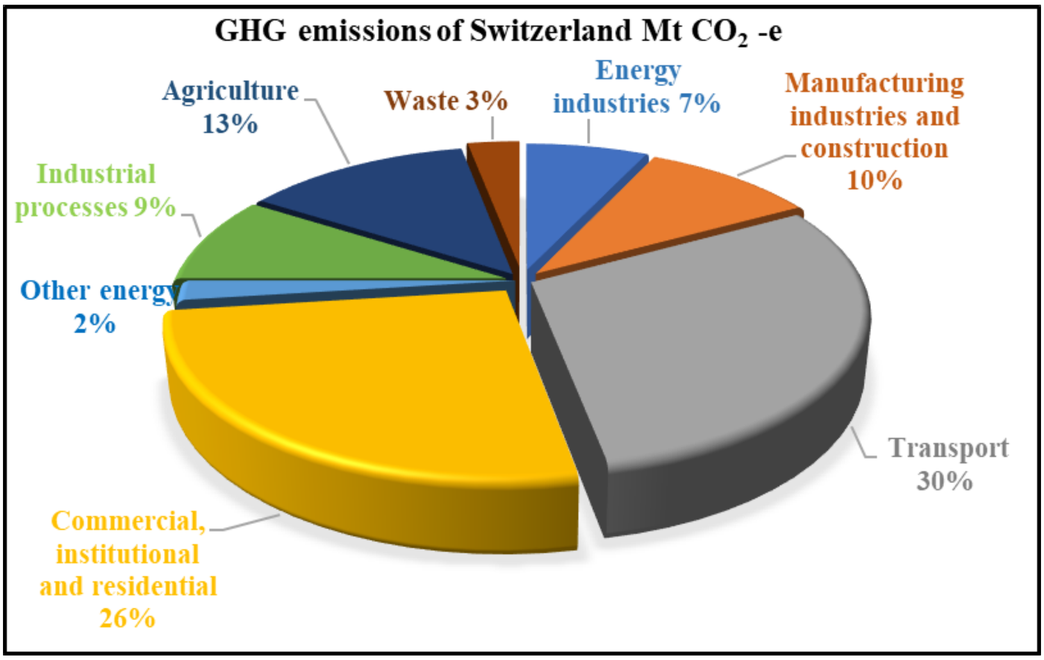

Fig. 5. GHG emissions of Switzerland in Mt CO_2 -e.

warming impact. Air travel is projected to double by 2040, yet global frameworks such as CORSIA and EU ETS remain relatively weak. Swiss policies have prioritized biofuels and carbon capture, but their neglect of major emissions has undermined the overall ineffectiveness (29).

Constraints faced in the Swiss ETS: Switzerland aims to reduce its GHG emissions by 37.5 % below the level of 1990 by 2030 through domestic action. The Internationally Transferred Mitigation Outcomes (ITMOs) needed to achieve the 2050 net-zero goal are not yet specified (30). Switzerland's energy policy foresees a phased nuclear exit, impacting 36 % of its electricity production. This presents energy security concerns, like other nations shutting down major energy producers (31). The test reconciles sovereignty, energy security and increasing electricity demand with balancing import dependency and economic stability. In 2015, Switzerland relied heavily on hydropower (57.9 %) and nuclear energy (32 %) for its electricity, which is a low-carbon source. However, imported fossil fuels still accounted for half of energy consumption, primarily due to transportation. Post-Fukushima happened in 2011, Energy Strategy 2050 pledged a nuclear phase-down by 2034 and Switzerland opted for a greener and riskier approach, increasing wind, solar and biomass. Switzerland's renewable expansion is constrained by solar's low irradiance, hydropower's spatial limitations, wind's low velocities and conservation issues (32). Wood is constrained by forest boundaries, biogas high prices and energy imports carry supply risks (33, 34). Switzerland faces significant climate challenges as its winter tourism sector relies on stable snowfall, which is increasingly threatened by rising temperatures and changing weather patterns (35).

New Zealand ETS

The New Zealand ETS is one of the world's first national GHG trading systems outside Europe, with distinctive sectoral coverage, which includes forestry, stationary energy, liquid fossil fuels (transport), industrial processes and waste (36). The free allocation in the NZ ETS was synchronized with Australia's emerging ETS to ensure trans-Tasman competitiveness and avoid carbon leakage. Australia was New Zealand's largest trading partner and took 23 % of exports at the time. There is no free allocation for electricity generation (37). Experienced New Zealand ETS participants capitalized on several options, whereas the less experienced struggled; some paid more than the USD 25 fixed price, foregoing cheaper options. Small businesses could not utilize free units to absorb electricity costs due to system constraints and small forestry operators sold units at a loss to cover compliance expenses (38, 39).

The largest emitter of NZ was agriculture, followed by the energy sector, contributing 40 % of GHG emissions, where forestry played a critical role in offsetting one-third of NZ emissions shown in Fig. 6. Successful national carbon strategies would account for forestry and harvested wood product carbon stocks and the benefits of material and energy substitution (40). Members could pay cash instead of surrendering, repaying, or refunding units using a fixed price option (FPO). This de facto price cap was originally USD 25 before 2020, raised to USD 35 in 2020 and subsequently replaced by a cost containment reserve in 2021. Increased emission prices have encouraged afforestation and reduced deforestation, with registrations increasing from 7000 to 80000 hectares per quarter between 2021 and mid-2022 as prices doubled. From 2023, the averaging accounting offers "low-risk" units to all, benefiting small landowners (41).

Constraints in the New Zealand ETS: New Zealand's transition from forestland to dairy farming exacerbates emissions by lowering carbon sequestration and raising methane production. Integrating the land-use sector into the New Zealand Emission Trading System ensures effectiveness, efficiency and equity (42). Early experience with ETS linking brings price volatility, policy uncertainty and environmental integrity risks across borders. It also carries the potential to transfer wealth, which has political and sovereignty implications (43). Forest owners can earn NZUs based on the long-term average carbon storage using averaging with no liabilities on harvest unless the land is cleared. While useful, it can lower incentives to lengthen rotations, increase carbon density, or establish permanent forests, since it relies on fixed future assumptions of rotation (44). NZ ETS reliance on the Kyoto carbon market collapsed emission prices and weakened

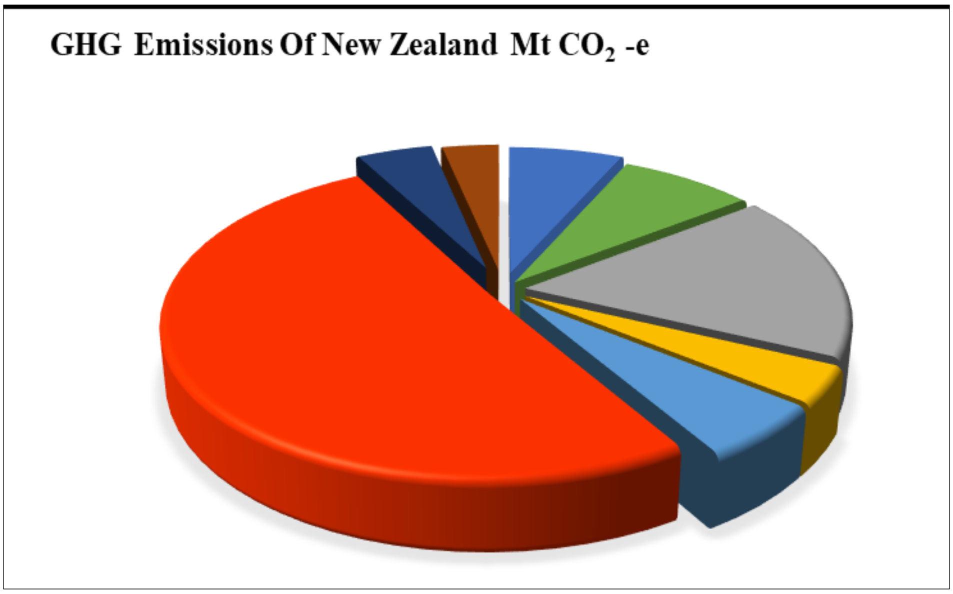

Fig. 6. GHG emissions of New Zealand in Mt CO_2 -e.

local reduction incentives. The authors preferred stronger domestic control consistent with New Zealand's Paris Agreement goals (45). The research found that the ETS was either too stringent or inadequate for certain industries, with five out of 24 industries lacking poor coverage and needed to reform regulations to achieve complete and effective sectoral coverage (46).

China ETS

The report believes that "there is no plausible path to limiting the global temperature rise to 1.5 °C without China", as it accounts for 15.94 Gt CO_2 eq of GHG emissions, where 31.11 % of global emissions were from the energy sector, which relies more on coal supply as illustrated in Fig. 7. China has adopted market-based carbon trading pilots in Shenzhen, Shanghai, Beijing, Guangdong, Tianjin, Hubei and Chongqing to control key carbon-emitting companies which is explained in Table 2. The excess allowances can be exchanged in the carbon market to manage carbon dioxide emissions (47, 48). Shenzhen launched China's inaugural national carbon trading program in 2013, covering 635 industries and 197 public facilities. On the opening day, 20000 tons were traded for RMB 0.61 million, which later rose to 120000 tons and RMB 8 million, before experiencing a 32 % decline (49). China's carbon trading pilots enable effective allocation strategies such as historical emissions, benchmarking and free allowance allocation, but face challenges including allowance oversupply, lack of credits for early abatement, double counting and their heavy reliance on historical emissions (50). Eastern China emits higher levels of carbon due to industrialization and urbanization, with cities like Tangshan at the forefront due to intensive coal and steel manufacturing. In contrast, Western regions emit less. China's intensity-based targets, design of the C-ETS, were established in Copenhagen and incorporated into its Five-Year Plans, which in turn inform the design of the C-ETS. Meanwhile, the UNFCCC CDM, national CDM policies and NDRC-approved CCER offsets have led to a credit surplus, prompting their exclusion from the market to stabilize carbon prices (51). Compliance remains the primary driver for organizations in emissions trading, but many seek ways to boost profitability through better carbon asset management. Although major organizations have made progress in reducing emissions since 2015, nearly half still lack defined reduction targets and exhibit limited understanding of marginal abatement costs (52). Additionally, densely populated cities such as Shanghai and Suzhou, as well as industrial hubs like Tianjin and Shijiazhuang, contribute substantially to carbon emissions.

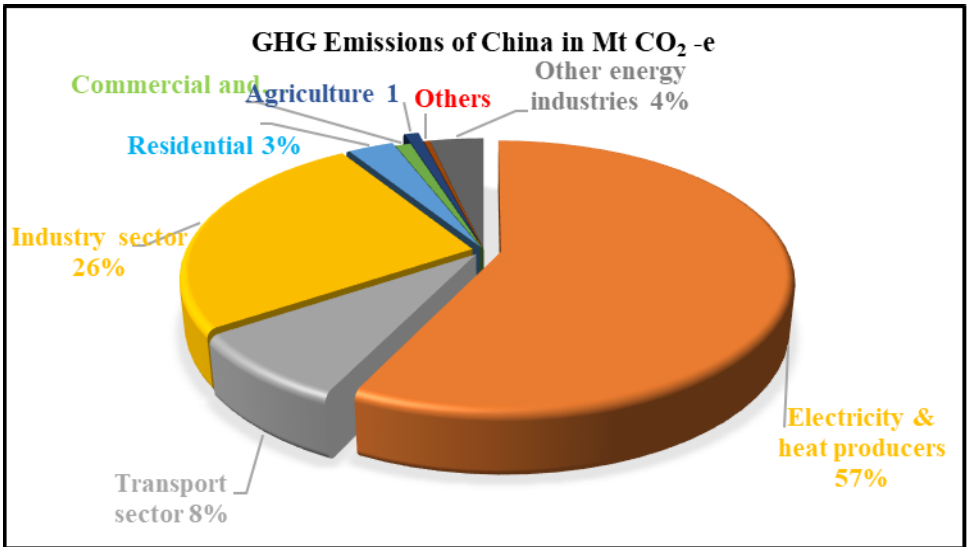

Fig. 7. GHG emissions of China in Mt CO_2 -e.

Table 2. Comparative framework of China's pilot program

Pilot program	Year	Scope	Price per unit	Gas covered	Govt. Revenue	Coverage threshold	GHG emission covered	Banking/ Borrowing
Guangdong	2013	Subnational (State/Province)	USD10.58	CO_2	USD 128 million	10000 tCO_2 -e	0.4	Banking
Shanghai	2013	Subnational (City)	USD10.06	CO_2	USD 27.03 million	10000 tCO_2 -e	0.36	Banking
Beijing	2013	Subnational (City)	USD16.26	CO_2	USD 18 million	5000 tCO_2 -e	0.24	Banking
Shenzhen	2013	Subnational (City)	USD 8.96	CO_2	USD 4 million	3000 tCO_2 -e	0.3	Banking
Tianjin	2013	Subnational (City)	USD 4.71	CO_2	USD 13 million	20000 tCO_2 -e	0.35	Banking
Chongqing	2013	Subnational (City)	USD 5.99	CO_2, CH_4, N_2O, HFCs, SF_6, PFCs	USD 13 million	13000 tCO_2 -e	0.51	Banking
Hubei	2013	Subnational (State/Province)	USD 5.62	CO_2	USD 14 million	10000 tCO_2 -e	0.27	Banking

The Local Development and Reform Committee governs China's carbon pilot program and pilot trading platforms, including the Hubei Emissions Exchange, Shanghai Environment and Energy Exchange, Tianjin Climate Exchange, Beijing Carbon Emissions Rights Electronic Trading Platform, Shenzhen Emissions Rights Exchange, Guangzhou Emissions Rights Exchange and Chongqing Public Resources Trading Center. China's carbon market has successfully curbed total and per capita carbon dioxide emissions, contributing around 0.26 % (53). Evidence indicates that following the implementation of the pilot carbon trading policy, firms reduced their coal use by 34 % and coal intensity by 33 %, with a more pronounced effect on large firms and energy-intensive industries (54). The carbon ETS is more effective in reducing emissions in the old industrial base and inland cities than in coastal and non-industrial base cities.

Constraints in China ETS: China, the world's largest GHG emitter, has pledged to peak CO_2 emissions by 2030 and achieve carbon neutrality by 2060. In 2020, China's carbon intensity, GHG emissions per unit of GDP, remained significantly higher than that of the US and EU, largely due to its heavy reliance on coal, as coal emits more carbon than natural gas. Within China, the electricity and heat industry contributed 47 % of the emissions, followed by the industrial sector at 28 % and transportation at 10 %, exceeding the global averages illustrated in Fig. 7 (55). China initiated its carbon emissions trading schemes in 2013, copying the EU ETS with little innovation, lacked clear policy and theoretical leadership, leaving many participating firms uncertain about the system's functioning (56). The international regulations prohibited China from trading carbon emissions on exchanges through spot, futures, or options markets, which caused domestic carbon prices to decline below global levels. This slowed China's carbon finance development, capping incentives and market activity and weakened China's bargaining power. Enterprises in Beijing, Hubei, and Guangdong faced heightened pressure to reduce emissions due to their limited free allowances, leading to higher production costs in complying with ETS requirements (57).

Regulatory inconsistencies and a lack of strict enforcement weakened market stability and decreased investor confidence, limiting the expansion of green investment. Carbon price volatility was due to changes in demand, economic fluctuation and policy change, which discouraged long-term green investment. Price controls and buffer stocks would stabilize the market and underpin low-carbon efforts (58). China's ETS pilot induced the Hawthorne effect by altering political incentives, prompting an increase in public statements on environmental objectives in pilot provinces. However, this resulted in limited commitment from local governments and minimal administrative effort toward effective implementation (59). Although carbon trading contributes to emission reduction, its effectiveness is hindered by its reliance on non-market mechanisms owing to market immaturity, narrow industry coverage, excessively generous free allowances and low carbon prices. They undermined the market's ability to drive down emissions effectively (60).

South Africa Carbon Trading

To cut GHG emissions to 350-420 megatons and achieve carbon neutrality by 2050, South Africa, Africa's largest emitter among the world's top 20 emitters, implemented a carbon tax in June 2019 (61). South Africa ratified the UNFCCC in 1997 and the Kyoto Protocol, which obliged industrialized nations to reduce their emissions, affecting future trade and investment. As Africa's largest GHG emitter, it has a moral obligation to take the lead, considering its high-energy economy and intensive use of coal, as shown in Fig. 8 (62). Carbon tax offers a lower marginal abatement cost than other tax options, making it a more feasible and efficient tool for emission reduction. They also suggested that an energy input sales tax was a suitable alternative if the carbon tax wasn't practical. GHG trading linkages have proven to be unstable, as evidenced by the withdrawals of New Jersey, the EU and Australia. Domestic opposition can hinder long-term commitment with unclear policy impacts (63). Sectors vulnerable to competition from imports and exports can face increased costs when a carbon price is introduced, rendering them less competitive. This may lead to job losses a nd a decline in GDP, posing a threat to economic stability. Cap-and-trade, with its flexibility and benefits, is more appropriate for sectors that handle GHG emissions in South Africa (64). For a middle-income country like South Africa, a carbon tax offers clear advantages, particularly given the nation's highly concentrated energy market, which may hinder the efficiency of an emissions trading system. Other factors to consider are political credibility, social welfare implications and long-term economic stability (65). South Africa's energy sector relies heavily on coal-based electricity, accounting for 83 % of the country's emissions and contributing 1.2 % to global emissions. As a resource-based economy, South Africa can utilize the digital economy to reduce carbon emissions through technological innovation and industrial transformation needed for practical applications in carbon trading (66). Several Eastern and Southern African initiatives support green economic growth that is linked to carbon pricing, including carbon taxes, levies, trading platforms, research funding and legislative measures (67).

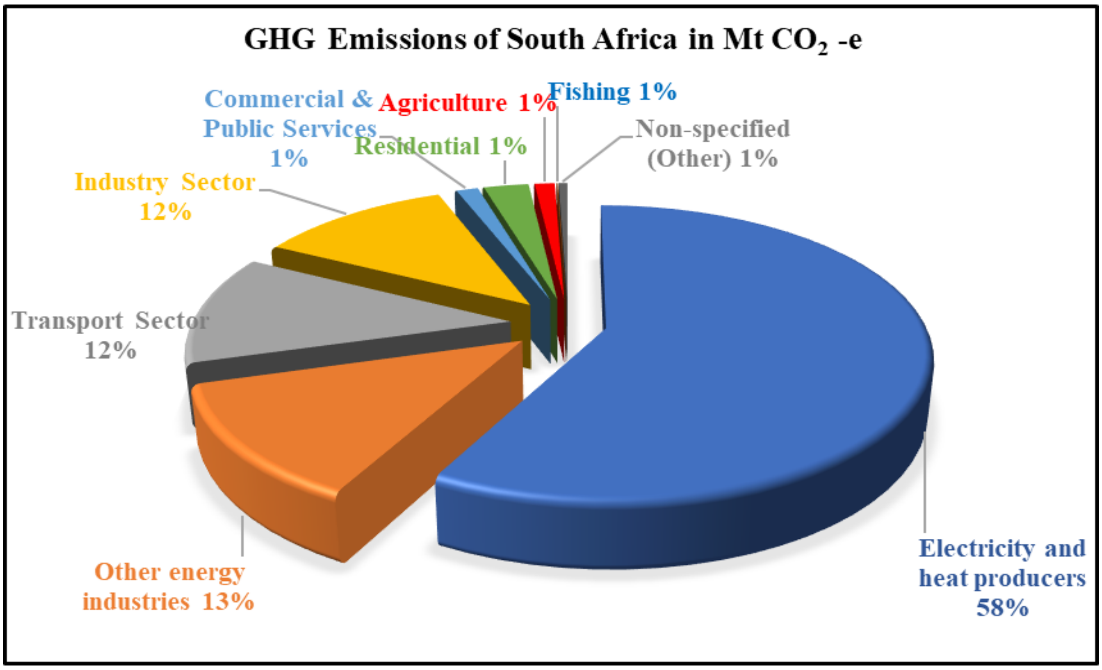

Fig. 8. GHG emissions of South Africa in Mt CO_2 -e.

South Africa's regulatory institutions of carbon trading are the South African Revenue Service and the Department of Environment, Forestry and Fisheries. The USD15 carbon tax disproportionately impacts developing countries, causing higher economic contractions due to emission costs. GDP decreases are 5.11 % in Iran, 4.27 % in Kazakhstan, 3.70 % in South Africa and 2.33 % in China and India compared to much smaller reductions in developed nations, such as 0.49 % in the US and 0.23 % in France (68). The penalty for non-compliance is USD 34.52 per tonne of CO_2. Raising the carbon tax by 5 % and 10 % decreased carbon emissions by 1.42 % and 2.57 %, respectively. Real GDP fell by 0.37 % and 1.75 % and the energy sector's output, one of the biggest contributors to emissions, fell by 4.39 % and 6.88 %. Exports decreased by 4.74 % and 5.77 % and household consumption fell by 2.34 % and 4.39 %. Its GDP share also declined by 0.45 % and 0.81 %. Despite the economic downturn, government revenue experienced a notable increase of 15.44 % and 20.83 %, respectively (69).

Constraints in South African Carbon Trading: South Africa, a significant exporter of carbon-intensive mining products and metals, had its export industry most impacted by carbon pricing, particularly in the absence of export rebates (70). Coal accounts for 75 % of South Africa's total emissions, primarily fueled by industrial operations and the domestic manufacture of transport fuels through coal-to-liquid technologies. A carbon tax with 60-100 % industry exemptions would decrease real GDP by 6.4 % by 2035, whereas eliminating all exemptions from 2022 would cause a 13.7 % decrease relative to the baseline (71). Additionally, they found that the carbon tax could have a major effect on South Africa's export industry, with exports from sectors such as Iron and Steel and Other Manufacturing possibly falling by as much as 50 %. The carbon tax could increase the cost of doing business, with smaller companies being most at risk as they have less to cover expenses or invest in cleaner technology (72). Fossil fuel-intensive industries may resist the carbon tax, potentially leading to broader opposition against related policies. The carbon tax could lower household consumption levels by approximately 2.34 %, increasing consumers' costs for reducing emissions. Carbon tax could disproportionately affect low-income populations due to constrained support mechanisms and the author suggests investing the revenue raised from the tax to safeguard vulnerable groups. In the absence of adequate support systems, the tax could widen disparities (73).

India Carbon Trading System

India ranks as the third-largest emitter of GHG emissions, with a significant 4.13 gigatonnes CO_2-eq as shown in Fig. 2. The Indian carbon market is dominated by private organizations, with consultancies and project developers being the most important players. The Paris Agreement aimed to keep global warming at well below 2 °C above pre-industrial levels and while actively pursuing efforts to limit it to 1.5 °C. India signed the Paris Agreement on Climate Change in 2016, committing to help limit the rise in global average temperature to below 2°C by the end of the century. The laissez-faire attitude of the Indian government towards CDM means that it neither actively promotes nor discourages it (74, 75). The PAT programme, introduced in July 2012, was to cut emission intensity by 20-25 % below 2005 levels by 2020 and the emissions are given in Fig. 9. Covering 478 industries across eight sectors and 54 % of India's industrial energy use, it set a three-year energy reduction target by 2015. Non-compliant firms could either pay a penalty or purchase tradeable energy-saving certificates from surplus industries (76). Indian CDM projects comprise 94019 of the world's 596,743 total Certified Emission Reductions and are projected to contribute 447158 kCERs in 2012 out of the world's total 2876911 kCERs. India holds 35 % of CDM projects in Asia (77).

The Energy Conservation (Amendment) Bill, 2022, authorizes the central government to bring a mechanism for a carbon credit trading scheme (78). A 1 % rise in the Index of Industrial Production (IIP) reduces the price of carbon emissions by ₹0.46 (79). The government limits allowable emissions for different industries over a specific compliance period, allowing companies with lower abatement costs to sell their permits in secondary markets to companies with higher abatement costs, which reduces emissions at the lowest cost. Companies and industries can opt to either reduce emissions or continue

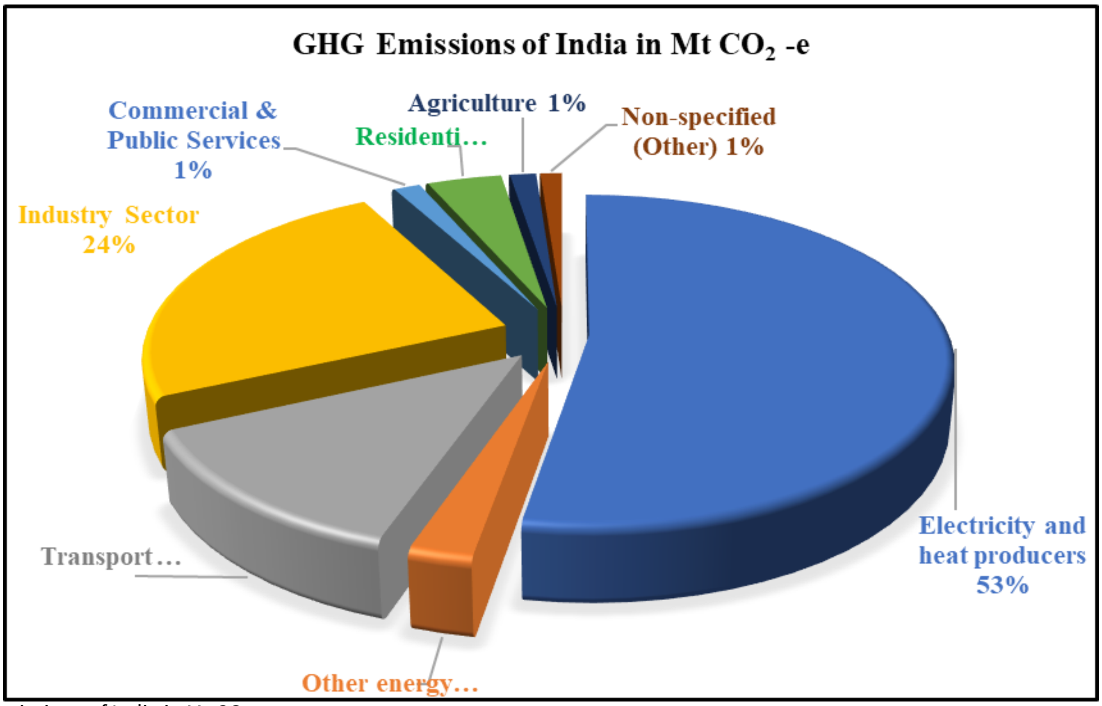

Fig. 9. GHG emissions of India in Mt CO_2 -e.

emitting, based on internal assessments influenced by market prices and available technological options. The volume of emissions is regulated, while the cost is determined by market forces of demand and supply (80). The ESCerts may be traded on two power exchanges, i.e., Power Exchange Indian Limited (PXIL) and Indian Energy Exchange (IEX) (81). The PAT scheme has gone up to 6 cycles and the energy consumption in PAT Cycle-1 of 2015 (Designated Customers) has increased from 164 million tonnes to 23.298 million tonnes in PAT Cycle-6 of 2020.

India launched the world's first ETS for particulate pollution in Surat on June 6, 2019. The program was designed to reduce air pollution from textile and dye mills by imposing a government-mandated limit on particulate emissions in participating industries (82). India's industrial reliance on fossil fuels continues to drive CO_2 emissions, further intensified by its growing economy. To achieve sustainability, India must promote clean manufacturing and curb emissions through policy measures such as carbon pricing and pollution taxes (83). Heavy-emission sectors such as power, steel and cement may employ carbon credit trading to reduce emissions, achieve national goals and benefit from the excess credits. Integrating India's market with international platforms may increase liquidity and investment, but could entail challenges of integration (84). To find the optimal approach for the Indian ETS, a combined strategy involving both safety valve triggers and a price-based Market Stability Reserve (MSR) is recommended. Safety valve triggers would assist in regulating early price surges by prolonging compliance dates or increasing offset credit caps. If prices continue to rise, a rule-based Market Stability Reserve can once again help stabilize the market. Similar to the RGGI model, this dual mechanism can strengthen price stability and reduce volatility (85).

Constraints in the Indian Carbon Trading System: India's rapid depletion of water, forests and minerals due to unsustainable use threatens long-term resource availability and poses a primary challenge to sustainable development (86). One of the main challenges is the absence of a specific policy framework for carbon trading in India. Despite its aggressive participation in the market, the lack of transparent legislation raises questions among stakeholders (87, 88) highlighted that the complexity of the carbon credit market posed a barrier to entry, which led to price volatility, deterred investment and relatively low interest from individual investors, further hindering its growth prospects A 2023 study found significant challenges, such as low awareness among stakeholders, regulatory barriers and transparency deficits in the carbon trading process. India incurs substantial losses due to the burning crop residues, which emit carbon emissions and in 2011 alone, it lost ₹109.97 billion. Most offset schemes are unregulated, resulting in greenwashing through unsubstantiated claims of emissions reduction. The business-led system provides minimal inclusion of rural stakeholders, such as farmers, who lose out on climate-smart advantages. Economic interests tend to dominate environmental goals, slowing down the regulation of carbon trading in line with sustainable development goals (89). India's 62 GW of solar capacity reduces carbon emissions by 150 million metric tons annually, demonstrating the climate mitigation potential of renewable energy (90). They also concluded that numerous projects struggle with funding and low awareness and community resistance hold back adoption.

The lack of clear, sustainable building rules slows the adoption of green technology in India's transport sector, which accounts for 14 % of CO_2 emissions. Around 88 % of these emissions are generated from road transport, emphasizing high prospects for emission reduction through low-carbon buildings (91). Fossil fuel subsidies skew energy priorities in contrast to renewables, which is an unfair advantage. Larger companies can purchase emission credits more readily, placing them in a competitive position over smaller ones, creating an uneven playing field based on financial health rather than environmental effectiveness (92). Biomass markets face inconsistent supply-demand dynamics and a lack of organization, inducing price volatility and uncertainty. Additionally, scarcity of land and the absence of a centralized fuel market impede the development of wind, solar and thermal energy capacity (93). The constraints of all the chosen countries are given in Table 3.

Table 3. Comparative constraints in carbon trading mechanisms across countries

Countries chosen	High-income countries			Upper-Middle Income Countries		Lower-Middle Income Countries
Constraints	**European Union**	**Switzerland**	**New Zealand**	**China**	**South Africa**	**India**
Coverage Limitations	Broad coverage (ETS 2 expanding	Covers most major emitters	Moderate, includes agriculture	Limited Power Sector	Initially limited, slow expansion	REC/ESC sectoral fragmentation
Price Volatility	Stabilized by the MSR & auctioning mechanism	High prices due to the limited allowances	Stable but influenced by forestry offsets	Prone to price fluctuations due to the pilot stage	Unstable, lack of liquidity	Price discovery is still evolving
Institutional and Legal Barriers	Strong governance under EU Law	Strong institutional base	Strong compliance framework	Developing the MRV system lacks a full	Weak enforcement, inconsistent political support	Initialising the legal/ Institutional framework
Monitoring, Reporting and	Well-established MRV & registry systems	Transparent MRV	Strong MRV policies	Weak MRV & data integrity issues	Fragmented MRV system	ESC registry improving, still
Public & Private Sector Readiness	High industry participation & awareness	Aligned with the EU Industries	Good sectoral alignment	Learning curve among enterprises	Industry resistance, low awareness	Participation compliance is still evolving
International Linkages	Linked with EU Member countries; potential for expansion	Linked to the EU ETS	Isolated, offset-based flexibility	No international linkages	Isolated, not yet linked	No formal linkage, under discussion

Source Ref. (94).

Conclusion

This comparative review of carbon trading schemes across three levels of economies demonstrates how varying contexts shape market-based methods for reducing emissions. High-income countries like the EU, Switzerland and New Zealand operate advanced carbon pricing systems. The EU ETS has achieved a 43 % reduction in emissions and generated around USD 47 billion in revenue in 2024, with permit prices averaging USD 64.76 per ton. Switzerland uses a hybrid model, where a CO_2 tax covers about 51 % of emissions and an ETS accounts for 33 %. New Zealand incorporates forestry offsets, with 170000 ha of forest sequestered since 2008. Upper-middle-income countries such as China and South Africa follow distinct approaches. China's Emissions Trading System currently covers its power sector but needs to expand to other high-emitting industries such as cement, steel and chemicals. South Africa's carbon tax, which covers 90 % of emissions, raised approximately USD 90 million in 2022, with the rate increasing to R290/T CO_2 in 2024. India, a lower-middle-income economy, is developing a national carbon market that aims to become the world's largest by 2030 through the trading of Renewable Energy Certificates (RECs) and Energy Saving Certificates (ESCs). Effective carbon trading requires the inclusion of sectors beyond industry and energy. Biochar application and agricultural carbon sequestration are double benefits through reduced emissions and enhanced productivity. A phased implementation approach in developing economies, starting with the energy sector, which accounts for 73 % of global emissions, offers a practical and feasible path before expanding to an economy-wide system. With the emergence of countries toward net-zero, carbon markets shall be the solution for cost-competitive decarbonization. These depend on how the system tailors to local contexts, institutionally sound design and synergies with aggregate climate policies. No single carbon trading model functions universally; however, cross-classification knowledge exchange can accelerate the development of effective systems tailored to local circumstances, both environmentally robust and economically viable in the face of urgent climate challenges.

Acknowledgements

The authors are grateful to the Department of Agricultural and Rural Management, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nādu, India.

Authors' contributions

MNP and CV participated in conceptualization; MNP and CV has done methodology; TS, RP and SS carried out resources; MNP and CV conducted data collection; MNP, CV and SS has been done investigation; MNP, CV and SS performed formal analysis; MNP, CV and SS helped in writing original draft; MNP, CV and TS has done the visualization; CV, TS, RP and SS conducted supervision. All authors read and approved the final paper.

Compliance with ethical standards

Conflict of interest: The authors declare no conflicts of interest.

Ethical issues: None

References

1. Wagner A, Steen B, Johansson G, Zanghellini E, Jacobsson P, Johansson P, et al. Carbon dioxide capture from ambient air using amine-grafted mesoporous adsorbents. Int J Spectrosc. 2013;2013 (1):690186. https://doi.org/10.1155/2013/690186
2. Grubb M. The Kyoto Protocol-a guide and assessment. Nature. 1999;402(6759):233-4. https://doi.org/10.1038/46293
3. Hepburn C. Regulation by prices, quantities, or both: a review of instrument choice. Oxf Rev Econ Policy. 2006;22(2):226-47. https://doi.org/10.1093/oxrep/grj014
4. Dixit S, Bardiya S. Carbon trading in developing economies: challenges, opportunities, and best practices. Int J Multidiscip Res. 2024;6(6). https://doi.org/10.36948/ijfmr.2024.v06i06.30282
5. Börzel T, Hamann R, Kranz N. Business and climate change governance: conclusions. In: Börzel T, Hamann R, Kranz N, editors. Business and climate change governance: South Africa in comparative perspective. London, UK: Palgrave Macmillan; 2013. p. 193-211. https://doi.org/10.1057/9781137302746_10

6. Eboli F, Davide M. The EU and Kyoto Protocol: achievements and future challenges. Rev Environ Energy Econ-Re3. 2012.

7. Laing T, Sato M, Grubb M, Comberti C. The effects and side-effects of the EU emissions trading scheme. Wiley Interdiscip Rev Clim Change. 2014;5(4):509-19. https://doi.org/10.1002/wcc.283

8. Zhang Y-J, Wei Y-M. An overview of current research on EU ETS: evidence from its operating mechanism and economic effect. Appl Energy. 2010;87(6):1804-14. https://doi.org/10.1016/j.apenergy.2009.10.020

9. Parker L. Climate change: the European Union's emissions trading system (EU-ETS). In: Global Climate Change Revisited; 2007. p. 61-82.

10. Parker L. Climate change and the EU emissions trading scheme (ETS): looking to 2020. Congressional Research Service; 2010.

11. Vollebergh HR, Brink C. What can we learn from EU ETS? CESifo Working Paper; 2020.

12. Bruninx K, Ovaere M. COVID-19, Green Deal and recovery plan permanently change emissions and prices in EU ETS Phase IV. Nat Commun. 2022;13(1):1165. https://doi.org/10.1038/s41467-022-28737-4

13. Anger A, Köhler J. Including aviation emissions in the EU ETS: much ado about nothing? A review. Transp Policy. 2010;17(1):38-46. https://doi.org/10.1016/j.tranpol.2009.10.010

14. Nadolny Ł. Skuteczność systemu handlu emisjami Unii Europejskiej w zakresie redukcji emisji gazów cieplarnianych. Acta Univ Lodziensis Folia Oeconomica. 2015;2(313). https://doi.org/10.18778/0208-6018.313.03

15. Pászto V, Zimmermannová J. Relation of economic and environmental indicators to the European Union Emission Trading System: a spatial analysis. GeoScape. 2019;13(1). https://doi.org/10.2478/geosc-2019-0003

16. Gomółka K, Kasprzak P. ETS prices and renewable energy sources share in the energy mix-example of Lithuania, Latvia and Estonia. Econ Environ. 2024;90(3):844. https://doi.org/10.34659/eis.2024.90.3.844

17. Sikora M, Orliński P. Hydrotreated vegetable oil fuel within the Fit for 55 package. Combust Engines. 2024;63(2):3-8. https://doi.org/10.19206/CE-174554

18. Wu L, Gong Y, Wang C, Tang W. The effectiveness of the MSR in stabilizing EU ETS market and incentivizing low-carbon investment. 2023. https://doi.org/10.21203/rs.3.rs-2369229/v1

19. Trotignon R, Jouvet P-A, Solier B, Quemin S, Elbeze J. European carbon market: lessons on the impact of a market stability reserve using the Zephyr model. Working Papers 1511, Chaire Economie du climat; 2015.

20. Falcke F, Madlener R. Potential impacts of the planned market stability reserve on speculators' behavior in the EU emissions trading system. FCN Working Paper No. 09/2016; 2016. https://doi.org/10.2139/ssrn.2916157

21. Azarova V, Mier M. MSR under exogenous shock: the case of COVID-19 pandemic. ifo Working Paper No. 338; 2020. https://doi.org/10.2139/ssrn.3724330

22. Ziller J. Advanced introduction to European Union law. Cheltenham: Edward Elgar Publishing; 2023. p. 162. https://doi.org/10.4337/9781802208945

23. Dechezleprêtre A, Nachtigall D, Venmans F. The joint impact of the European Union emissions trading system on carbon emissions and economic performance. J Environ Econ Manage. 2018;118:102758. https://doi.org/10.1787/4819b016-en

24. Jaraitė J, Maria CD. Did the EU ETS make a difference? An empirical assessment using Lithuanian firm-level data. Energy J. 2016;37(2):68-92. https://doi.org/10.5547/01956574.37.2.jjar

25. Marin G, Marino M, Pellegrin C. The impact of the European Emission Trading Scheme on multiple measures of economic performance. Environ Resour Econ. 2018;71:551-82. https://doi.org/10.1007/s10640-017-0180-4

26. Chan HSR, Li S, Zhang F. Firm competitiveness and the European Union emissions trading scheme. Energy Policy. 2013;63:1056-64. https://doi.org/10.1016/j.enpol.2013.09.032

27. Narassimhan E, Gallagher KS, Koester S, Alejo JR. Carbon pricing in practice: a review of existing emissions trading systems. Clim Policy. 2018;18(8):967-91. https://doi.org/10.1080/14693062.2018.1467827

28. Pan J, Cross JL, Zou X, Zhang B. To tax or to trade? A global review of carbon emissions reduction strategies. Energy Strategy Rev. 2024;55:101508. https://doi.org/10.1016/j.esr.2023.101508

29. Hintermann B, Zarkovic M. Carbon pricing in Switzerland: a fusion of taxes, command-and-control, and permit markets. ifo DICE Rep. 2020;18(01):35-41.

30. Prébandier M. Personal carbon trading applied to Swiss air travel-Guaranteeing a fair access to climate ambitious aviation. Infoscience; 2024.

31. Panos E, Kannan R, Hirschberg S, Kober T. An assessment of energy system transformation pathways to achieve net-zero carbon dioxide emissions in Switzerland. Commun Earth Environ. 2023;4(1):157. https://doi.org/10.1038/s43247-023-00768-0

32. Demski C, Poortinga W, Whitmarsh L, Böhm G, Fisher S, Steg L, et al. National context is a key determinant of energy security concerns across Europe. Nat Energy. 2018;3(10):882-8. https://doi.org/10.1038/s41560-018-0235-8

33. Burg V, Bowman G, Hellweg S, Thees O. Long-term wet bioenergy resources in Switzerland: drivers and projections until 2050. Energies. 2019;12(18):3585. https://doi.org/10.3390/en12183585

34. Van Vuuren DP, Stehfest E, Gernaat DE, Van Den Berg M, Bijl DL, De Boer HS, et al. Alternative pathways to the 1.5 C target reduce the need for negative emission technologies. Nat Clim Chang. 2018;8(5):391-7. https://doi.org/10.1038/s41558-018-0119-8

35. Thees O, Erni M, Lemm R, Stadelmann G, Zenner EK. Future potentials of sustainable wood fuel from forests in Switzerland. Biomass Bioenergy. 2020;141:105647. https://doi.org/10.1016/j.biombioe.2020.105647

36. Welfens PJ, Yu N, Hanrahan D, Geng Y. The ETS in China and Europe: dynamics, policy options and global sustainability perspectives. Int Econ Econ Policy. 2017;14(3):517-35. https://doi.org/10.1007/s10368-017-0371-0

37. Richter JL, Mundaca L. Market behavior under the New Zealand ETS. Carbon Manag. 2013;4(4):423-38. https://doi.org/10.4155/cmt.13.42

38. Hood C. Reviewing existing and proposed emissions trading systems. OECD; 2010. p. 110.

39. Bösch M, Elsasser P, Rock J, Weimar H, Dieter M. Extent and costs of forest-based climate change mitigation in Germany: accounting for substitution. Carbon Manag. 2019;10(2):127-34. https://doi.org/10.1080/17583004.2019.1577180

40. Carver T, Dawson P, O'Brien S, Kotula H, Kerr S, Leining C, et al. Including forestry in an emissions trading scheme: lessons from New Zealand. Front For Glob Change. 2022;5:956196. https://doi.org/10.3389/ffgc.2022.956196

41. Bullock D. Emissions trading in New Zealand: development, challenges and design. Environ Polit. 2012;21(4):657-75. https://doi.org/10.1080/09644016.2012.688360

42. Leining C, Kerr S. Lessons learned from the New Zealand emissions trading scheme. AgEcon Search. Working Paper; 2016. http://doi.org/10.22004/ag.econ.290573

43. Carver T, Dawson P, Kerr S. Including forestry in an emissions trading scheme: lessons from New Zealand. SSRN; 2017. https://doi.org/10.2139/ssrn.3015082

44. Leining C, Kerr S. Managing scarcity and ambition in the NZ ETS. AgEcon Search. Working Paper; 2019. http://doi.org/10.22004/ag.econ.290395

45. Tao M, Poletti S, Wen L, Sheng MS. Enhancing New Zealand's emissions trading scheme: a comprehensive sector-level assessment for a stronger regulatory framework. J Environ Manag. 2024;352:120106. https://doi.org/10.1016/j.jenvman.2023.120106

46. Keohane N, Petsonk A, Hanafi A. Toward a club of carbon markets. Clim Change. 2017;144:81-95. https://doi.org/10.1007/s10584-017-2045-1

47. Zhao X-G, Wu L, Li A. Research on the efficiency of carbon trading market in China. Renew Sustain Energy Rev. 2017;79:1-8. https://doi.org/10.1016/j.rser.2017.05.051

48. Liu L, Chen C, Zhao Y, Zhao E. China's carbon-emissions trading: overview, challenges and future. Renew Sustain Energy Rev. 2015;49:254-66. https://doi.org/10.1016/j.rser.2015.04.051

49. Xiong L, Shen B, Qi S, Price L, Ye B. The allowance mechanism of China's carbon trading pilots: a comparative analysis with schemes in EU and California. Appl Energy. 2017;185:1849-59. https://doi.org/10.1016/j.apenergy.2016.02.088

50. Stoerk T, Dudek DJ, Yang J. China's national carbon emissions trading scheme: lessons from the pilot emission trading schemes, academic literature, and known policy details. Clim Policy. 2019;19(4):472-86. https://doi.org/10.1080/14693062.2018.1517643

51. Li K, Luo Z, Hong L, Wen J, Fang L. The role of China's carbon emission trading system in economic decarbonization: evidence from Chinese prefecture-level cities. Heliyon. 2024;10(1):e23799. https://doi.org/10.1016/j.heliyon.2023.e23799

52. Shi B, Li N, Gao Q, Li G. Market incentives, carbon quota allocation and carbon emission reduction: evidence from China's carbon trading pilot policy. J Environ Manag. 2022;319:115650. https://doi.org/10.1016/j.jenvman.2022.115650

53. Zhou Q, Cui X, Ni H, Gong L, Mao S. The impact of China's carbon trading policy on enterprises' energy-saving behavior. Heliyon. 2024;10(2):e24326. https://doi.org/10.1016/j.heliyon.2024.e24326

54. Zhao C, Ju S, Xue Y, Ren T, Ji Y, Chen X. China's energy transitions for carbon neutrality: challenges and opportunities. Carbon Neutrality. 2022;1(1):7. https://doi.org/10.1007/s43979-022-00007-3

55. Deng Z, Li D, Pang T, Duan M. Effectiveness of pilot carbon emissions trading systems in China. Clim Policy. 2018;18(8):992-1011. https://doi.org/10.1080/14693062.2017.1398772

56. Zhao S, Wang M, Chen L, Li J. Economic incentives for pollution control in China through the lens of the carbon trading market and its effectiveness and challenges. Law Econ. 2024;3(3):50-4. https://doi.org/10.56397/LE.2024.03.07

57. Bai J, Ma W, Wang Y, Jiang J. Political incentives in market-based environmental regulation: evidence from China's carbon emissions trading scheme. Heliyon. 2024;10(4):e25730. https://doi.org/10.1016/j.heliyon.2024.e25730

58. Pan X, Pu C, Yuan S, Xu H. Effect of Chinese pilots carbon emission trading scheme on enterprises' total factor productivity: the moderating role of government participation and carbon trading market efficiency. J Environ Manag. 2022;316:115228. https://doi.org/10.1016/j.jenvman.2022.115228

59. Abiodun TP, Nwulu N, Olukanmi P. Pioneering emission trading in Africa: an architectural design of a blockchain-powered carbon trading system. J Br Blockchain Assoc. 2024;7(2). https://doi.org/10.31585/jbba-7-2-(4)2024

60. Jooste D. Emissions trading scheme for South Africa: Opportunities and challenges. Stellenbosch University; 2011.

61. Ranson M, Stavins RN. Linkage of greenhouse gas emissions trading systems: learning from experience. Clim Policy. 2016;16(3):284-300. https://doi.org/10.1080/14693062.2014.997658

62. Oke AE, Aigbavboa CO, Dlamini SA. Carbon emission trading in South African construction industry. Energy Procedia. 2017;142:2371-6. https://doi.org/10.1016/j.egypro.2017.12.176

63. Goldblatt M. Comparison of emissions trading and carbon taxation in South Africa. In: Putting a price on carbon in South Africa and other developing countries. London: Routledge; 2020. p. 511-26. https://doi.org/10.4324/9781849775717-5

64. Zhang J, Li J, Ye D, Sun C. The impact of digital economy of resource-based city on carbon emissions trading by blockchain technology. Comput Intell Neurosci. 2022;2022(1):6366061. https://doi.org/10.1155/2022/6366061

65. Maumoh I, Onoja A, Alhassan I, Muhideen S. Opportunities, progress and challenges in carbon emission pricing and markets for East and South African regions. Res Sq. 2022. https://doi.org/10.21203/rs.3.rs-2197259/v1

66. Nong D, Simshauser P, Nguyen DB. Greenhouse gas emissions vs CO_2 emissions: comparative analysis of a global carbon tax. Appl Energy. 2021;298:117223. https://doi.org/10.1016/j.apenergy.2021.117223

67. Abel S, Mukarati J, Jeke L, Le Roux P. Carbon tax and environmental quality in South Africa. Int J Energy Econ Policy. 2023;13(2):484-8. https://doi.org/10.32479/ijeep.13923

68. Arndt C, Davies R, Makrelov K, Thurlow J. Low carbon development and carbon taxes in South Africa. AgEcon Search. 2011. p. 24.

69. Van Heerden J, Blignaut J, Bohlmann H, Cartwright A, Diederichs N, Mander M. The economic and environmental effects of a carbon tax in South Africa: a dynamic CGE modelling approach. S Afr J Econ Manag Sci. 2016;19(5):714-32. https://doi.org/10.4102/sajems.v19i5.1401

70. Steenkamp L-A. To incentivise or penalise: an analysis of the proposed carbon tax in South Africa. In: The green market transition. Cheltenham: Edward Elgar Publishing; 2017. p. 47-63. https://doi.org/10.4337/9781788111171.00014

71. Nemavhidi M, Jegede AO. Carbon tax as a climate intervention in South Africa: a potential aid or hindrance to human rights? Environ Law Rev. 2023;25(1):11-27. https://doi.org/10.1177/14614529231155718

72. Benecke G. Varieties of carbon governance: taking stock of the local carbon market in India. J Environ Dev. 2009;18(4):346-70. https://doi.org/10.1177/1070496509347084

73. Sirohi S. CDM: is it a 'win–win' strategy for rural poverty alleviation in India? Clim Change. 2007;84(1):91-110. https://doi.org/10.1007/s10584-007-9270-9

74. Gupta A. Climate change and Kyoto Protocol: an overview. In: Handbook of environmental and sustainable finance. Academic Press; 2016. p. 3-23. https://doi.org/10.1016/B978-0-12-803615-0.00001-4

75. Vashishtha S, Vashishtha DS. The evolution of the Indian carbon market: challenges, opportunities, and policy frameworks. SSRN; 2025. https://doi.org/10.2139/ssrn.5082032

76. Kumar P. Energy Conservation Amendment Bill 2022: it all boils down to targets for industries. Down To Earth. 2022;10.

77. Gorain S, Malakar A, Chanda S. An analysis of carbon market and carbon credits in India. Asian J Agric Ext Econ Sociol. 2021;39(2):40-9. https://doi.org/10.9734/ajaees/2021/v39i230570

78. Jaspal M. To price or not to price? making a case for a carbon pricing mechanism for India. New Delhi: ORF, Observer Research Foundation; 2022.

79. Mitra, A. Reconciling India's Climate and Industrial Targets: A Policy Roadmap. Observer Research Foundation; 2021.

80. Hazra ND. Emission trading schemes (ETS) in India: an overview. Sustain Agri Food Environ Res. 2023;11. https://doi.org/10.7770/safer-V11N1-art2634

81. Karedla Y, Mishra R, Patel N. The impact of economic growth, trade openness and manufacturing on CO_2 emissions in India: an

autoregressive distributive lag (ARDL) bounds test approach. J Econ Finance Adm Sci. 2021;26(52):376-89. https://doi.org/10.1108/JEFAS-06-2020-0114

82. Manjunatha N, Kumar R. A study on carbon credits trading in Indian context. Int J Commer Manag Stud. 2024;9(3).

83. Acworth W, Schambil K, Bernstein T. Market stability mechanisms in emissions trading systems. Berlin: ICAP; 2020.

84. Munot S. Green economy and sustainable development in India: challenges and opportunities. Int J Sci Res. 2022;13(4):330-5. https://doi.org/10.21275/SR24405172819

85. Ray S, Ray A. Some aspects of carbon trading: issues and challenges with reference to India. Adv Appl Econ Finance. 2012;1(2):95-106.

86. Jain JK, Jain H, Agrawal M. Prospects and challenges of carbon credit trading in India. Int J Adv Res Commer Manag Soc Sci. 2023;6(1): 83–94.

87. Dixit S, Bardiya S. Carbon trading in developing economies: challenges, opportunities, and best practices. Int J Multidiscip Res. 2024;6(6). https://doi.org/10.36948/ijfmr.2024.v06i06.30282

88. Niu Y, Abdullayev V, Alyar AV, Kamran AT. Green technologies and their role in mitigating climate change: a comparative study across developing nations. ESTIDAMAA. 2023;2023:27-35. https://doi.org/10.70470/ESTIDAMAA/2023/004

89. Patil M, Boraste S, Minde P. A comprehensive review on emerging trends in smart green building technologies and sustainable materials. Mater Today Proc. 2022;65:1813-22. https://doi.org/10.1016/j.matpr.2022.06.137

90. Esty DC, Winston A. Green to gold: how smart companies use environmental strategy to innovate, create value, and build competitive advantage. Hoboken: John Wiley & Sons; 2009.

91. Bhattacharjee P. Benefits, risks and trade-offs in renewable and low carbon technologies for green energy electricity production in India. Sachetas. 2023;2(2):49-57. https://doi.org/10.55955/220005

92. Panos E, Kannan R, Hirschberg S, Kober T. An assessment of energy system transformation pathways to achieve net-zero carbon dioxide emissions in Switzerland. Commun Earth Environ. 2023;4(1):157. https://doi.org/10.1038/s43247-023-00884-w

93. Zeng X, Duan M, Yu Z, Li W, Li M, Liang X. Data-related challenges and solutions in building China's national carbon emissions trading scheme. Clim Policy. 2018;18(Suppl 1):90-105. https://doi.org/10.1080/14693062.2018.1454889

94. Carver T, Dawson P, Kerr S. Including forestry in an emissions trading scheme: lessons from New Zealand. SSRN; 2017. https://doi.org/10.2139/ssrn.3015082

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.