


The heterogeneous effects of emissions trading systems on energy consumption

Wai Yan Shum^a, Xiujie Tan^{b,c}, Xuan-Hoa Nghiem^d, Tsun Se Cheong^{a,f,g}, Ning Ma^{e,*} 

^a School of Business, The Hong Seng University of Hong Kong, Hong Kong

^b Institute for International Studies, Wuhan University, Wuhan, China

^c Climate Change and Energy Economics Study Center, Wuhan University, Wuhan, China

^d International School, Vietnam National University, Hanoi, Vietnam

^e Hainan College of Economics and Business, Haikou, China

^f Australia-China Relations Institute, University of Technology Sydney, Sydney, Australia

^g International Business School, Hainan University, Haikou, China

ARTICLE INFO

Handling Editor: Mark Howells

Jel code:

Q01

Q40

Q48

Q50

Q58

Keywords:

Emission trading scheme

Hubei

Energy consumption

Allocation methods

ABSTRACT

Various measures have been proposed to reduce energy consumption (and ultimately emission) among which emission trading scheme (ETS) has been on top of the agenda. However, the majority of the existing literature focuses on the general impact of ETS while ignoring its potential heterogeneous effects. This paper investigates the influence of ETS on energy consumption with respect to different groups of stakeholders in China's Hubei province. To overcome the shortcomings of traditional econometric methods, the distribution dynamics method (which can capture transition probabilities and future evolutions) is employed. Empirical results confirm the significant and inhibiting impact of ETS on energy consumption in Hubei province, China. The superior role of benchmark and historical allocation methods in mitigating energy consumption is also confirmed. As the ETS can lower energy consumption in different areas (urban and rural), different types of firms (State-owned and private) and different industries (high- and low-polluting ones), Hubei provincial leaders are recommended to utilize this kind of scheme to decouple economic growth and energy consumption, thus protecting the environment in this area. Furthermore, other provinces in China may take the Hubei ETS as a shining example and implement appropriate steps similar to those of the Hubei ETS to yield similar benefits.

Abbreviations

COVID-19	Coronavirus disease
GHG	Greenhouse gas emission
ETS	Emission trading scheme
ICT	Information and Communication Technologies
OMCDMP	Operation and Management of Clean Development Mechanism Projects
CWPECER	Comprehensive Work Plan for Energy Conservation and Emission Reduction
GDP	Gross Domestic Product
CO ₂	Carbon emissions
NDRC	National Development and Reform Commission
MPP	Mobility Probability Plot
RTEC	relative total energy consumption

1. Introduction

The world's spotlight over the past few years has shone on the COVID-19 pandemic and the ongoing Russia-Ukraine conflict, thus diverting attention from other critical issues. The dissipation of these events have caused other pressing issue to re-emerge among which climate change and environmental degradation constitute most crucial problems. These phenomenon, if left uncontrolled, may lead to far-reaching, catastrophic consequences on various aspects of the economy and human life (including but not limited to: increasing sea levels, more frequently occurred natural disasters, ever-higher temperatures) [1,2]. Among the established causes of climate change and environmental degradation, greenhouse gas (GHG) emissions is usually regarded as the leading cause to environmental degradation and climate change (which in turn, is attributed to energy consumption).

* Corresponding author

E-mail address: china_ma_ning@hotmail.com (N. Ma).

<https://doi.org/10.1016/j.esr.2025.101935>

Received 23 April 2025; Received in revised form 13 July 2025; Accepted 28 September 2025

Available online 21 October 2025

2211-467X/© 2025 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

Aware of the devastating effects of climate change and environmental degradation, researchers have taken efforts to figure out causes and potential solutions to these problems. Numerous solutions/measures have been put forward to tackle one of the most critical, lingering issues in the 21st century, ranging from the adoption of information and communication technologies-ICT [1], production and consumption of renewable energy [3,4], the use of green finance [2], the reduction of energy consumption [5], the integration of different measures or even the implementation of emissions trading schemes (ETS).

Among these proposals, ETS come to prominence as these schemes may bring about substantial benefits for the economy and society as a whole such as lower emissions, lower total energy consumption [6], greater clean/renewable energy consumption [7], higher green/clean innovation [8]; higher firms' total factor productivity. Better still, ETS are often cost-effective, making it attractive for developing countries as they may not need to invest initial huge investments into other solutions (such as information and communication technologies-ICT adoption, renewable energy production or green finance). As the emitter of 27 % of global carbon emissions and more than 33 % of global GHG,¹ ETS has been top of the agenda in China's measures to contain climate change, accelerate its energy transition and achieve zero-carbon in 2050.

Commonly considered the world's second largest economy and biggest emitter, China's economic growth and prosperity have been confronted with serious challenges posed by climate change. In response to these threats, China has adopted various measures to contain its energy consumption and ultimately GHG emissions, ranging from the acceleration of renewable energy production and consumption, improvement in energy efficiency, ICT adoption and especially its large-scale ETS. China's nation-wide ETS comes into full-scale operation since July 16th 2021, becoming the world's largest ETS. However, as Liu et al. [9] posit, China's national ETS remains under-developed, immature, leaving room for further improvements. However, before the official launch of the national ETS, China has adopted seven regional ETS in different areas across the country.

While there have been quite a few studies examining the effects of these ETS on various aspects of the Chinese economy, ranging from emission reduction, productivity or energy consumption, most of these studies employ a total/aggregate approach, implying that the existing literature appeared to overlook the specific effects of ETS on different stakeholders. Specifically, current studies only pay attention to ETS at different provinces or industries while failing to take into account its impact on companies' behaviors. As Chinese firms account for more than 18 % of national greenhouse gas emissions – making them a major stakeholder in China's fight against climate change [10], ignoring the role of ETS in altering firms' activities would lead to misleading conclusions, inferences and ill-informed policy design and implementation. Furthermore, the behavior of a firms may also vary, depending on its ownership structure (whether it is State-owned or private) and its location. Therefore, it is of critical importance to examine the influence exerted by ETS on firms' energy consumption activities, thus providing important insights into companies' behaviors in response to the introduction of ETS. This study is aimed at filling this void in the literature and therefore, making several significant contributions to the literature.

First, it evaluates the effectiveness of one of China's largest pilot ETS – the Hubei ETS (which is believed to bear strong resemblance to China's overall economic conditions) – on total energy consumption using a novel approach. Rather than just examining total energy consumption of the Chinese economy, the current manuscript aims to investigate the ETS-consumption of energy nexus from a novel approach using different points of view: State-owned and private firms; urban v. s rural areas;

¹ World Bank (2022): <https://www.worldbank.org/en/news/press-release/2022/10/12/china-s-transition-to-a-low-carbon-economy-and-climate-resilience-needs-shifts-in-resources-and-technologies#:~:text=China%20emits%2027%20percent%20of,of%20the%20world's%20greenhouse%20gases.>

high-emission and low-emission industries; over-capacity and other industries as well as allocation methods. Results from this study may carry important implications for relevant stakeholders at the national level (governments, policymakers), industry levels (different industries) and firm-level (State-owned and private firms).

Second, rather than making use of traditional econometric methods – which fail to account for multimodal distribution or changes in shapes of the distribution, this paper utilizes distribution dynamic techniques which take into account the shape and temporal development of the distribution. Third, it significantly adds to the literature on ETS in China in particular and in developing/emerging nations in general (together, these economies constitute biggest emitters). As Hu et al. [11] posit, the majority of studies on ETS are conducted using data from developed economies with advanced institutional and legal environments. Meanwhile, developing economies (such as China) are usually riddled with weak institutions and prevalent corruption, posing major hurdles to the smooth adoption and implementation of market-based environmental instruments and policies [11,12]. Findings from this study indicate that even under a corrupt environment and weak legal and institutional environments, market-based instruments and policies aimed at protecting the environment may still prove useful, thus offering important implications and lessons for other developing nations to design and implement their ETS.

In order to achieve these goals, this study seek answers to the following research questions.

- (1) Does the implementation of the ETS in Hubei province lead to lower firms' total energy consumption?
- (2) Are the effects of the Hubei ETS varied according to firms' ownership structure (State-owned and private), their location (urban and rural areas) and industries (high-polluting and low-polluting).

Empirical results from dynamic distribution methods confirm the benefits of ETS on reduction of firms' energy consumption, regardless of their ownership structures, location or industries.

The remainder of the paper proceeds as follows: Section 2 provides a review of the literature; Section 3 describes distribution dynamic techniques and data used in the model. Section discusses the results while Section 5 concludes the paper.

2. Literature review

2.1. Overview of China's emission, its efforts and ETS plan

Being the world's most populous nation, the largest emitter, the second largest economy (and largest developing one), over the past several decades, China has enjoyed high economic growth which in turn, made it confronted with a spate of serious problems such as depleted natural resources, climate change, environmental degradation. Deeply aware of the consequences caused by these phenomena, China has spared no effort to implement different measures to cure the root causes of these problems including measures to lower energy consumption, reduce emissions, enhance energy efficiency and saving. In the early 2000s, China adopted its Operation and Management of Clean Development Mechanism Projects (OMCDMP) and its Comprehensive Work Plan for Energy Conservation and Emission Reduction (CWPECER). Since then, China has become clearer, more ambitious and determined in setting specific, quantified targets for emission reduction. For example, China formally declared in 2009 that its CO₂ emission per each unit of GDP would be reduced by 40–45 % compared with that of 2005. However, these measures were administrative in nature, mainly consisting of command and control directions or interventions [11,13,14].

Conscious of the fact that costs incurred by these command and control measures and interventions may outweigh the benefits provided by them (explicitly acknowledged in their 11th Five Year Plan), China

has tried to adopt other market-based initiatives among which the ETS stand out as the most promising one [15]. In 2011, China's National Development and Reform Commission (NDRC) officially approved the launch of seven pilot ETS projects in Beijing, Hubei, Shanghai, Chongqing, Shenzhen and Guangdong.² These pilot ETS came into being in 2013, marking the first milestone in China's emission trading markets. Then in 2021, China decided to launch its national-scale ETS.

Among these seven pilot ETS, the Hubei ETS captures special attention owing to several reasons. First, Hubei region bears strong resemblance to mainland China in terms of certain characteristics. China and Hubei's levels of development are close to each other with industrial sector playing a major role in discharging emissions and accelerating growth/development [15]. On top of that, Hubei also possesses its own unique features as its industrialization process remains ongoing. Furthermore, among the seven regions with the ETS, Hubei is the only region characterized by a heavy industrial structure. Finally, the ETS in Hubei has been well-known for its smooth, effective operations and continuous innovation [15]. Therefore, evaluation of the Hubei ETS may carry important implications for China's remaining regional ETS and even its recently launched national ETS.

In terms of the Hubei pilot ETS itself, there have been several studies assessing the effects of this pilot ETS. However, these studies focus only on the Hubei region only [15,16] while ignoring other aspects such as the possible differences between State-owned firms and private firms, between urban and rural areas or between different industries. The current study is aimed at filling this void in the literature.

2.2. Literature review of ETS

While being recognized as one of the most crucial inputs for economic growth, energy is also confirmed to release adverse impacts on the society such as climate change, global warming, severe weather events – which are usually labeled as the negative externalities of energy [9]. To minimize these negative effects, it would be helpful to either adopt measures to reduce emissions or improve energy efficiency. Numerous measures and proposals have been put forward to reduce energy consumption (and ultimately lower emissions and climate change). These measures, to name but a few, include the adoption of ICT ([2], 2024 [1]), the use of green finance [5] and digital finance (Bakry et al., 2024), the utilization of the financial sector [3] or even forestation activities (Kocoglu et al., 2024). In addition to these measures, Kartal [17] affirms the beneficial effects of renewable energy as well as the detrimental effects of fossil fuel on emissions.

As Kartal argues, to realize net-zero target and achieve environmental sustainability, several actions need to be taken simultaneously. Therefore, in addition to the above-mentioned measures (that are relatively voluntary), another effective approach is to find ways to internalize these negative externalities. In other words, policymakers can put in place mechanisms to encourage and/or force firms to reduce their energy consumption, mitigate emissions and boost energy efficiency. One of the most frequently adopted measures is the imposition of environmental tax. Usually touted as an essential and effective tool to enhance environmental quality by facilitating preventative actions and mitigating environmental pollution [18–21]. Consequently, the significant role of environmental taxes in mitigating energy consumption (emission) and improving environmental quality has been studied extensively in the literature. Kartal [20,21] confirm the dampening effect of environmental taxes in several developed nations. Similarly, Yin et al. [22] record a long-run beneficial impact of environmental tax on renewable energy usage. Aziz et al. [23] confirm the benefits offered by

environmental taxation in several Asian economies. However, in a recent study, Ahmad et al. [24] posit that countries may need to put in place stronger mechanisms to better utilize environmental taxes. This is in line with Yasmeen et al. [25] who opine that to make environmental taxes effective, a country must improve its governance quality.

As mentioned above, the use of mitigation strategies should not be used separately. Rather, countries are advised to implement several plans at the same time. Another tool, usually regarded as a market-oriented environmental instrument to lower emission and energy consumption is ETS. This special trading scheme has become all the more popular due to the severity of the effects of climate change and is usually regarded as the most effective political strategy [26]. However, it should be noted that the idea of ETS has been inception more than 60 years ago by Dales [11,27]. According to Dales [27], to internalize the pollution caused by firms, it would be helpful to put in place so-called emission trading scheme. In this scheme, firms are given a total maximum amount of emissions that they can discharge together. Each firm will also be allocated a certain amount of emissions that they are allowed to emit. If one firm is able to lower their emissions at a cheaper and more effective manner than others do, the firm may want to sell its remaining “quota” on the market at the available price [11,28]. Liu et al. [15] posit that ETS may meet the need for greater flexibility in GHG emission reduction. Furthermore, ETS can also offer extra incentives for firms to improve their GHG reduction. These advantages are expected to facilitate emission trading between high-polluting and low-polluting firms, thus enabling people to minimize the costs incurred during the process of carbon emission mitigation. Therefore, ETS is usually regarded as a cost-effective market instrument in mitigating energy consumption, emission and climate change [29].

The inhibitory effects of ETS on energy consumption and emissions can be attributed to and achieved through several mechanisms. First, as ETS imposes caps and higher costs for carbon emissions, firms may be prompted to take actions by either reducing energy consumption [30, 31] or improving energy efficiency (through the introduction of green technologies) [32,33]. Furthermore, ETS can lead to structural changes in different industries, optimize factor allocation as well as encourage low-carbon energy consumption [11,34–38]. These improvements, in turn, are expected to result in lower emissions [39]. The second channel through which ETS can lower emissions is through fundamental alterations in the energy mix. It is widely believed that ETS is capable of causing a shift from the production and consumption of high-carbon energy to low-carbon energy as ETS might increase the costs of using coal, thus forcing firms to scale back their use of coal and switch to other kinds of low-carbon energy (including renewable energy). As a result, total emissions will be reduced [40–47].

As ETS is able to lower energy consumption, mitigate emissions and facilitate energy transition, this market-based environmental protection tool is also expected to decouple economic growth from fossil fuel consumption and lead to low-carbon development. In other words, ETS will have a crucial role to play in boosting economic growth without increasing emissions [29]. In addition to the reduction in energy consumption and emissions, ETS may bring about other positive externalities. For example, Hu et al. (2020) argue that the introduction of ETS may lead to the realization of so-called Porter hypothesis [48] which states that under pressures of the ETS, firms can initiate technological progress.

ETS is also able to bring about other benefits to economic growth. Zhang et al. [49] confirm that the implementation of ETS may help minimize GDP losses associated with emission reduction in the US, Japan and South Korea. Meanwhile, Liu et al. [15] find that the integration of ETS can limit the losses in GDP associated with carbon emissions in Hubei region. Dong et al. [50] even confirm the validity of the Porter hypothesis and therefore, positive impact of ETS on economic growth in China. Zhang et al. (2020) record the increasing impact of ETS on industrial output in China. ETS is also found to exert beneficial effects of ETS on employment (job creation effect) as well as poverty reduction

² The main aspects of these seven ETS include: (1) Coverage; (2) Cap setting; (3) Permit allocation; (4) Allowance trading; (5) Monitoring, reporting and verification (MRV); and (6) Compliance. For a detailed review of these aspects, see Hu et al. [11].

[51,52]. On top of these positive impacts, ETS is also found to be advantageous in different areas as it is capable of: improving air quality [53]; lessening (income) inequality [10]; spurring firms' productivity [54,55] and innovation [56]; enhancing firms' investment efficiency [57,58]; boosting high-quality manufacturing development [59], export performance [60] and financial performance [61].

From discussions above, it can be concluded that ETS may have wide-ranging, substantial benefits to offer. However, most studies either focus on developed nations. Studies on developing economies mainly focus on China with few articles investigating the Hubei ETS pilot project. Moreover, these papers focus on total energy consumption while ignoring the difference between energy consumption of different subjects (State-owned v. s private firms; rural v. s urban areas etc.). This gap may make it difficult for policymakers in drawing useful implications and crafting and implementing policies (even can lead to misleading, biased policy decisions). This manuscript is aimed at filling this void in the literature.

3. Methods and data

3.1. Methods

Although they may provide succinct statistical summaries, conventional econometric methods ignore important information about multimodal distributions. Consequently, using these techniques might result in biased/misleading conclusions and inferences [62]. Conventional methodologies also fall short of providing a thorough perspective of the whole pattern of distributions and dynamic evolution [63]. Furthermore, one limit of the econometric models in forecasting is that they can only give the forecast of the dependent variable but cannot predict the change in the shape of a distribution. The distribution dynamics technique, on the other hand, focuses on the examination of the shape and temporal development of the distribution.

Another advantage of the distribution dynamics technique over standard econometric analysis is the robustness to outliers. This benefit results from the fact that distribution dynamics analysis focuses primarily on the likelihood (probability) that entities will change their states. This likelihood/probability, meanwhile, mainly depends on the occurrences of these entities and less on calculated values of them. The derivation of the slope parameter, which is dependent on the existence of outliers, makes traditional econometric analysis susceptible to their effect.

There are two primary types of Quah's distribution dynamics technique: the conventional Markov transition matrix analysis and the stochastic kernel approach. Due to the arbitrary demarcation used in the classic Markov transition matrix analysis, determining the grid values is difficult. However, compared to the conventional Markov transition matrix technique, the stochastic kernel approach permits an objective demarcation and thus it was employed in this research.

The bivariate kernel estimator is shown below:

$$\hat{f}(x,y) = \frac{1}{nh_1h_2} \sum_{i=1}^n K\left(\frac{x - X_{it}}{h_1}, \frac{y - X_{it+1}}{h_2}\right) \quad (1)$$

where n is number of observations, x (y) is relative standard coal used by a company in t ($t+1$) periods. X_{it} (X_{it+1}) denotes observed/realized value of relative standard coal used by that company in t ($t+1$) periods. Moreover, the h_1 and h_2 terms denote bandwidths calculated by Silverman's (1986) technique, while K denotes (normal) density function. This paper employs Silverman (1986) flexible bandwidth-based adaptive kernel approach to deal with the problem of data sparseness. The procedure consists of two phases. The first step is the computing of a pilot estimate followed by an adjustment of the bandwidth by a factor that is based on kernel density. Assuming that distribution in $(t + \tau)$ period hinges only on t , the ensuing process will become first-order and will not alter over different time periods, distributions in period (t) and

period $(t + \tau)$ will follow the process:

$$f_{t+\tau}(z) = \int_0^\infty g_\tau(z|x)f_t(x)dx \quad (2)$$

In this equation, $g_\tau(z|x)$ represents transition kernel plotting distribution t period to $(t + \tau)$ period, while $f_t(x)$ denotes function of kernel density of distribution of variable at period t , while $f_{t+\tau}(z)$ denotes τ -period-ahead function of density of z (conditional on x). As a larger sample size would boost the reliability of the findings, annual transitions are employed in the study. The ergodic density function (if it exists) can be derived from equation (3).

$$f_\infty(z) = \int_0^\infty g_\tau(z|x)f_\infty(x)dx \quad (3)$$

where $f_\infty(z)$ represents the ergodic density function given infinite τ . The ergodic distribution is the steady-state distribution in the long run.

Mobility Probability Plot (MPP) [63] is used to present the findings on the transition of entities in the distribution. The MPP can be derived using calculation of $p(x)$ (which denotes the probability of net upward mobility probability):

$$p(x) = \int_x^\infty g_\tau(z|x)dz - \int_0^x g_\tau(z|x)dz \quad (4)$$

The probability of net upward mobility is represented by the MPP, a value range from -100 to 100 . According to [64], a positive (negative) value indicates the possibility of the entity experiencing an upward/downward change in the variable's distributions. MPP is believed to possess certain advantages over conventional techniques like contour maps or three-dimensional charts that are often employed in distribution dynamics research. First, it provides deep insights into dynamics of the transition process of a variable including the cases when probability mass of the distribution could be strongly concentrated. Additionally, several MPPs may be superimposed on a single figure, allowing for an effective comparison of the transitional dynamics across groups.

3.2. Data collection and preliminary analysis

We compiled a balanced panel dataset of 113 enterprises covered by the Hubei ETS pilot from 2009 to 2019, with detailed descriptive statistics presented in Table 1. Energy consumption is calculated in tons of standard coal, while the remaining variables are dummy variables. For the ownership heterogeneity variable, state-owned enterprises are coded as 1, and other enterprises as 0. For the regional heterogeneity variable: enterprises in the Wuhan Metropolitan Circle (the "1 + 8" cities, including Wuhan, Huangshi, Ezhou, Huanggang, Xiaogan, Xianning, Xiantao, Tianmen, and Qianjiang) are coded as 1, and other enterprises as 0. For the industry heterogeneity variable, enterprises in high-emission industries such as electricity, steel, cement, and chemicals are coded as 1, and other enterprises as 0. For the overcapacity heterogeneity variable, enterprises in overcapacity industries such as steel, cement, glass, and non-ferrous metals are coded as 1, and other enterprises as 0. For the allocation method heterogeneity variable, enterprises adopting the benchmarking method are coded as 1, and other enterprises as 0.

4. Results and discussions

The efficiency of the ETS pilot will be the subject of Section 4.1. Comparing the energy usage of government and private enterprises in Section 4.2 will help researchers understand ownership heterogeneity. By comparing the energy consumption of enterprises in urban and rural areas, Section 4.3 will then look at the regional consumption heterogeneity. Next, Section 4.4 will assess emission-scale heterogeneity by comparing energy consumption in high- and low-emitting industries. Section 4.5 will explore production capacity heterogeneity by

Table 1
Summary statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
Energy consumption (tce)	1188	355,133	655,662	2113	4,530,633
State-owned enterprises	1110	0.3901	0.4880	0.0000	1.0000
Enterprises in the Wuhan Metropolitan Circle	1110	0.4595	0.4986	0.0000	1.0000
High-emission enterprises	1110	0.7027	0.4573	0.0000	1.0000
Overcapacity enterprises	1110	0.4685	0.4992	0.0000	1.0000
Benchmarking	1100	0.4091	0.4920	0.0000	1.0000

This table provides descriptive statistics of the variables involved in the study. Source: Authors' calculations

contrasting the energy consumption patterns of overcapacity industries with those of other industries. The consumption heterogeneity bought by the quota allocation technique will be examined in Section 4.6.

4.1. The effectiveness of the ETS pilot

The energy consumption patterns pre- and post-pilot are examined. First, it examines the historical transition dynamics before and after the Hubei ETS pilot using changes in all firms' relative total energy

consumption (RTEC). The section then uses each previously estimated historical transition dynamic to determine the firm's historical mobility, as illustrated by the MPP. Finally, depending on the fundamental historical transition dynamics movement pre-pilot and post-pilot, this part presents and displays the steady-state perspective of ergodic distributions for all firms before and after the pilot.

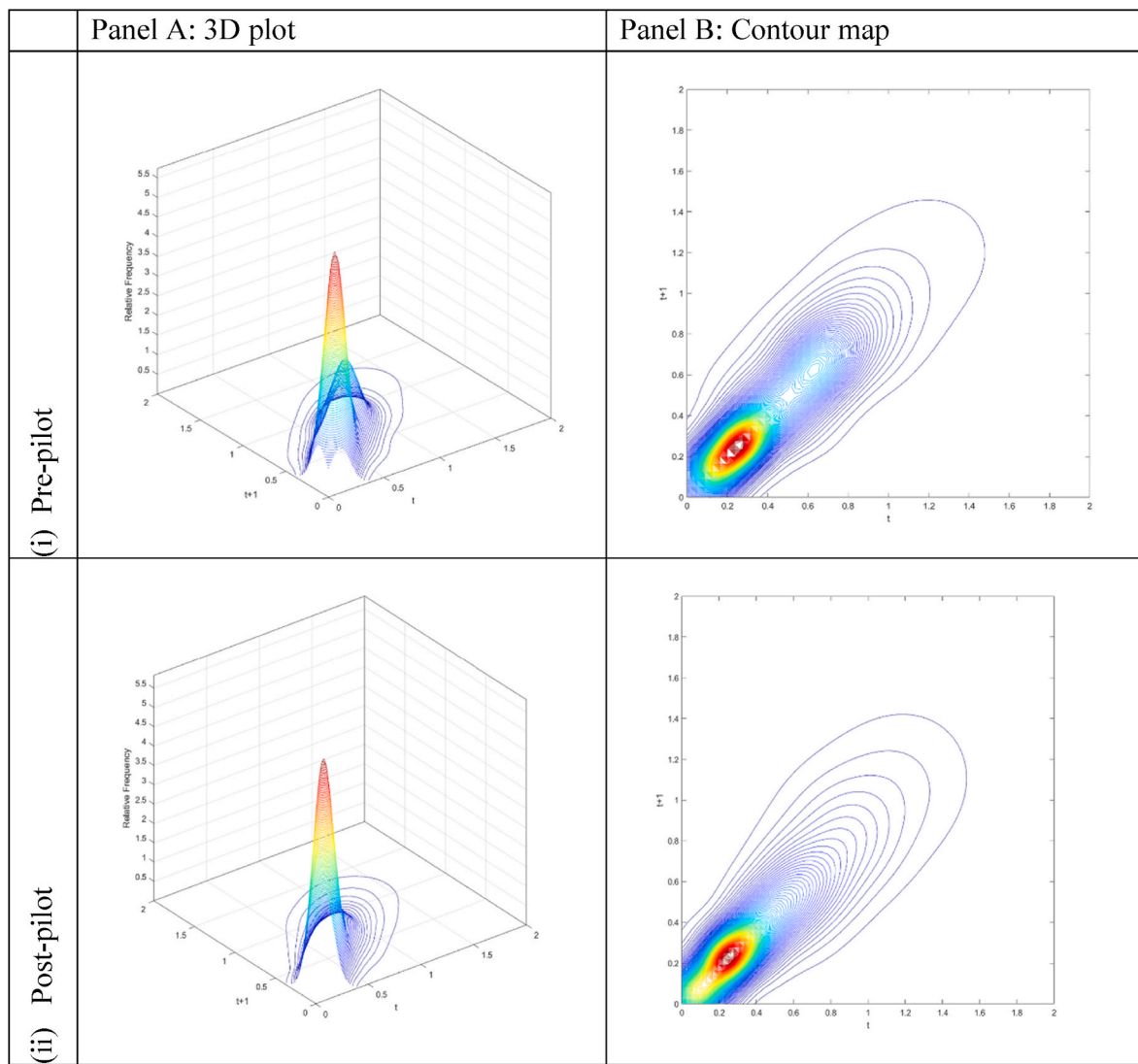


Fig. 1. 3D and contour plots of transition probability kernels of RTEC pre- and post-pilot. This figure displays the 3D plots and contour plots of total energy consumption on the left hand side and right hand side of the figure, respectively. The upper half of the figure shows the 3D and contour before while the lower half of the figure shows the 3D and contour after the implementation of the ETS in Hubei. Source: Author's calculations.

4.2. Historical transition dynamics before and after the pilot

Fig. 1, Panel A, indicates the three dimensions (3D) relative total consumption (RTEC) plots for all firms pre- and post-pilot using kernel-based transition probability. The relative frequency displayed at the firm level in Fig. 1 Panel A indicates the likelihood of moving from a specific value of RTEC in the t th year to a different value of RTEC in the $(t+1)$ th year. As RTEC is determined as a ratio to the firm-level average, the RTEC average equals to one (1). If smaller than one, an RTEC is below average, while if it is greater than one, it implies above average value of RTEC. Remarkably, several RTEC companies have values higher than 3. However, since there is no likelihood due to the observation of mass concentration, such contour lines are not presented.

The transition probability has two distinct probability mass concentrations before the ETS pilot [see Fig. 1 Panel A (i)]. In the three-dimensional graphic, a probability mass concentration is used to represent the concentration of firms close to a certain point. Each 3D display contains a contour map of the firm units (see Fig. 1 Panel B), as it is difficult to discern a point's RTEC values from a 3D plot. From the contour map in Fig. 1 Panel B (i), it is simpler to determine the values of the peaks. The primary peak was observed at around the value of (0.24, 0.24), while secondary peak occurs around (0.62, 0.62). The concentration pattern reveals one thing: majority of businesses have below-average RTECs, while another set of firms has consumption levels that are marginally higher but still below the RTEC average of one.

The only probability mass concentration that can be seen after the pilot is shown in Fig. 1 Panel A (ii). The first peak, (0.23, 0.23), is visible around the RTEC value on the associated contour maps in Fig. 1 Panel B (ii). The primary peak from before the programme is slightly higher in value than after the programme's peak. Furthermore, after the programme is implemented, the secondary peak from before the programme disappears. It demonstrates that the initiative is successful in reducing energy use.

It is challenging to determine an enterprise's mobility from the cumulative probability distribution in the 3D plots or even with the help of the contour maps. It would be more effective to look at the MPP analysis to review the pilot program's effectiveness.

4.2.1. Historical MPPs before and after the pilot

The MPP can show the upward or downward mobility of firms. With a range of -100 to 100 , the MPP shows the historically predicted net upward mobility value (percentage of RTEC) (see Fig. 2). If it is positive, it indicates a firm with positive historical value of net upward mobility at a particular consumption level represented by the RTEC value. When it shifts from areas above to below horizontal axis (lower), MPP will cross it. It's important to understand that the firms on left-hand side of

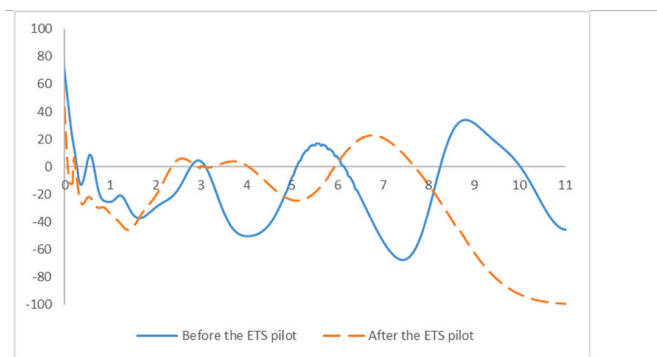


Fig. 2. MPP of RTEC pre- and post-ETS pilot. This figure displays the likelihood that a firm will increase or decrease its energy consumption, corresponding to the positive or negative value of the MPP. Note: Net upward mobility (%) represented by vertical axis while RTEC value represented by horizontal axis. Source: Author's calculations.

crossing point are assumed to have positive while those on right-hand side have a negative value. As a result, several firms will assemble the around the intersections.

Fig. 2 shows that the MPP for all firms overlaps the horizontal axis before the programme at the RTEC levels of 0.27, 0.65, 3.34, 6.13, and 10.16. Because of this, businesses gathered around these intersections, as seen in Fig. 1 Panel A. (i). While almost all of these businesses had historically low consumption levels (between 0.27 and 0.65), a few have consumption levels that are noticeably higher than the national average for firms, sometimes by a factor of 10.16. As a result, the MPP's multiple intersection points show a distinct split in historical energy use among firms prior to the programme. The stratification of energy usage persisted after the pilot programme. The horizontal axis of the MPP of companies is intersected at several RTEC values, including 0.22, 0.24, 3.11, 4.12, 5.97, and 7.68. However, each of these values is lower than it was prior to the pilot programme. The MPP comparison demonstrates that this trading scheme programme launched in Hubei was influential on reduction of energy consumption.

4.2.2. Future ergodic distributions in pre-pilot and post-pilot periods

The RTEC distribution at firm level will reach its steady state eventually from the historical dynamics underpinning the MPPs while maintaining the transition dynamics. The dynamic transition model will predict the RTEC distribution given the current consumption patterns. The term "ergodic distribution" will subsequently be used to refer to the projected long-run and steady-state distribution.

Fig. 3a indicates the ergodic distribution that existed before the programme, while Fig. 3b indicates the distribution that existed following the program. Five peaks at various RTEC levels can be seen in the before-the-program ergodic distribution. At RTEC values of 0.27 and 0.65, the tallest peak and the secondary peak, respectively, are visible in Fig. 3a. If the consumption habits from before the programme are maintained, the majority of the enterprises will have below consumption levels (i.e., 0.27 and 0.65). Simultaneously, several small groups of firms will depart from the low-consumption practice and will cluster at consumption levels of 3.34, 6.13, and 10.16, indicating that they will have consumption levels that are 3.34, 6.13, or even 10.16 times higher than the average firm if the pre-program consumption practices are left in place.

Multiple convergence clubs are hardly noticeable after the programme. The most prominent peaks can be seen at roughly RTEC level 0.16, while the other peaks can be seen at roughly RTEC values 2.71, 4.12, and 8.21 if one looks at the tail behavior, as shown in (Fig. 3b). According to this, the vast majority of businesses will eventually reach a consumption level of 0.16 if consumption patterns can be kept up after the programme. It means that businesses will cut back on their consumption levels.

4.2.3. Effectiveness of the Hubei ETS pilot

The historical transition dynamic, historical MPPs, and future ergodic distribution comparisons between the pilot program's before and after periods imply the same conclusion: most enterprises emit less after the pilot. Thus, it can be said that the programme successfully cuts down on energy use.

4.3. Impact of Hubei ETS from an ownership viewpoint: state-owned vs private enterprises

This section looks at how different state-owned and private businesses use energy. Only the ergodic distributions and the MPPs that underlie them will be provided and discussed to analyse the ownership nature heterogeneity. As explained in the methodology section, the MPP can explain the transition dynamics that underlie the RTEC. The projected ergodic distributions for state-owned and private businesses are shown in Fig. 4a and c (before the program) and Fig. 4b and d (after the program), respectively. Fig. 5 indicates the MPPs for those businesses.

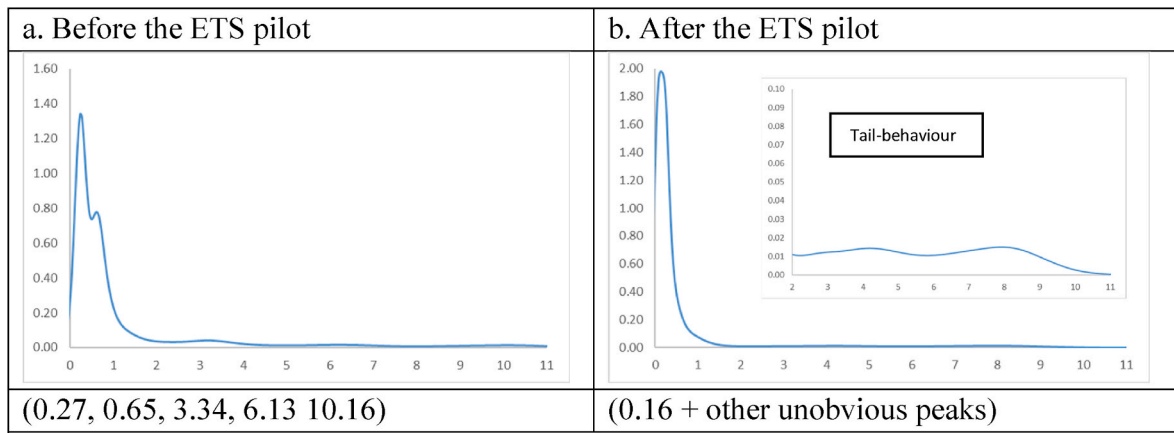


Fig. 3. Ergodic distributions of RTEC pre- and post-pilot program in Hubei. This figure displays the projected long-run, steady-state distribution of relative total energy consumption of firm, based on its current consumption level. Probability density is represented by vertical axis while RTEC values by horizontal axis and peak values in parentheses.

Source: Authors' own estimation.

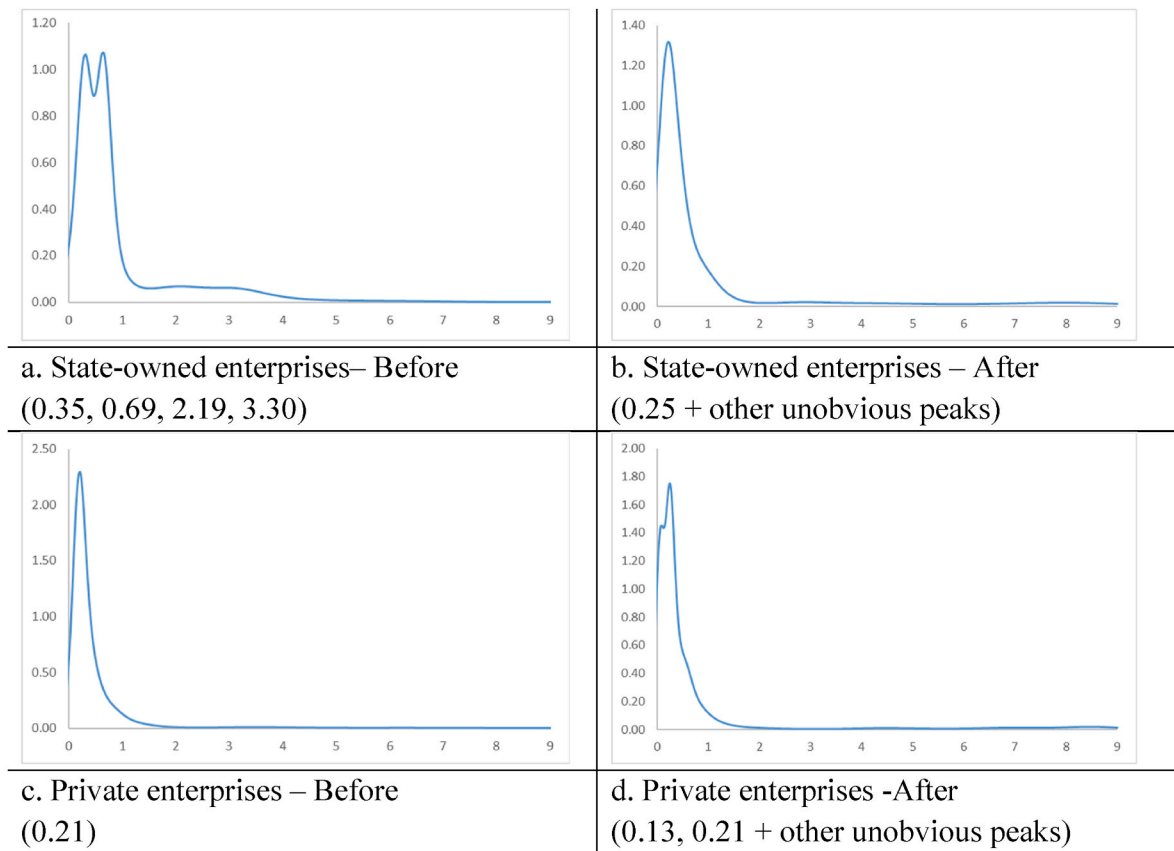


Fig. 4. Ergodic distributions for state-owned and private enterprises' relative total energy consumption (RTEC) before and after the Hubei ETS pilot. This figure displays the projected long-run, steady-state distribution of relative total energy consumption of firm, based on its current consumption level. Unlike Fig. 3, this Fig. 4 differentiates between State-owned and private firms in order to see the differences between these two types of ownership before and after the introduction of the ETS. Probability density is represented by vertical axis while RTEC values by horizontal axis and peak values in parentheses.

Source: Authors' calculation.

4.3.1. State-owned enterprises' consumption before and after the Hubei ETS pilot

On the one hand, the first two peaks before the programme are located at below-average RTEC values of 0.35 and 0.69, respectively, as shown from the ergodic distribution (Fig. 4a). It indicates that most state-owned firms consume less than the firm-level average. On the other hand, the two peaks with RTEC values of 2.19 and 3.30 show that

some firms consume more than the firm-level average. This suggests that if the pre-program dynamic stays constant, state-owned firms will have radically different consumption habits.

After the program, just one obvious peak can be seen at the RTEC value of 0.25 (Fig. 4b). Additionally, the ergodic distribution is less distributed, leading to the conclusion that most enterprises will spend less after the programme, assuming the post-program practices can be

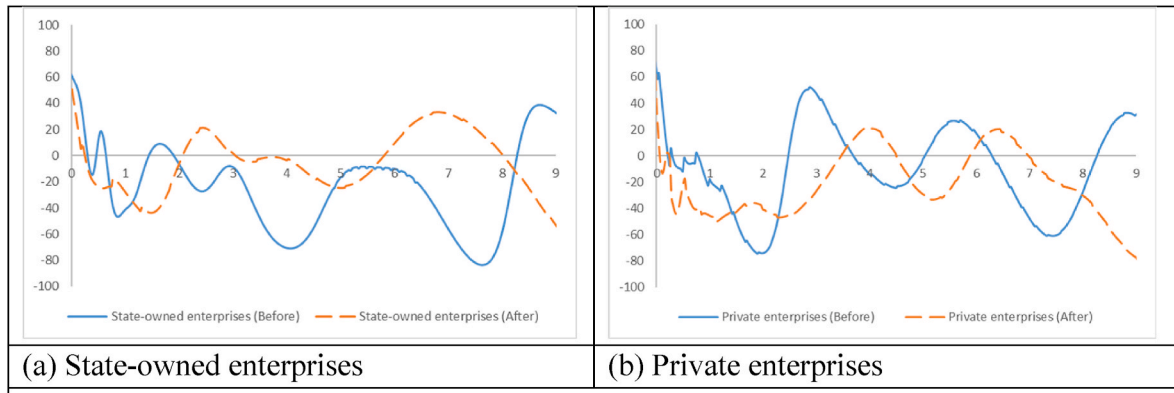


Fig. 5. Mobility probability plot for rural and urban enterprises' RTEC pre- and post-pilot periods. This figure displays the likelihood that a firm will increase or decrease its energy consumption, corresponding to the positive or negative value of the MPP. RTEC values are shown on the horizontal axis, and the vertical axis displays net upward mobility (per cent). Source: Authors' estimation.

maintained.

The MPPs shown in Fig. 5a indicate the same conclusion. The junction points of the MPPs line up with the convergence clubs seen in the ergodic distributions. Be aware that the before-the-program MPP with RTEC values from 2.00 to 8.00 does not cross the horizontal axis at any point. This suggests that since there is a very small chance that businesses will cluster around the range, there shouldn't be any peaks within the RTEC values of 2.00–8.00. Therefore, the peaks appearing around the RTEC values of 2.19 and 3.30, as seen in Fig. 4a, are not supposed to be observable. One explanation is that the average expected value is

distorted by a few companies with extremely high consumption levels. Since these peaks (i.e. 2.19 and 3.30) disappeared after the program, it can imply that a few high-energy businesses were forbidden under the scheme. One can infer from the ergodic and MPPs analysis that the initiative was successful in lowering state-owned firms' total consumption. Additionally, it ceases businesses from engaging in extremely high consumption practices.

4.3.2. Private enterprises' emissions pre- and post-pilot periods

Ergodic distribution of energy use for private businesses before and

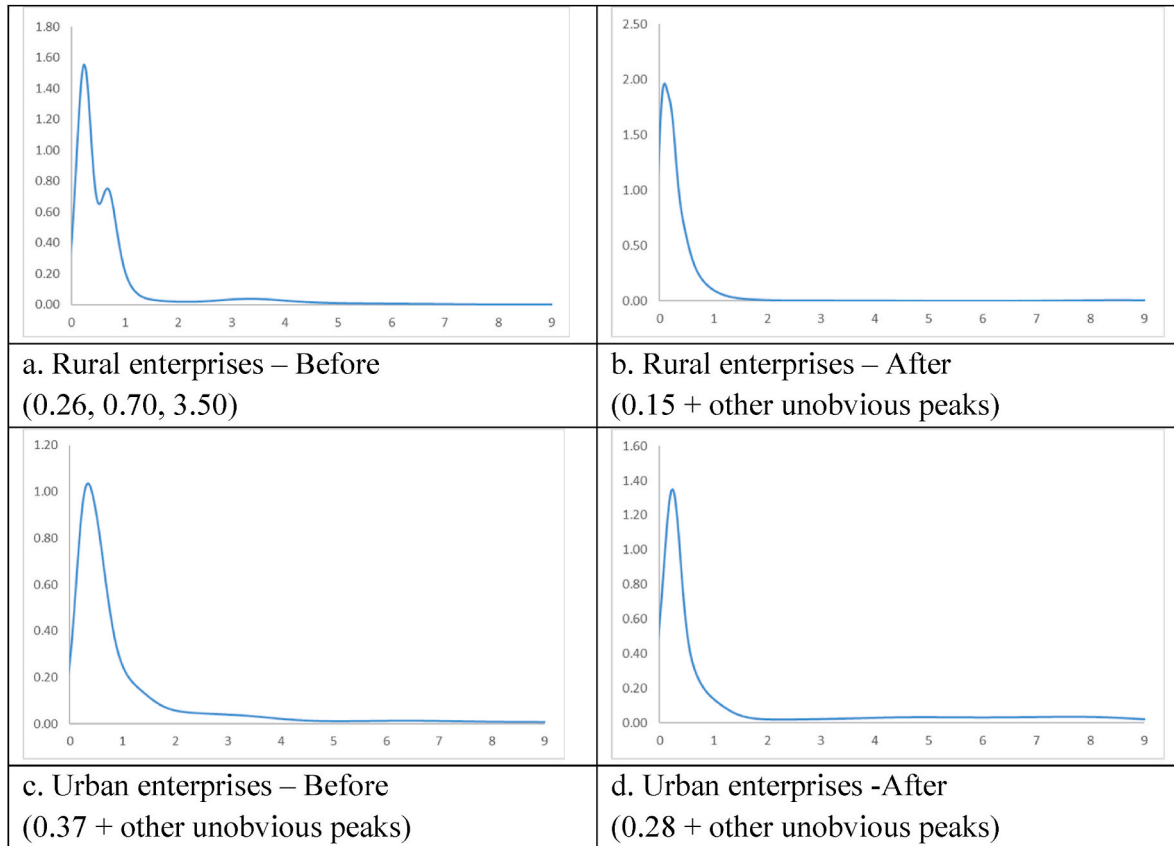


Fig. 6. Ergodic distributions for rural and urban enterprises' RTEC in pre- and post-pilot periods. This figure displays the projected long-run, steady-state distribution of relative total energy consumption of firm, based on its current consumption level. Unlike Fig. 3, this Fig. 6 differentiates between firms located in urban and rural areas in order to see the impact of location. The RTEC values are indicated on the horizontal axis while the vertical axis shows net upward mobility (per cent). Source: Authors' estimation.

after the programme is shown in Fig. 4c and d. When the value of RTEC fluctuates around 0.21, pre-pilot prominent peak appeared. Following Hubei ETS programme, the primary peak was divided into two separate peaks, one with an RTEC value of 0.13 and the other with a value of 0.21. They are either below or the same as the value of the primary peak before the program. This implies that the programme successfully lowered private firms' energy consumption levels. As shown in Fig. 5b, the MPPs support the same conclusion. To the left of the RTEC value of 1.50, MPP moves to the left-hand side in the post-pilot period. This explains why the ergodic distribution's convergence clubs moved to the left within the RTEC values of 0.00 and 1.50. Additionally, no intersection points can be seen after the program's RTEC value of 7.00, indicating the likelihood of excessive consumption is lower than previously.

4.4. Impact of Hubei ETS from a regional viewpoint: rural vs urban enterprises

In order to analyse the differences in energy consumption patterns between the two regions and investigate regional energy consumption heterogeneity, the original data set was separated into urban and rural businesses. Before and after the programme, Fig. 6 indicates the projected ergodic distributions for rural and urban areas, and Fig. 7 indicates corresponding MPPs.

4.4.1. Rural enterprises' emissions pre- and post-pilot periods

Three major peaks of RTEC values of 0.26, 0.70, and 3.50 can be seen in the ergodic distribution of rural companies prior to the programme (Fig. 6a). If the emission practices from before the programme do not change, rural enterprises will cluster around the RTEC values of 0.26, 0.70, as well as 3.50, respectively. These values suggest that almost all businesses would exhibit consumption levels much smaller than the average. However, few of them will consume, on average, 3.50 times more than the firm average as a whole. The various peaks in the ergodic distribution support the historical MPP analysis, as shown in Fig. 7a.

After the program, only one distinct peak can be seen at the RTEC value of 0.15, as shown in (Fig. 6b), which depicts the program's ergodic distribution. Furthermore, the ergodic distribution is less distributed, leading to the conclusion that most rural enterprises will spend less in the future provided the program's policies can be maintained.

The MPPs shown in (Fig. 7b) align with the ergodic distribution analysis. Firstly, the intersection points of the MPPs line up with the convergence clubs seen in the ergodic distributions. Moreover, after the programme, the MPP moved to the left for firms with RTEC values less than 1, implying that following the programme, rural companies with below-average RTEC will reduce their energy consumption. In addition, no positive net upward mobility can be seen with RTEC values greater

than 8 after the programme, in contrast to the MPP before the programme, which has positive net upward mobility with values greater than 8. This implies that the programme forbids rural businesses from engaging in extremely high consumption practices.

4.4.2. Urban enterprises' emissions before and after the Hubei ETS pilot

Fig. 6c and d compare the urban firms' ergodic distributions before and after the programme. One can see that the before-the-program ergodic distribution's tallest peak (i.e. 0.26) is higher than the after the program's peak (i.e. 0.15). Moreover, no obvious peaks with an RTEC value larger than 0.15 can be observed after the program. It implies that following the program, the congregation of firms around the RTEC values of 0.70 and 3.60 before the program disappeared. Thus, the programme can be said to be quite effective at lowering urban businesses' energy use.

Fig. 7b's depiction of the MPPs before and after the programme validated what can be inferred from transition dynamics, as shown in Fig. 6c and d. Following the programme, the first intersection relocated to the left. Additionally, following the program, no intersection points with RTEC values greater than 8.00 could be found. As a result, it can be inferred that the programme both decreased general energy consumption among urban firms and simultaneously ceased exceptionally high consumption.

4.5. Impact of Hubei ETS from an emissions scale viewpoint: high-emission vs low-emission industries

To further understand the consumption heterogeneity associated with the emission scale, the database was separated into high-emission and low-emission firms and examined the differences in energy consumption behaviours between the two groups of firms. Next, this section will compare the expected emission levels of the two industries using the ergodic distribution. Their MPPs will shed light on the underlying historical firm mobility that caused the variations in projected consumption levels between the two types of sectors. Fig. 8 indicates the RTEC ergodic distributions for high- and low-emission industries prior to and during the programme, respectively, whereas Fig. 9 indicates the corresponding MPPs.

4.5.1. Emission from high-emission industries' pre- and post-pilot periods

Fig. 8a and b shows the high-emission industries' long-term (steady-state) ergodic distributions pre- and post-pilot periods. Pre-pilot ergodic distribution shows two clear peaks at RTEC values of 0.28 and 0.69. After the programme, the entire ergodic distribution has a single prominent peak which appears around the RTEC value of 0.16. It demonstrates if the post-programme dynamics persist, it is evident that

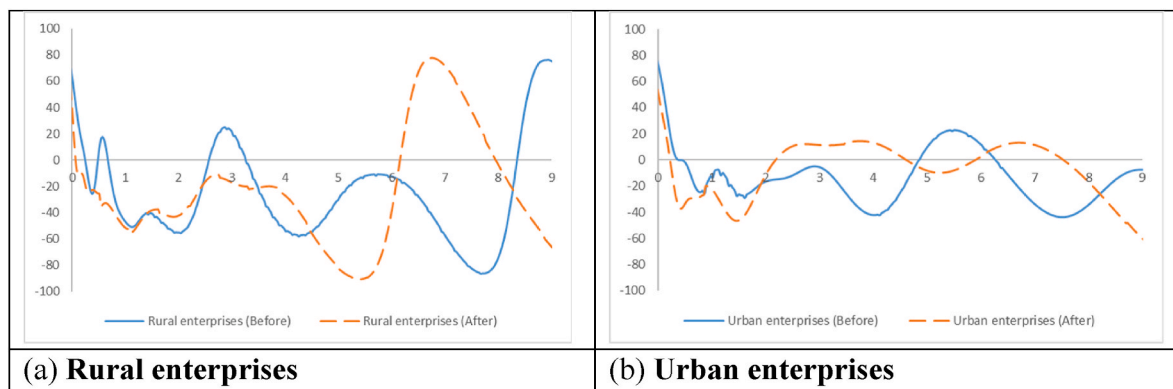


Fig. 7. Mobility probability plot for rural and urban enterprises' RTEC pre- and post-pilot periods. This figure displays the likelihood that a firm will increase or decrease its energy consumption, corresponding to the positive or negative value of the MPP. The RTEC values are shown on the horizontal axis and net upward mobility (per cent) on vertical axis.

Source: Authors' calculation.

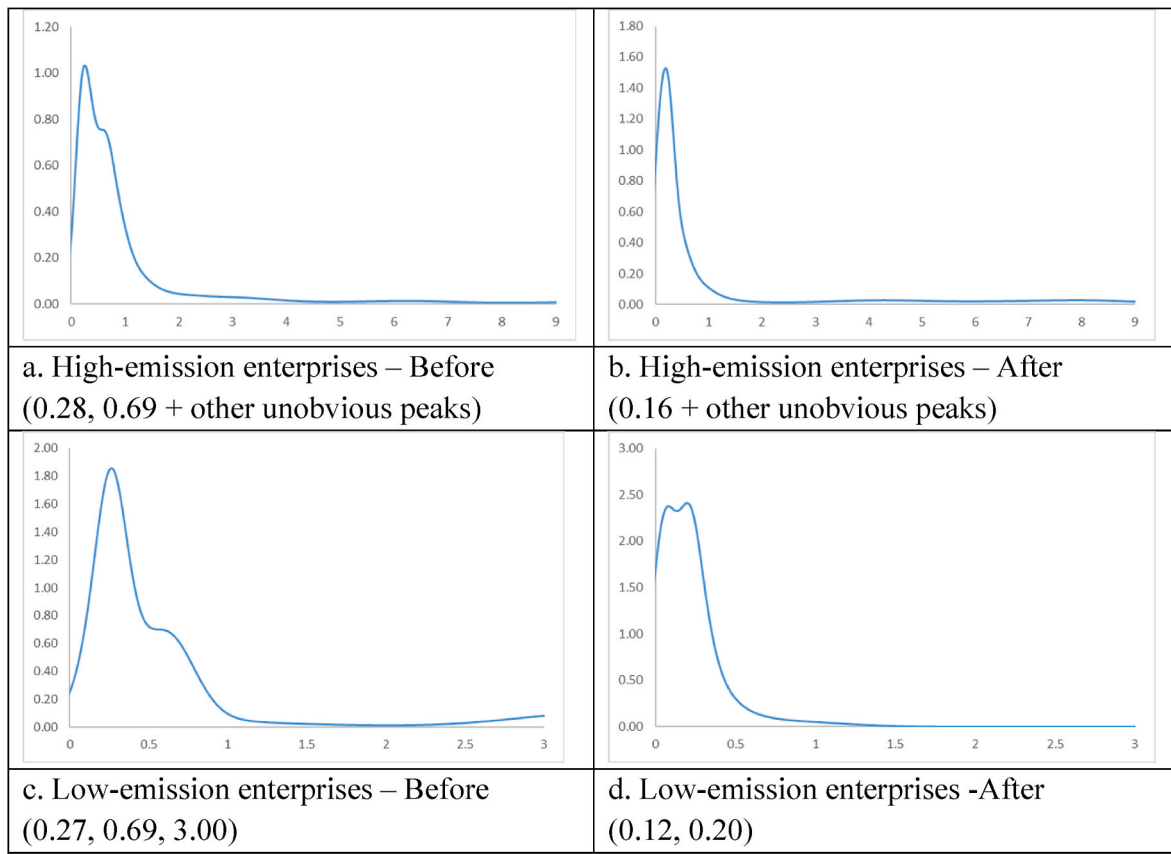


Fig. 8. Ergodic distributions for high and low-emission enterprises' RTEC pre- and post-pilot periods. This figure displays the projected long-run, steady-state distribution of relative total energy consumption of firm, based on its current consumption level. Unlike Fig. 3, this Fig. 8 differentiates between firms classified as high-polluting and low-polluting ones. Probability density is displayed on vertical axis while RTEC values on horizontal axis and peak values in parentheses. Source: Authors' calculation.

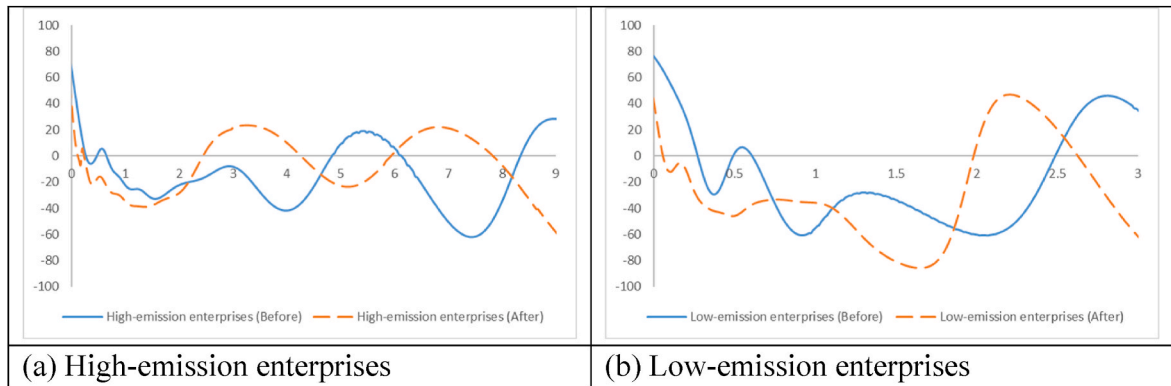


Fig. 9. Mobility probability plot for high- and low-emission enterprises' relative total energy consumption (RTEC) before and after the Hubei ETS pilot. Source: Authors' calculation. This figure displays the likelihood that a firm will increase or decrease its energy consumption, corresponding to the positive or negative value of the MPP. The vertical axis indicates net upward mobility (%), and the horizontal axis indicates the RTEC values. Source: Authors' calculations

the majority of enterprises in high-emission industries will eventually converge to RTEC values that are lower than those from before the programme.

The MPPs before and after the pilot (Fig. 9a) support what can be inferred from the transition dynamics (Fig. 8a and b). The programme causes the first intersection to shift to the left. Additionally, no intersection points are visible after the programme when the RTEC value is greater than 8. This demonstrates how the pilot lowers businesses' total energy usage while averting exceptionally high consumption in the

high-emission industries.

4.5.2. Emissions from low-emission industries' before and after the Hubei ETS pilot

The highest peak and secondary peak of the after-the-programme ergodic distribution, relative to the before-the-programme ergodic distribution, dropped from the RTEC of 0.27 to 0.12 and from 0.69 to 0.20, correspondingly (Fig. 8c and d). Moreover, before the program, a small peak close to the RTEC value of 3 can also be observed; this peak

vanishes after the programme. In addition, the entire MPP shifted to the left after the program (Fig. 9b). Thus, all evidence points to the programme’s significant impact on reducing energy use.

4.6. Impact of Hubei ETS from a production capacity viewpoint: comparing overcapacity industries with other industries

This section evaluates energy consumption between two groups; overcapacity industries are represented by the first group, whereas the second group represents other remaining industries. Comparing the ergodic distributions and MPPs before and after the ETS pilot allows one to gauge how well the programme has affected the two distinct groups. Fig. 10 indicates RTEC for overcapacity and other remaining industries before and after the programme, and Fig. 11 indicates the corresponding MPPs.

4.6.1. Overcapacity industries’ emissions pre- and post-pilot periods of Hubei ETS

Three convergence clubs showing RTEC values of 0.28, 0.61, and 3.39 are visible before the programme (Fig. 10a). After the programme, there is one peak with an RTEC value of 0.26. (Fig. 10b). The peak is less than the value of the primary peak from before the programme. There aren’t any other peaks that have higher values, either. The intersection points of the MPPs, which occur at approximately the same values as the peaks in the ergodic distribution, provide support for the data found through the ergodic distribution analysis (Fig. 11a). As a result, the data support an effective programme to scale back energy use.

4.6.2. The other industries’ emissions pre- and post-pilot periods of Hubei ETS

Before- and after-pilot ergodic distributions exhibit their initial most evident peaks at about the same RTE value of 0.20, as seen in Fig. 10c and d. The peak prior to the actual programme is more pronounced, though the dispersion is less concentrated after the treatment. Because of this, more businesses cluster around the RTEC value of 0.20 after the programme, even if the first most evident peak emerges at nearly the same RTEC value before and after. Furthermore, after the programme, no other greater value peaks can be seen. The MPP for the other industries (Fig. 11b) supports the implications of the ergodic distribution; following the programme, the entire MPP migrated to the left. The evidence points to successful growth for firms consuming less energy after the pilot.

4.7. Impact of Hubei ETS from a quota allocation policy viewpoint: benchmarking vs historical allocation methods

This section investigates the effects of the pilot program’s quota allocation procedures on the company’s energy consumption. The database was divided into two parts. Companies in one group—the benchmarking group—use benchmarking allocation techniques. In contrast, companies in the other group, the historical and alternative methods group, use historical and alternative techniques (i.e., the historical group). Fig. 13 indicates the MPPs for these groups, respectively, whereas Fig. 12 indicates the future ergodic distributions for the benchmarking and historical groups before and after the programme.

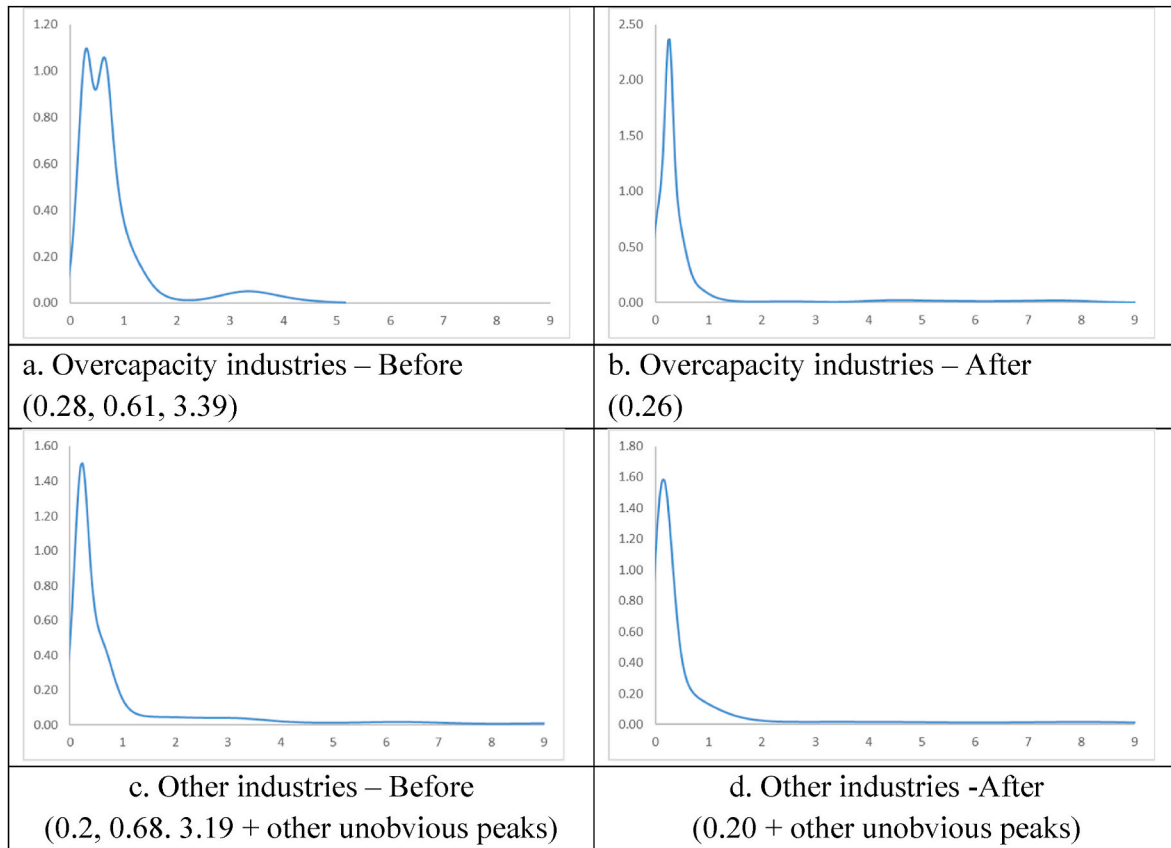


Fig. 10. Ergodic distributions for overcapacity industries and the other industries’ RTEC in pre- and post-pilot periods. This figure displays the projected long-run, steady-state distribution of relative total energy consumption of firm, based on its current consumption level. Unlike Fig. 3, this Fig. 10 differentiates between firms operating in over-capacity industries and those operating in the remaining industries. Probability density is represented in vertical axis while RTEC values by horizontal axis and peak values in parentheses.

Source: Authors’ calculation.

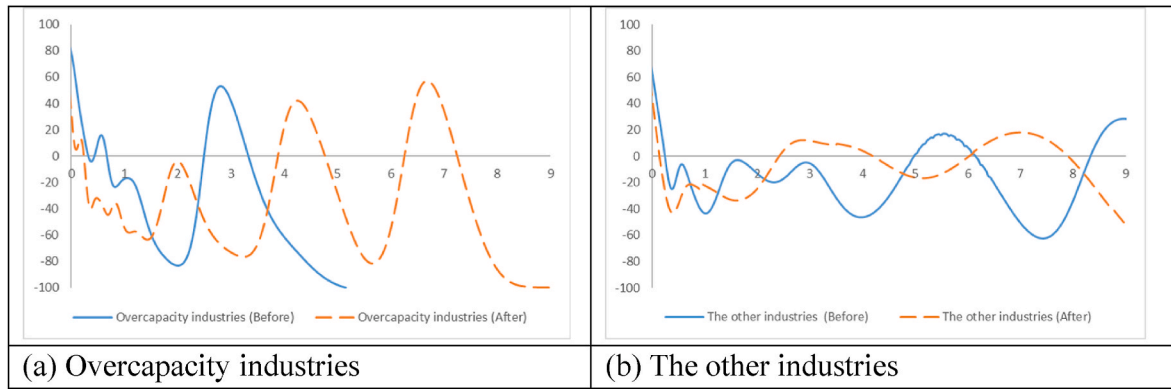


Fig. 11. Mobility probability plot for high- and low-emission enterprises' RTEC in pre- and post-pilot periods. This figure displays the likelihood that a firm will increase or decrease its energy consumption, corresponding to the positive or negative value of the MPP. Net upward mobility (%) is represented by vertical axis while RTEC values by horizontal axis. Source: Authors' calculation.

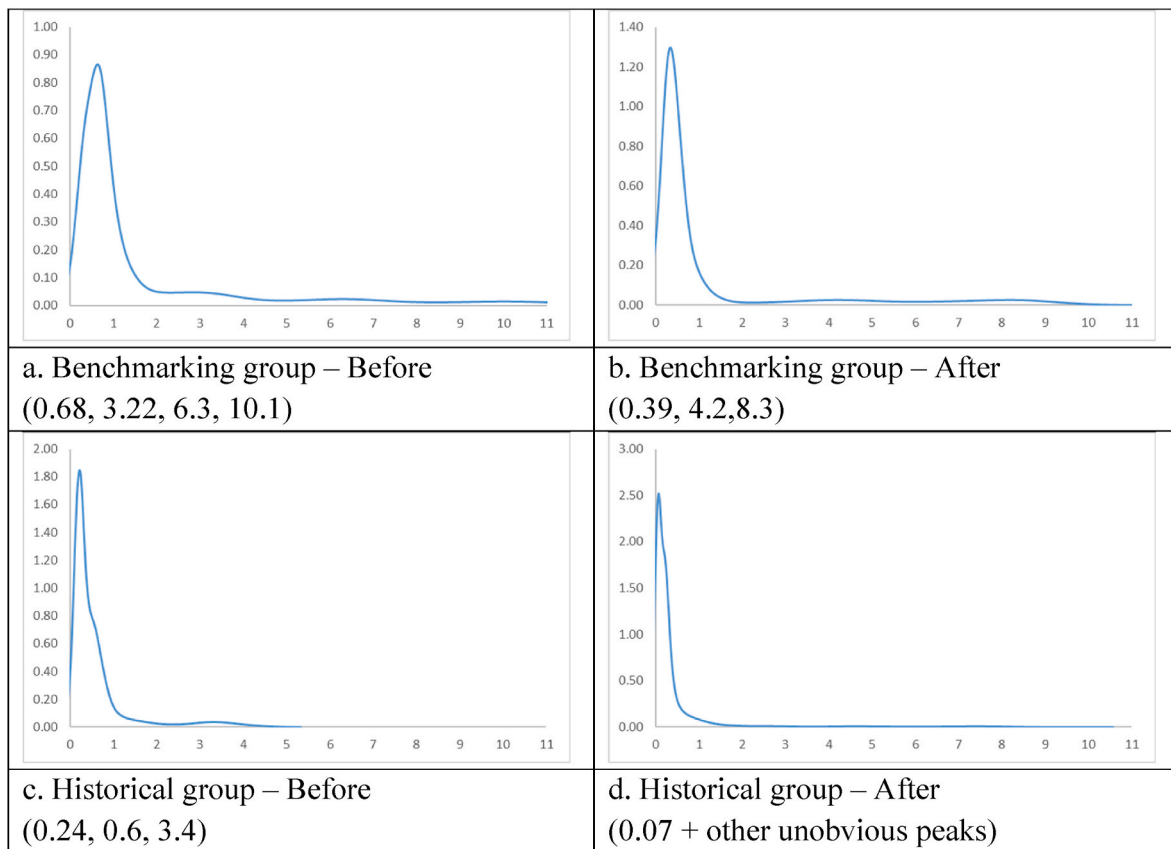


Fig. 12. Ergodic distributions for benchmarking and historical groups' relative total energy consumption (RTEC) before and after the Hubei ETS pilot. This figure displays the projected long-run, steady-state distribution of relative total energy consumption of firm, based on its current consumption level. Unlike Fig. 3, this Fig. 12 differentiates between firms subject to benchmarking allocation group and those involving in the historical, alternation allocation methods. Probability density is represented by vertical axis while RTEC values by horizontal axis and peak values in parentheses. Source: Authors' calculation.

4.7.1. Benchmarking allocation method

The benchmarking groups' before- and after-pilot ergodic distributions exhibit their initial most evident peaks at approximately the RTE values of 0.68 and 0.39, respectively, as shown in Fig. 12a and b. As a result, more businesses after the program cluster around a lower RTEC value. Also, note that peaks with high RTEC values can be seen in both the ergodic distributions before and after the programme; these peaks' values are lower following the programme. It implies that the program

successfully rescued the overall level of energy consumption. The MPP for the benchmarking group validates ergodic distribution implications (Fig. 13a); MPP shifted to the left following the program. Thus, the benchmarking method effectively allocates the quotas to lower energy consumption.

4.7.2. Historical allocation method

Before and after the programme, the ergodic distributions of the

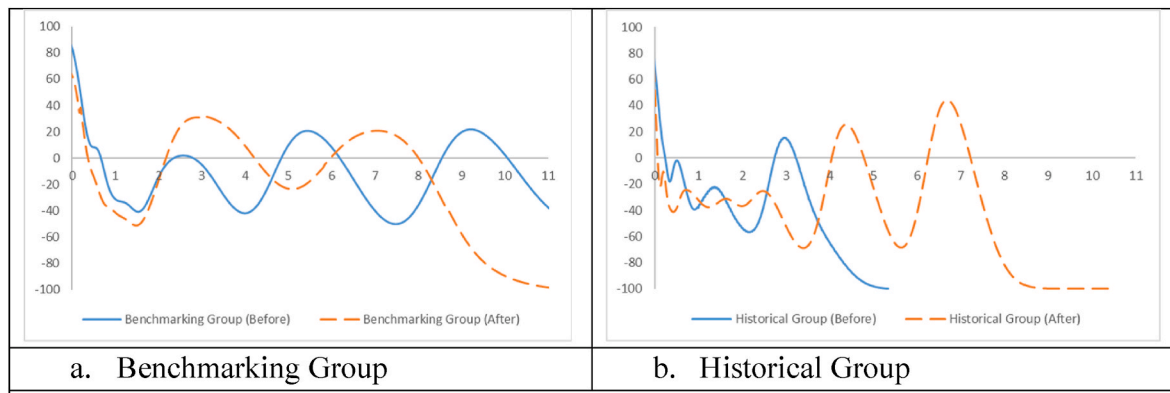


Fig. 13. Mobility probability plot for benchmarking and historical groups' RTEC in pre- and post-pilot periods. This figure displays the likelihood that a firm will increase or decrease its energy consumption, corresponding to the positive or negative value of the MPP. Net upward mobility (%) is represented by vertical axis while RTEC values by horizontal axis.

Source: Author's calculations.

historical group are very different (Fig. 12c and d). The convergence clubs were incredibly dispersed prior to the programme. Multiple convergences at various RTEC values can also be observed. Some of the values are little, while others are big. This demonstrates that companies adopting historical allocation techniques had more diverse emission practices prior to the pilot. Following the programme, one clear peak was visible at about the RTEC value of 0.07, indicating that most firms would converge at an RTEC value much below the firm average, demonstrating the effectiveness of the historical allocation approach for assigning quotas. Note that the after-the-program MPP has intersection points which, however, translate into unobvious peaks in the ergodic distribution that can be disregarded (Fig. 13b).

5. Conclusion, policy implications/recommendations, limitations and future research directions

5.1. Summary of results and policy implications

As debates on the effectiveness and efficiency of ETS programs remain intense [16,65,66], recent challenges caused by the Russian-Ukraine conflict, the Israel-Hamas war and especially potential tariffs imposed by the US strengthen the need to reduce energy consumption, improve energy efficiency. Therefore, it is of critical importance to evaluate the ultimate impact of ETS from new perspectives. The current study employs the distribution dynamics approach to investigate the impact of Hubei ETS on energy consumption in the Hubei region. Empirical findings from a comparison of historical transition dynamics, historical MPP, and future ergodic distributions before and after the pilot for all firms allow us to conclude that after the ETS pilot, most companies reduced their emissions. To ensure robustness of results, this paper also divided data into different groupings and discovered that the pilot program effectively lower energy consumption for most firms and simultaneously prevents extremely high energy consumption practices. Specifically, with respect to types of ownership, the initiative successfully lowered state-owned firms' overall energy consumption levels as well as limiting the likelihood of excessive energy consumption. Under the ETS pilot, state-owned firms are constrained from engaging in extremely high energy consumption practices. Better still, the programme successfully lowered private firms' energy consumption levels. From a regional perspective, the programme lower rural firms' overall consumption level and forbids rural businesses from engaging in extremely high consumption practices. The same conclusion also holds true for urban firms as the programme decreased general energy consumption among urban firms and simultaneously ceased exceptionally high consumption. In terms of pollution, the ETS pilot programme lowers high-emission businesses' total energy usage while averting

exceptionally high consumption. The same applies to low emission firms: all convergence clubs shifted to the left, and the convergence club with high RTEC value disappeared after the program.

The above-mentioned discussions and summary of results validate the benefits provided by the Hubei ETS which in turn, give rise to several policy implications and recommendations. First, as the ETS in Hubei region makes significant contributions to reducing energy consumption in both State-owned and private firms, in rural and urban areas, in high- and low-polluting industries as well as in total energy consumption, there is potential to obtain the decoupling of economic growth and energy consumption in Hubei in ETS-adopting regions. Therefore, leaders of other Chinese provinces may want to consider implementing ETS in their regions to reap the benefits of ETS, facilitate the energy transition and mitigate the consequences of climate change, thus contributing to realizing the net-zero target by 2050.

Furthermore, the application of ETS does not necessarily be limited to Chinese provinces only. Rather, developing countries and even developed nations may draw useful experiences from the Hubei ETS to craft and implement their own schemes. As the benchmarking and historical methods prove useful in allocating quotas with a view to reducing energy consumption, this finding implies that other countries or region may wish to adopt this approach when designing and implementing their ETSs.

5.2. Limitations and future research directions

While the authors tried their best to conduct a thorough study, this paper is still inherited with certain drawbacks. A limitation of this research lies in the fact that it solely focuses on the Hubei ETS while ignoring the other regions or the recently launched China's national ETS. Therefore, in future research, scholars may want to examine the impact of other regional ETS or the national ETS or employ different approaches that take into account relevant factors. Furthermore, this manuscript focuses exclusively on the impact of ETS on energy consumption while ignoring other sustainable development goals (SDGs) such as decent and sustainable economic growth (SDG8), inequality (SDG5, SDG10) or sustainable cities and communities (SDG11). Therefore, scholars are strongly recommended to investigate the effects of ETS on other SDGs in their future research.

Credit author statement

Author's Contribution: Wai Yan Shum: Conceptualization, Writing-Original draft, Data curation, Visualization, preparation, Writing-Reviewing and Editing; Xiujie Tan: Conceptualization, Methodology Writing- Original draft, Software; Xuan-Hoa Nghiem:

Conceptualization, Writing- Original draft, Data curation, Visualization, preparation, Writing- Reviewing and Editing; Tsun Se Cheong: Conceptualization, Writing- Original draft, Data curation, Visualization, preparation, Writing- Reviewing and Editing; Ning Ma: Conceptualization, Writing- Original draft, Data curation, Visualization, preparation, Writing- Reviewing and Editing.

Funding

This work was supported by the National Natural Science Foundation of China (72174059), Philosophy and Social Science Planning Projects in Hainan Province (HNSK(ZC)23-155), Hainan College of Economics and Business (hnjmk2021301), Hainan College of Economics and Business (HNJMT2022-103), Hainan Province Education Teaching Reform Research and Scientific Research Projects (Hnjgwt2025-7).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

- X.-H. Nghiem, W. Bakry, H.-A.N. AL-Malkawi, S. Farouk, Does technological progress make OECD countries greener? New evidence from panel CS-ARDL, *Manag. Environ. Qual. Int. J.* 34 (6) (2023) 1555–1579.
- W. Bakry, G. Mallik, X.-H. Nghiem, A. Sinha, X.V. Vo, Is green finance really “green”? Examining the long-run relationship between green finance, renewable energy and environmental performance in developing countries, *Renew. Energy* 208 (2023) 341–355.
- S. Nasreen, F.I. Khan, X.-H. Nghiem, The effects of financial development and technological progress on environmental sustainability: novel evidence from Asian countries, *Environ. Sci. Pollut. Control Ser.* 30 (2023) 53712–53724.
- B. Guo, Q. Guo, F. Amri, S. Abbas, X.H. Nghiem, Powering environmental sustainability through renewable energy and natural resources: a dynamic ARDL simulation approach, *Environ. Sci. Pollut. Control Ser.* 30 (2023) 90906–90923.
- W. Bakry, X.-H. Nghiem, S. Farouk, X.V. Vo, Does it hurt or help? Revisiting the effects of ICT on economic growth and energy consumption: a nonlinear panel ARDL approach, *Econ. Anal. Pol.* 78 (2023) 597–617.
- T. Abe, T.H. Arimura, Causal effects of the Tokyo emissions trading scheme on energy consumption and economic performance, *Energy Policy* 168 (2022) 113151.
- H. Zhi, L. Ni, D. Zhu, The impact of emission trading system on clean energy consumption of enterprises: evidence from a quasi-natural experiment in China, *J. Environ. Manag.* 318 (2022) 115613.
- Y. Sun, S. Shen, C. Zhou, Does the pilot emissions trading system in China promote innovation? Evidence based on green technology innovation in the energy sector, *Energy Econ.* 126 (2023) 106984.
- J. Liu, J. Hou, Q. Fan, H. Chen, China's national ETS: global and local lessons, *Energy Rep.* 8 (2022) 428–437.
- Y. Zhang, N. Chen, S. Wang, M. Wen, Z. Chen, Will carbon trading reduce spatial inequality? A spatial analysis of 200 cities in China, *J. Environ. Manag.* 325 (2023) 116402.
- Y. Hu, S. Ren, Y. Wang, X. Chen, Can carbon emission trading scheme achieve energy conservation and emission reduction? Evidence from the industrial sector in China, *Energy Econ.* 85 (2020) 104590.
- R. Hanna, US environmental regulation and FDI: evidence from a panel of US-based multinational firms, *Am. Econ. J. Appl. Econ.* 2 (2010) 158–189.
- F. Jotzo, A. Löscher, Emissions trading in China: emerging experiences and international lessons, *Energy Policy* 75 (2014) 3–8.
- S. Zheng, M.E. Kahn, A new era of pollution progress in urban China? *J. Econ. Perspect.* 31 (2017) 71–92.
- Y. Liu, X.-J. Tan, Y. Yu, S.-Z. Qi, Assessment of impacts of Hubei pilot emission trading schemes in China—A CGE-analysis using TermCO₂ model, *Appl. Energy* 189 (2017) 762–769.
- Y. Wen, P. Hu, J. Li, Q. Liu, L. Shi, J. Ewing, Z. Ma, Does China's carbon emissions trading scheme really work? A case study of the Hubei pilot, *J. Clean. Prod.* 277 (2020) 124151.
- M.T. Kartal, The role of consumption of energy, fossil sources, nuclear energy, and renewable energy on environmental degradation in top-five carbon producing countries, *Renew. Energy* 184 (2022) 871–880.
- A.C. Pigou, Co-operative societies and income tax, *Econ. J.* 30 (1920) 156–162.
- F. Chien, M. Sadiq, M.A. Nawaz, M.S. Hussain, T.D. Tran, T. Le Thanh, A step toward reducing air pollution in top Asian economies: the role of green energy, eco-innovation, and environmental taxes, *J. Environ. Manag.* 297 (2021) 113420.
- M.T. Kartal, Impact of environmental tax on ensuring environmental quality: Quantile-based evidence from G7 countries, *J. Clean. Prod.* 440 (2024) 140874.
- M.T. Kartal, Quantile-based effect of energy, transport, and total environmental tax on ecological footprint in EU5 countries, *Environ. Sci. Pollut. Control Ser.* 31 (2024) 20033–20047.
- H.-T. Yin, J. Wen, J. Ma, C.-P. Chang, Carbon tax: catalyst or hindrance for renewable energy use in climate change mitigation? *Energy Strategy Rev.* 51 (2024) 101273.
- G. Aziz, S. Sarwar, M.W. Hussain, A. Saeed, The importance of extended-STIRPAT in responding to the environmental footprint: inclusion of environmental technologies and environmental taxation, *Energy Strategy Rev.* 50 (2023) 101216.
- F. Ahmad, N. Abid, J. Aftab, A. Javed, Tracing the trajectories of energy intensity, environmental tax revenues, and environmental neutrality in major European economies, *Energy Strategy Rev.* 58 (2025) 101650.
- R. Yasmeen, G. Hao, Y. Ye, W.U.H. Shah, M.A. Kamal, The role of governance quality on mobilizing environmental technology and environmental taxations for renewable energy and ecological sustainability in belt and road economies: a methods of Moment's quantile regression, *Energy Strategy Rev.* 50 (2023) 101258.
- B. Lin, Z. Jia, The impact of emission trading scheme (ETS) and the choice of coverage industry in ETS: a case study in China, *Appl. Energy* 205 (2017) 1512–1527.
- J.H. Dales, *Pollution, Property & Prices: an Essay in Policy-Making and Economics*, Edward Elgar Publishing, 1968.
- M.R. Taylor, *Innovation under cap-and-trade Programs*, vol.109, Proceedings of the National Academy of Sciences, 2012, pp. 4804–4809.
- X. Tan, Q. Sun, M. Wang, T.S. Cheong, W.Y. Shum, J. Huang, Assessing the effects of emissions trading systems on energy consumption and energy mix, *Appl. Energy* 310 (2022) 118583.
- B. Lin, Z. Jia, Impacts of carbon price level in carbon emission trading market, *Appl. Energy* 239 (2019) 157–170.
- S. Ren, Y. Hu, J. Zheng, Y. Wang, Emissions trading and firm innovation: evidence from a natural experiment in China, *Technol. Forecast. Soc. Change* 155 (2020) 119989.
- E. Cagno, A. Trianni, Exploring drivers for energy efficiency within small-and medium-sized enterprises: first evidences from Italian manufacturing enterprises, *Appl. Energy* 104 (2013) 276–285.
- Y.-J. Zhang, Y.-L. Peng, C.-Q. Ma, B. Shen, Can environmental innovation facilitate carbon emissions reduction? Evidence from China, *Energy Policy* 100 (2017) 18–28.
- D. Acemoglu, P. Aghion, L. Bursztyn, D. Hemous, The environment and directed technical change, *Am. Econ. Rev.* 102 (2012) 131–166.
- B. Wang, J. Zhao, Y. Wei, Carbon emission quota allocating on coal and electric power enterprises under carbon trading pilot in China: mathematical formulation and solution technique, *J. Clean. Prod.* 239 (2019) 118104.
- Z. Yang, M. Fan, S. Shao, L. Yang, Does carbon intensity constraint policy improve industrial green production performance in China? A quasi-DID analysis, *Energy Econ.* 68 (2017) 271–282.
- Z.A. Nayyar, N.A. Zaigham, A. Qadeer, Assessment of present conventional and non-conventional energy scenario of Pakistan, *Renew. Sustain. Energy Rev.* 31 (2014) 543–553.
- C. Liu, C. Ma, R. Xie, Structural, innovation and efficiency effects of environmental regulation: evidence from China's carbon emissions trading pilot, *Environ. Resour. Econ.* 75 (2020) 741–768.
- Y. Yu, S. Li, H. Sun, F. Taghizadeh-Hesary, Energy carbon emission reduction of China's transportation sector: an input-output approach, *Econ. Anal. Pol.* 69 (2021) 378–393.
- E. Delarue, H. Lamberts, W. D'haeseleer, Simulating greenhouse gas (GHG) allowance cost and GHG emission reduction in Western Europe, *Energy* 32 (2007) 1299–1309.
- A. Gambhir, T.A. Napp, C.J. Emmott, G. Anandarajah, India's CO₂ emissions pathways to 2050: energy system, economic and fossil fuel impacts with and without carbon permit trading, *Energy* 77 (2014) 791–801.
- M.-K. Kim, T. Kim, Estimating impact of regional greenhouse gas initiative on coal to gas switching using synthetic control methods, *Energy Econ.* 59 (2016) 328–335.
- R. Pearce, The coal question that emissions trading has not answered, *Energy Policy* 99 (2016) 319–328.
- W. Li, Z. Jia, The impact of emission trading scheme and the ratio of free quota: a dynamic recursive CGE model in China, *Appl. Energy* 174 (2016) 1–14.
- I.G. Wilson, I. Staffell, Rapid fuel switching from coal to natural gas through effective carbon pricing, *Nat. Energy* 3 (2018) 365–372.
- C.-P. Anke, H. Hobbie, S. Schreiber, D. Möst, Coal phase-outs and carbon prices: interactions between EU emission trading and national carbon mitigation policies, *Energy Policy* 144 (2020) 111647.
- Y. Zhou, L. Huang, How regional policies reduce carbon emissions in electricity markets: fuel switching or emission leakage, *Energy Econ.* 97 (2021) 105209.
- M.E. Porter, C.V.D. Linde, Toward a new conception of the environment-competitiveness relationship, *J. Econ. Perspect.* 9 (1995) 97–118.
- X. Zhang, T.-Y. Qi, X.-M. Ou, X.-L. Zhang, The role of multi-region integrated emissions trading scheme: a computable general equilibrium analysis, *Appl. Energy* 185 (2017) 1860–1868.

- [50] F. Dong, Y. Dai, S. Zhang, X. Zhang, R. Long, Can a carbon emission trading scheme generate the porter effect? Evidence from pilot areas in China, *Sci. Total Environ.* 653 (2019) 565–577.
- [51] X. Yang, P. Jiang, Y. Pan, Does China's carbon emission trading policy have an employment double dividend and a porter effect? *Energy Policy* 142 (2020) 111492.
- [52] G. Zhang, N. Zhang, The effect of China's pilot carbon emissions trading schemes on poverty alleviation: a quasi-natural experiment approach, *J. Environ. Manag.* 271 (2020) 110973.
- [53] Z. Weng, T. Liu, Y. Wu, C. Cheng, Air quality improvement effect and future contributions of carbon trading pilot programs in China, *Energy Policy* 170 (2022) 113264.
- [54] J. Xiao, G. Li, B. Zhu, L. Xie, Y. Hu, J. Huang, Evaluating the impact of carbon emissions trading scheme on Chinese firms' total factor productivity, *J. Clean. Prod.* 306 (2021) 127104.
- [55] X. Pan, C. Pu, S. Yuan, H. Xu, 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.* 316 (2022) 115228.
- [56] M. Lv, M. Bai, Evaluation of China's carbon emission trading policy from corporate innovation, *Finance Res. Lett.* 39 (2021) 101565.
- [57] Y.-J. Zhang, W. Wang, How does China's carbon emissions trading (CET) policy affect the investment of CET-covered enterprises? *Energy Econ.* 98 (2021) 105224.
- [58] W. Chen, L. Zhang, L. Shi, Y. Shao, K. Zhou, Carbon emissions trading system and investment efficiency: evidence from China, *J. Clean. Prod.* 358 (2022) 131782.
- [59] L. Wang, Z. Wang, Y. Ma, Does environmental regulation promote the high-quality development of manufacturing? A quasi-natural experiment based on China's carbon emission trading pilot scheme, *Soc. Econ. Plann. Sci.* 81 (2022) 101216.
- [60] D. Liu, S. Ren, W. Li, SO₂ emissions trading and firm exports in China, *Energy Econ.* 109 (2022) 105978.
- [61] Y. Chen, Z. Xu, Z. Zhang, W. Ye, Y. Yang, Z. Gong, Does the carbon emission trading scheme boost corporate environmental and financial performance in China? *J. Clean. Prod.* 368 (2022) 133151.
- [62] D. Quah, Empirical cross-section dynamics in economic growth, *Eur. Econ. Rev.* 37 (1993) 426–434. [https://doi.org/10.1016/0014-2921\(93\)90031-5](https://doi.org/10.1016/0014-2921(93)90031-5).
- [63] Cheong, T. S & Yanrui, Wu. Convergence and transitional dynamics of China's industrial output: a county-level study using a new framework of distribution dynamics analysis. *China Econ. Rev.*, 48, 125-138..
- [64] Y.G. Wei, K.H.K. Chung, T.S. Cheong, D.K.H. Chui, The evolution of energy market and energy usage: An application of the distribution dynamics analysis, *Front. Energy Res.* 8 (2020) 122. <https://doi.org/10.3389/fenrg.2020.00122>.
- [65] X.-G. Zhao, G.-W. Jiang, D. Nie, H. Chen, How to improve the market efficiency of carbon trading: a perspective of China, *Renew. Sustain. Energy Rev.* 59 (2016) 1229–1245.
- [66] X.-G. Zhao, L. Wu, A. Li, Research on the efficiency of carbon trading market in China, *Renew. Sustain. Energy Rev.* 79 (2017) 1–8.