Impact of California and RGGI's ETS Policies on Carbon Emissions Reduction

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***Abstract*—The Emission Trading System (ETS) has become a widely adopted market-based instrument for controlling carbon emissions. This study applies a difference-in-differences (DID) approach, supplemented by a *β*-convergence analysis, to evaluate the impact of ETS policies in California and states in the Regional Greenhouse Gas Initiative (RGGI) on CO_2 emissions. The results reveal clear heterogeneity: While states such as Maine, Massachusetts, Maryland, New Hampshire, and New Jersey achieved significant reductions, the effects in California, Connecticut, and Delaware are limited, and New York, Rhode Island, and Vermont show no evidence of mitigation. These variations reflect differences in energy and industrial structures, allowance price dynamics, and policy implementation. The findings highlight that effective ETS design requires sufficient price stringency, broad sectoral coverage, and strong enforcement mechanisms, offering lessons not only for U.S. states but also for emerging carbon markets.**

***Keywords*—Emissions Trading System, carbon pricing, CO_2 emissions, California, RGGI, Difference-in-Differences**

I. Introduction

Over the past few decades, the impact of human activities on climate change has become an undisputed fact. In particular, global warming caused by greenhouse gases (GHGs) emissions has become one of the most pressing environmental issues worldwide. Since 1970, global surface temperatures have increased at a faster rate than during any other 50-year period in at least the past 2000 years. Furthermore, between 2011–2020, global surface temperatures were approximately 1.1 °C higher than those recorded in 1850–1900 [1]. The observed warming is primarily due to anthropogenic emissions of GHGs, mainly carbon dioxide (CO_2) and methane (CH_4). Among these gases, CO_2 is particularly important, accounting for 76% of total GHGs emissions. According to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report, current CO_2 concentrations are higher than at any time in at least the last 2 million years [2]. Globally, the main sources of greenhouse gas emissions include electricity and heat (31 %), agriculture (11 %), transportation (15%), forestry (6 %), and manufacturing (12 %). Among these, the burning of coal, natural gas, and oil for electricity heat generation remains the single largest source of global GHGs emissions [2]. These facts highlight the urgent need for coordinated action to mitigate climate change.

Beyond environmental concerns, the absence of effective environmental policies imposes significant social and cultural costs. Communities located near industrial facilities often face disproportionate exposure to air pollution, which is strongly linked to respiratory diseases, premature mortality, and rising public health expenditures [3, 4]. Moreover, the costs and benefits of environmental degradation are unequally distributed. Low-income households devote a larger share of their income to energy expenditures and are therefore more vulnerable to price shocks, whereas high-income households often capture disproportionate benefits from green investment incentives. These dynamics underscore that climate change is not only an environmental crisis but also a social justice issue, highlighting the urgency of adopting effective policies that ensure both environmental protection and social equity [5].

To mitigate the trend of global warming, countries have signed the Paris Agreement, which aims to limit the increase in global temperatures to 1.5 °C by the end of this century. Under this agreement, countries commit to reducing GHGs emissions in accordance with the principle of Nationally Determined Contributions (NDC). According to this principle, countries can reduce carbon emissions through multiple approaches, including policy formulation, technological innovation, market mechanisms, and public participation. These strategies aim to reduce GHGs emissions, improve energy efficiency, and promote renewable energy. Among these approaches, carbon pricing has gained significant attention as one of the most effective measures.

Carbon pricing mainly consists of carbon taxes levied on companies and individuals, and a carbon trading system that allows market participants to buy and sell emission credits. Among them, the emission trading system has become a relatively popular carbon pricing method because it adopted the "Cap & Trade" system, and a large number of European countries jointly formulated and adopted the International Emissions Trading System in the 1997 Kyoto Protocol. The theoretical foundation of Emissions Trading Systems (ETS) can be traced back to Coase's seminal work on the problem of social cost. According to Coase, when property rights are well-defined and transaction costs are negligible, externalities such as pollution can be efficiently addressed through voluntary bargaining among affected parties [6]. In the context of carbon emissions, ETS institutionalizes this logic by assigning property rights to emit GHGs in the form of tradable allowances and allowing firms to exchange these rights in a market. This market-based approach enables cost-effective abatement: firms with lower marginal abatement costs can sell excess permits to firms facing higher costs, thus minimizing the overall cost of reducing emissions [7]. Therefore, ETS can be viewed as a practical application of the Coase Theorem in environmental policy, aligning private incentives with socially optimal outcomes through market coordination.

To assess the practical effectiveness of ETS as a market-based instrument for reducing carbon emissions, numerous empirical studies have been conducted. Lise *et al.* [8] analyzed the impact of emissions trading on electricity prices

across 20 EU countries and found that wholesale electricity prices increased by approximately 12–27% compared to pre-emissions trading levels. However, under the condition of perfect competition and demand price elasticity of 0.2, the carbon price of 20e/t, it can reduce emissions by more than 210Mt. Based on a carbon price of 40 e/t, the total emission reduction increases to 363Mt. Biancalani *et al.* [9] also confirm that from 2005 to 2020, the EU ETS contributed to a significant reduction of approximately 15.4% in carbon dioxide emissions across the analyzed industries. Estimations of counterfactual carbon emissions using raw sector emissions datasets further indicate that between 2008 and 2016, the EU ETS reduced CO_2 emissions by approximately 1.2 billion tons compared to a scenario without carbon markets (a reduction of 3.8%). This amount is nearly half of the total emissions reductions achieved by EU governments under the Kyoto Protocol, with greater reductions observed in sectors covered by the EU ETS [10].

Although a large number of studies have shown that the EU ETS is effective in reducing carbon emissions, there is also evidence of its unintended negative effects. For instance, when considering optimal energy mix decisions for a power sector subject to an ETS under demand uncertainty, Berseni found that in the long term, ETS hinders the expansion of renewable energy technology capacity, rather than facilitating it [11]. Additionally, emissions are expected to increase under a business-as-usual scenario. While the EU ETS has achieved remarkable results in some respects, it also faces many challenges and criticisms.

However, these experiences provide valuable references for other countries, especially large carbon emitters such as the United States. The United States, as one of the world's largest economies, also plays a crucial role in the world in terms of carbon emissions. In 2022, the country's total GHGs emissions reached 6.343 billion tons of carbon dioxide equivalent, mainly due to the increase in CO_2 emissions from the combustion of fossil fuels. The United States ranks as the second-largest CO_2 emitter globally, following China. But when per capita is taken into account, the United States leads the world in carbon emissions [12]. In terms of countermeasures, unlike the European Union, which responds to climate change through a centralized policy mechanism, the United States takes a more decentralized approach due to its federal system, with states having greater autonomy over carbon emissions policies. California, for example, launched its cap-and-trade program in 2013, making one of the state's major policies to reduce GHGs emissions. This program is the world's fourth-largest emissions trading program after China, the European Union, and South Korea. Its goals include reducing GHGs emissions to 1990 levels by 2020, achieving 40% reduction from 1990 levels by 2030, and an 80% reduction by 2050. In addition to California, 11 northeastern states (including Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, Vermont, and Virginia) have also formed the Regional Greenhouse Gas Initiative (RGGI) as the first interstate carbon trading system in the United States. RGGI focuses on the electric power sector and controls carbon emissions by auctioning allowances, with revenues going primarily to energy efficiency programs and renewable energy development. Revenues are used for energy efficiency programs and renewable energy development. In addition, more states are beginning to explore joining existing carbon markets or creating new ones. Pennsylvania, for example, is considering joining RGGI.

Beyond the analysis of ETS policies themselves, a growing body of literature has also examined the broader structural and socioeconomic factors that influence carbon emissions. Research by York, Rosa, and Dietz shows that population size has a proportional effect on CO_2 emissions and energy footprint, and affluence also monotonically increases CO_2 emissions and energy footprint [13]. Similarly, Muhammad *et al.*'s study on Malaysia also confirmed that economic growth is the main contributor to carbon dioxide emissions. When trade opening brings prosperity, CO_2 emissions will increase accordingly. The U-shaped relationship between urbanization and CO_2 emissions was also confirmed by this study. Namely, urbanization initially reduces carbon dioxide emissions, but after reaching a threshold level, it increases CO_2 emissions [14]. In addition, Jin&Kim's panel cointegration test results indicate that there is a long-term equilibrium relationship between carbon emissions, renewable energy consumption, and nuclear energy consumption, and the development and expansion of renewable energy is crucial to preventing global warming [15]. Unlike the above factors, the impact of technological progress on carbon emissions is more complex. Ganda investigated how innovation and technology investments affect carbon emissions in selected Organization for Economic Cooperation and Development (OECD) economies from 2000 to 2014. The study finds that renewable energy consumption and R&D expenditures show a statistically significant negative relationship with carbon emissions, but the number of ternary patent families suggests a positive and significant relationship with carbon emissions. With respect to the number of researchers, Ganda finds a positive but statistically insignificant correlation with carbon emissions, suggesting that a larger research workforce does not necessarily translate into lower emissions without effective application of green technologies [16]. Chen *et al.* found that although technological progress in China reduced carbon emissions overall during the period of the study, and that technological progress in central and western China reduced carbon emissions significantly, carbon emissions in the eastern part of the country slightly increased. These findings suggest that the relationship between technological progress and carbon emissions is not straightforward; it is influenced by both environmental factors and production technology changes [17]. These findings highlight the importance of considering broader socioeconomic and technological drivers when evaluating the emission reduction effects of ETS policies.

Although several states in the United States have taken a number of measures to address carbon emissions, such as implementing emissions trading systems, the effects of these measures vary across regions. Currently, most existing studies on the effects of ETS policies have focused on regions such as the European Union and China, providing in-depth analysis and evaluation of ETS implementation. However, as a large carbon-emitting country, the United States has a unique federal system that allows each state to design and implement different climate policies according to its own

conditions. The diversity of this system has led to a research gap in the study of carbon emission policies in the United States. Moreover, most of the existing experiments rely on quantitative analysis but rarely directly assess the impact of ETS policies on carbon emissions. To address this gap, this article employs a Difference-Indifferences (DID) approach to systematically study the effects of ETS implementation in U.S. states. By comparing the changes in carbon emissions in states that have implemented ETS policies with those that have not implemented them during the same time period, this study aims to evaluate the actual effects and impacts of ETS policies in different state policy environments and provide more specific information for future policy formulation.

II. Materials and Methods

ETS is a form of carbon pricing designed specifically for CO_2 and other GHGs. There are two main types of trading systems: cap-and-trade systems and baseline and credit systems. In a cap-and-trade system, emissions caps are fixed, and emission permits can be auctioned or allocated for free based on specific criteria. In contrast, a baseline and credit system does not impose a fixed emissions limit. Instead, polluters that reduce emissions beyond their obligations can earn "credits", which they can sell to entities requiring additional allowance. Although these mechanisms theoretically provide strong incentives for emission reductions, their actual effect must be assessed using precise empirical data. The DID approach is able to compare differences in carbon emissions between states that have implemented ETS and those that have not, after controlling for time and inherent regional characteristics. Through this method, we can more accurately quantify the actual effects of ETS policies and evaluate their effectiveness in different policy environments.

The basic DID regression specification is given by:

$$Y=\alpha+\beta_1\cdot\text{Intervention}+\beta_2\cdot\text{Time}+\delta_1\cdot(\text{Intervention}\cdot\text{Time})+\varepsilon \quad (1)$$

where Y is the dependent variable of interest, *Intervention* is a cross-sectional dummy variable, with values 0 and 1 representing the control group and the treatment group. *Time* is a time dummy variable, where 0 and 1 represent the periods before and after the policy implementation.

β_1 captures the differences that may have existed between the treatment and control groups before the policy was implemented, and β_2 captures the factors that would have caused Y to change in the absence of the policy. The interaction term *Intervention* · *Time* equals 1 only if both *Intervention* and *Time* are equal to 1. In this case, δ_1 measures the real impact of the policy, which is also the main focus of this study.

The error term ε represents unobserved factors that may affect Y. Assuming that $\mathbb{E}(\varepsilon_{it} \mid \textit{Intervention}) = 0$, the average treatment effect δ_1 is given as:

$$\begin{aligned}\delta_1 = {} & \mathbb{E}\,(Y \mid \text{Intervention} = 1, \text{Time} = 1) \\ & - \mathbb{E}\,(Y \mid \text{Intervention} = 0, \text{Time} = 1) \\ & - \mathbb{E}\,(Y \mid \text{Intervention} = 1, \text{Time} = 0) \\ & - \mathbb{E}\,(Y \mid \text{Intervention} = 0, \text{Time} = 0)\end{aligned} \quad (2)$$

The validity of the difference-in-differences (DID) design relies on the parallel trends assumption, which states that, in the absence of the ETS policies, the treated group and the control group would have followed similar CO_2 emission trajectories. To assess this assumption, we plot in Fig. 1 the group-level average CO_2 emissions for California, the RGGI states, and the control group.

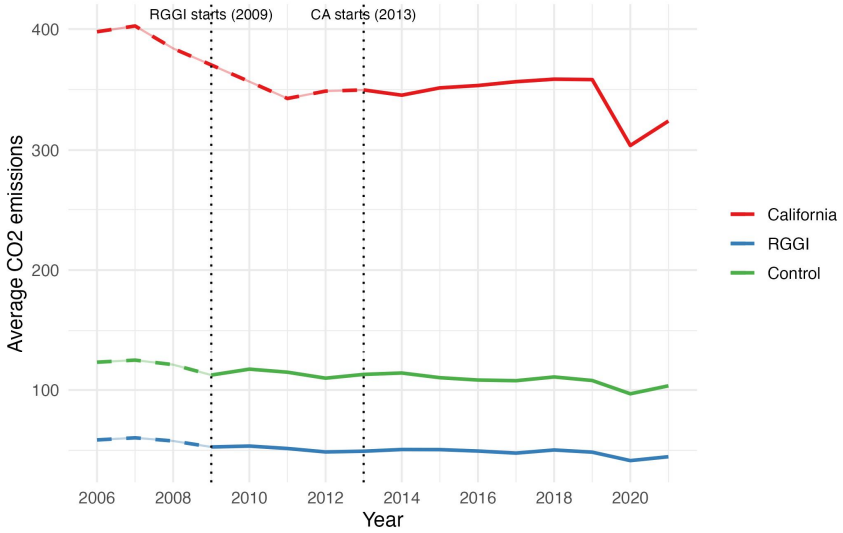

Fig. 1. CO_2 emission for California, the RGGI states, and the control group, from 2006 to 2021.
Source: U.S. Environmental Protection Agency.

For the RGGI states, the pre-2009 path is nearly parallel to that of the control group. For California, the year-to-year pattern also moves in the same direction as the control group before 2013. Fig. 1 shows emissions rose from 2006 to 2007, declined from 2007 to 2009, then after a slight decrease in 2011–2012 began to rise again. Although California's absolute emission level is much higher, making the visual amplitude appear larger, the sequence of increases and decreases matches that of the control group during the pre-policy years. These visual comparisons provide supporting evidence that the parallel trends assumption is reasonably satisfied for both the RGGI and California analyses, ensuring the credibility of the DID estimates.

In the United States, under the influence of the federal

system, each state introduces its own policies according to the situation. Thus, in addition to the Intervention we are studying, it will also be affected by changes in other factors due to unobservable institutional differences. To control for this heterogeneity between the control and treatment groups, other control variables will be introduced in the model to refine it. At this point, the model will be represented as:

$$Y=\alpha+\beta_0 \cdot X+\beta_1 \cdot \text{Intervention}+\beta_2 \cdot \text{Time}+ \delta_1 \cdot (\text{Intervention} \cdot \text{Time}) + \varepsilon \quad (3)$$

where X represents factors affecting variable Y.

The concept of β-convergence has been increasingly applied in environmental studies to examine whether regions with higher initial emissions reduce faster than others. Incorporating this approach allows us to test whether ETS policies promote convergence in emissions intensity across states, while also controlling for natural convergence effects that could otherwise confound the estimated policy impact. According to the β-convergence method in DID introduced by Lin & Li, the growth rate of carbon dioxide emissions can be expressed as [18]:

$$\ln\left(\frac{E_t}{E_{t-1}}\right)= \alpha - b \cdot \ln E_{t-1} + \beta_0 \cdot X_t + \beta_1 \cdot c_t + \beta_2 \cdot d_t + \delta_1 \cdot (c_t \cdot d_t) + \varepsilon_t \quad (4)$$

where $b = 1 - e^{-\beta}$, and β denotes the convergence rate of carbon dioxide emissions. E_t represents total CO_2 emissions. Lagged emissions are introduced to control for potential mean regression or natural convergence of carbon emissions. The convergence term allows us to test whether countries with higher initial emissions tend to have slower emissions growth, a dynamic that reflects the coordination effects of environmental regulation.

Meanwhile, the cross-sectional dummy variable *Intervention* is replaced by our research object c_t, and the time dummy variable *Time* is replaced by d_t. δ_1 is used to test whether the growth rate of total carbon dioxide emissions in states that implement ETS policies is significantly slower than that in states that do not implement ETS policies. If its value is significantly greater than zero, ETS will help reduce the growth rate of carbon emissions and can be considered an effective policy to reduce carbon dioxide emissions.

In the United States, although no national ETS exists, several regional programs have been implemented. The most notable examples are California's cap-and-trade program and the Regional Greenhouse Gas Initiative (RGGI) in the northeastern states. California's ETS was established under Assembly Bill 32, passed in 2006, and officially launched in 2013. The program aims to return GHGs emissions to 1990 levels by 2020. It covers nearly all major emission sources, including power plants, industrial facilities, refineries, and fuel distributors. Allowances are auctioned or traded on secondary markets, with the total cap declining annually in line with state reduction targets. Compliance reviews occur every three years. California's system is also linked to Quebec's carbon market, enabling cross-border allowance trading.

In contrast, RGGI is an interstate cooperative ETS launched in 2009, following a 2005 agreement among participating states. It focuses on the electric power sector by setting emissions caps and conducting allowance auctions. Each allowance represents one ton of CO_2, and power producers must hold sufficient permits to cover their emissions. Auction revenues are allocated to energy efficiency programs, renewable energy development, and consumer benefit initiatives. Current RGGI members include Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, Vermont, and Virginia. However, because Virginia joined only in 2021, after the study period, it is treated as part of the control group in this analysis.

For empirical identification, this study defines California and the ten RGGI states (excluding Virginia) as the treatment group, while all other U.S. states serve as the control group. To improve model specification, we include a set of control variables commonly associated with CO_2 emissions in the literature: GDP, urban population ratio, and R&D expenditure. GDP captures the effect of economic activity; the urban population ratio reflects the degree of urbanization, which may influence energy demand and transportation structure; and R&D expenditure proxies for technological innovation, which can affect emissions either positively or negatively depending on the context. The selection of these variables is supported by prior empirical studies [13–17].

The sample consists of panel data covering all 50 U.S. states from 2006 to 2021. The control variables include the GDP level, urban population proportion, and R&D expenditure of each state. The GDP data comes from USAFACTS, the urban population share data comes from the U.S. Census Bureau, the R&D expenditure data comes from the NSF, and the carbon emissions data comes from the US EPA.

III. Results and Discussion

A. Validity of the System GMM Estimation

To estimate the impact of ETS policies on carbon emissions, this study employs the System Generalized Method (System GMM) estimator because the model contains lagged dependent variables and potential endogeneity that would otherwise cause dynamic panel bias. Compared with standard fixed-effects or difference GMM estimators, System GMM combines level and first-difference equations and uses lagged level variables as instruments, which provides consistent estimates for our dynamic panel setting [19]. Model validity is confirmed through standard diagnostic tests: the Arellano-Bond test for serial correlation in differenced residuals [20], and the Sargan test for overidentifying restrictions. According to Table 1, the AR(1) test confirms expected first-order serial correlation, while the AR(2) test is insignificant, indicating valid instruments. The Sargan test also fails to reject the null, supporting the appropriateness of the instrument set and the overall model specification.

B. Main Results and Interpretation

1) Urbanization and carbon emissions

From Table 1, model results indicate that urbanization is positively associated with CO_2 emissions. In California, where the transportation sector is the largest contributor to GHGs, increased urbanization likely leads to greater reliance

on private vehicles and higher fuel consumption [21]. Additionally, urban expansion typically involves more commercial and residential construction, which drives up energy use for heating, cooling, lighting, and other building services. According to the World Bank, the building sector accounts for 38% of global energy-related CO_2 emissions [22]. As most of these energy demands are still met by fossil fuels, urban growth tends to exacerbate carbon emissions in the absence of low-carbon infrastructure.

2) GDP and carbon emissions

The effect of GDP on carbon emissions varies across regions. In California, economic growth is positively associated with increased emissions. For instance, California's GHGs emissions rose by 12.6 million tons of CO_2 equivalent in 2021, largely due to post-pandemic economic recovery [21]. In contrast, RGGI states exhibit a negative relationship between GDP and emissions, which is consistent with the Environmental Kuznets Curve (EKC) hypothesis. According to the EKC, emissions initially increase with income growth but eventually decline once a certain income threshold is surpassed [23]. In RGGI states, this trend may be driven by stricter environmental regulations, improved energy efficiency, and greater adoption of renewable energy, which collectively reduce fossil fuel dependency and lower emissions.

Table 1. Estimated results of the model

	CA	CT	DE	ME	MA	MD	NH	NJ	NY	RI	VT
CO_2e_lag	-0.013	0.0008	0.0069	0.0029	0.0014	-0.0004	0.0005	0.0008	0.0014	0.0023	0.0021
lngdp	0.0052	-0.0049	-0.0085	-0.0058	-0.0053	-0.0043	-0.0049	-0.0047	-0.0052	-0.0057	-0.0055
up	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0005	0.0003
lnrd	-0.0016	0.0015	0.0003	0.0009	0.0015	0.0020	0.0019	0.0017	0.0014	0.0013	0.0015
ct_dt	-0.0039	0.0095	-0.0022	-0.0119*	-0.0126*	-0.0082*	-0.0154**	-0.0332***	0.0012	0.0076	0.0055
AR(1)	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
AR(2)	0.1524	0.1533	0.2304	0.0784	0.1259	0.0666	0.1978	0.1333	0.1272	0.2487	0.0679
Sargan	0.8641	0.8641	0.8641	0.8641	0.8641	0.8641	0.8641	0.8641	0.8641	0.8641	0.8641

Note: For the policy variable *ct_dt*, ***, ** and * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Coefficients of other control variables are not annotated with significance to maintain table clarity.

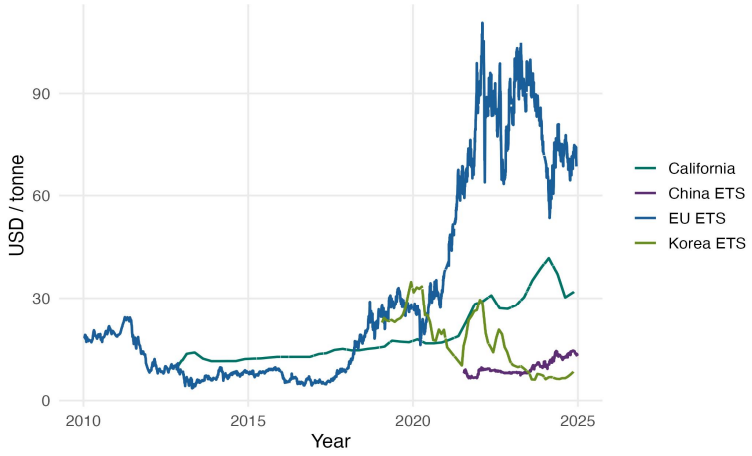

Fig. 2. The primary quota prices across the four major carbon trading markets, from 2010 to 2025.
Source: International Carbon Action Partnership(ICAP) ETS Price Tracker (2024).

3) R&D and carbon emissions

The impact of R&D expenditure on carbon emissions also differs by region. In California, increased R&D investment is associated with lower emissions, likely due to the state's sustained support for clean energy innovation. Since 2012, the California Energy Commission's Electric Program Investment Charge Program (EPIC) program has invested over $1 billion in clean energy projects, attracting an additional $7.8 billion in private funding [24]. Furthermore, California's leadership in electric vehicle (EV) infrastructure, accounting for over 25% of U.S. public charging stations and 34% of national EV registrations by mid-2024, also reflects the state's technology-driven emissions reduction efforts [25].

In contrast, R&D spending in RGGI states appears to correlate with increased emissions. This counterintuitive result may stem from the allocation of R&D funds to energy-intensive sectors such as heavy industry or high-tech manufacturing. Additionally, new technologies often require substantial energy input during development and deployment, potentially increasing emissions in the short term. This aligns with the "rebound effect" proposed by Sorrell (2007), which suggests that energy efficiency gains can paradoxically increase total energy demand [26]. As Boardman (2004) notes, the full emissions-reduction benefits of energy innovation often take time to materialize [27]. For example, in Maryland, R&D in bioenergy may initially increase emissions due to the energy intensity of biomass processing, despite potential long-term benefits.

C. ETS Policy Effectiveness across States

The treatment group/control group dummy variable interaction term, which represents the ETS policy effect, has a negative coefficient, indicating that the growth of CO_2 emissions in states with ETS policies is relatively slower than that in states without ETS policies. According to Table 1, in several states where the results were significant, all states

exhibit negative coefficients, suggesting that ETS policies in these states have contributed to reducing CO_2 emissions. It is worth noting that California, Connecticut, Delaware, New York, Rhode Island, and Vermont did not pass the significance test, indicating that the mitigation effect of the ETS policies in these states is very limited.

The small, insignificant coefficient for California is somewhat surprising, given that California's cap-and-trade program is often considered one of the most comprehensive in the U.S. However, this result can be explained by two key characteristics of the California carbon market that began to emerge in 2016: the quarterly quota auction no longer sold all available quotas for the year, and the secondary market price fell below the auction price floor [28]. California policymakers designed a weak carbon market with a broad range of complementary policies that led to a reduction in allowance demand, making it difficult to isolate the impact of the ETS alone. In addition, regulatory market reforms in April 2014 led to substantial emission leakages from the power sector. These factors combined to cause the ETS to have insignificant results in reducing California's carbon emissions [29].

The differences in ETS effectiveness across RGGI states are attributed to state-level policy implementation variations. Some states (Maine, Massachusetts, Maryland, New Hampshire, New Jersey) exhibit larger negative coefficients, suggesting more substantial emissions reductions. This aligns with findings from Murray and Maniloff, who found that RGGI had contributed to emissions reductions in participating states [30]. In contrast, the results for CT, DE, NY, RI, and VT are not significant, possibly due to emission leakage issues caused by the limited geographical scope of the regional energy management system and interconnected electricity markets. Schmalensee and Stavins also pointed out that the RGGI program has limited direct impact on CO_2 emissions in the power industry, and government programs that reduce energy demand and thus reduce CO_2 emissions and quota requirements are mainly brought about by the program's auctions [31]. Borghesi's study of the EU ETS emphasizes that price fluctuations may affect the effectiveness of emission reductions, especially when policymakers do not set a price floor. Low prices result in polluters having no incentive to reduce pollution levels [32]. Data shows that although the average CO_2 emission quota price of four of the world's five major carbon emissions trading systems increased by 40% from January 2021 to January 2022, RGGI's quota price is still the lowest among them, at $14 per ton, which is only higher than China-ETS. Fig. 2 shows that the primary quota prices in several major carbon markets in the world have continued to decline in recent years. This may explain why the carbon emission reduction effects in some RGGI states are not significant [33].

D. Sources of Heterogeneity in ETS Impacts

Beyond the aggregate results, the heterogeneous effectiveness of ETS across states can be better understood by considering structural and institutional differences. These variations indicate that the observed outcomes are shaped not only by the presence of a carbon market but also by state-specific contexts that condition how the policy operates in practice.

One important dimension is the composition of the energy mix. In California, the relatively high and rising share of renewable energy, reinforced by complementary policies such as the Renewable Portfolio Standard, has made it difficult to disentangle the independent effect of the ETS. By contrast, several RGGI states, including Vermont and Rhode Island, remain more dependent on fossil-fuel generation, leaving them with fewer substitution options and limited incentives to abate when carbon prices are low [31].

Industrial structure further contributes to these differences. California's economy is dominated by service-oriented and high-technology industries, which are less emission-intensive and thus face lower compliance costs. In parts of the RGGI region, however, traditional manufacturing and other energy-intensive activities still represent a larger share of economic activity. For these states, abatement tends to be more costly and adjustment slower, reducing the short-term effectiveness of ETS policies [30].

Market design and price dynamics also influence the magnitude of observed impacts. RGGI allowance prices have remained at relatively low levels, averaging around $14 per ton in 2022, which provides only a weak incentive for substantial abatement. As illustrated in Fig. 2, primary quota prices across several major ETSs have diverged considerably in recent years. The EU ETS has experienced a sharp increase since 2018, which has been associated with stronger abatement incentives [10], while California has maintained only moderate prices, and China's national ETS has remained at very low levels since its inception. The experience of low-price systems is consistent with previous findings that weak carbon prices provide limited incentives for emissions reduction [31, 33]. This international comparison offers a useful parallel for understanding the limitations of RGGI. When allowance prices persistently remain at the lower end, the effectiveness of ETS policies is inevitably constrained, which helps explain why the estimated ETS effect is statistically insignificant in several RGGI states. Meanwhile, California's carbon market, although characterized by quarterly auctions and a price floor, has also faced challenges. The presence of multiple complementary policies has reduced demand for allowances, leading to instances of unsold permits in some auctions. This weakened demand has muted the price signal and undermined the independent impact of the ETS on emissions reductions [28].

Differences in policy implementation further explain cross-state heterogeneity. Within RGGI, the use of auction revenues varies substantially across states. Massachusetts and Maryland, for example, have systematically directed revenues toward energy efficiency and renewable energy programs, thereby amplifying the mitigation effect. By contrast, some states have allocated revenues more sparingly and, in certain cases, used portions of the proceeds for general fiscal purposes rather than directly supporting abatement programs, which has weakened the enforcement strength of the ETS [30, 31]. California's case is somewhat different. The state enforces its ETS with a formal structure of quarterly auctions and a price floor, but the presence of multiple overlapping complementary policies, such as renewable portfolio standards and energy efficiency mandates, has reduced the independent demand for allowances. This overlap has diminished the stand-alone enforcement role of

the ETS, making its independent effect more difficult to isolate. Moreover, the sectoral scope of RGGI is limited primarily to the power sector, whereas broader systems such as the EU ETS extend coverage to additional high-emission industries. This narrower coverage further reduces enforcement stringency and helps explain why ETS impacts differ across jurisdictions.

Taken together, these factors suggest that the heterogeneous outcomes observed across California and the RGGI region are consistent with underlying structural and institutional conditions. The effectiveness of ETS is conditioned by energy mix, industrial composition, market stringency, and policy enforcement. Understanding these contextual determinants is therefore essential for evaluating carbon markets, as the presence of a trading system alone does not guarantee uniform reductions in emissions.

IV. Policy Recommendations

Building on the empirical findings, several policy insights can be drawn to enhance the effectiveness and equity of Emissions Trading Systems. For RGGI, the persistently low allowance prices have weakened the incentive for abatement. Strengthening the price floor or tightening the overall cap would help increase price stringency. In addition, auction revenues should be systematically allocated to energy efficiency and renewable energy programs rather than dispersed or redirected to general fiscal purposes, thereby ensuring that the revenues reinforce the environmental objectives of the policy.

California's case highlights that the effectiveness of an ETS is shaped not only by its formal market design but also by the interaction with overlapping climate policies. Although the state operates quarterly auctions and maintains a price floor, the presence of extensive complementary policies, such as renewable portfolio standards and efficiency mandates, has reduced the independent demand for allowances. This overlap has diluted the stand-alone role of the ETS. Future reforms should better coordinate ETS with other state-level policies and consider stronger linkages with other carbon markets in order to improve overall market efficiency.

At the cross-national level, the comparison between the EU ETS and China's national ETS provides useful insights. The EU ETS, with relatively high allowance prices and broad sectoral coverage, has been more effective in incentivizing emissions reductions. By contrast, China's ETS has so far been characterized by lower prices and a narrower coverage, limiting its impact. These cases highlight that the effectiveness of ETS policies critically depends on both price stringency and coverage.

V. Conclusion

This study uses the DID method to examine the impact of the implementation of ETS policies on carbon emissions in California and RGGI states. The results show that GDP is positively correlated with the growth rate of CO_2 emissions in California, while it has a negative correlation with CO_2 emissions in RGGI states. R&D spending has decreased CO_2 emissions in California, but has a positive correlation with carbon emissions within RGGI, and the urbanization process has increased the accumulation of per capita CO_2 emissions. At the same time, the emission reduction effect of ETS varies from state to state. The implementation of ETS in ME, MA, MD, NH, and NJ has significantly reduced CO_2 emissions, as indicated by the strong negative coefficients in these states. This suggests that ETS implementation in these states has resulted in substantial emission reductions compared to non-ETS states. The interaction coefficients of CA, CT, and DE are also negative, but none of them pass the significance test, indicating that the mitigation effect of ETS in these states is limited. In addition, NY and RI exhibit positive coefficients, yet their results fail to pass the significance test, indicating that the mitigation effect of ETS in these states is limited.

These findings confirm that the effectiveness of ETS varies substantially across states. Variations in energy mixes, industrial composition, allowance price dynamics, and policy implementation all contribute to the uneven outcomes of ETS. For example, California's overlapping complementary policies have muted the stand-alone role of its ETS, while RGGI states differ widely in how auction revenues are allocated and reinvested, which in turn affects enforcement strength.

These insights point to important policy implications. Effective ETS design requires not only the establishment of a trading system, but also sufficient price stringency, broad sectoral coverage, and strong enforcement mechanisms. In particular, linking auction revenues directly to energy efficiency and renewable investments, avoiding policy overlap that weakens market signals, and maintaining credible price floors are essential for ensuring environmental effectiveness.

Overall, this study contributes to the growing literature on emissions trading by providing new empirical evidence on the heterogeneous effects of ETS in the United States and by identifying the structural and institutional conditions that shape policy outcomes. The findings underscore that ETS effectiveness cannot be judged in isolation from these broader contexts, and future research could further examine how different policy designs interact with economic structures and market conditions across jurisdictions.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Zhuohong Shen conceived the study, collected the data, conducted the empirical analysis, interpreted the results, and wrote the manuscript. The author has read and approved the published version of the manuscript.

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