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Impacts of local and regional carbon markets in Hong Kong and China's Greater Bay Area: A dynamic CGE analysis

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ABSTRACT

We examine the potential economic impacts of local and regional carbon markets in Hong Kong and China's Greater Bay Area, taking a computable general equilibrium approach. We find that Hong Kong's proposed carbon-neutrality target requires policy-compliance costs as large as ≤21.0 % of its baseline gross domestic product, but regional cooperation can help reduce the costs substantially. For example, the costs will decline by ≤23.0 % if Hong Kong forms an integrated carbon market with Shenzhen. The cost savings will further increase to ≤38.2 % if Hong Kong cooperates with Shenzhen and Guangdong to create an extended regional carbon market. Such an integrated carbon market will be mutually beneficial, and will also help Shenzhen and Guangdong meet their own carbon-reduction goals at ≤13.9 % and ≤5.2 % lower costs, respectively. These regional cooperation scenarios, though benefiting all participants, will make Hong Kong—which sets an ambitious climate-mitigation target at the city level, despite its tiny local carbon market—the biggest winner. Accordingly, Hong Kong has a great incentive to promote an integrated regional carbon market, but increasing its feasibility may require an institutional device to reduce the imbalance in benefit across regional stakeholders.

1. Introduction

Hong Kong's government has recently set a carbon-neutrality goal for 2050, in line with the global 1.5 °C target proposed under the Paris Agreement (IPCC, 2021). Achieving this goal requires Hong Kong to cut absolute emissions by 6.6 % each year between 2020 and 2050 (Environment Bureau, 2021; Jiang et al., 2020). This mitigation target—net-zero carbon emissions by 2050—is far more stringent than its initial goal of an annual emissions reduction of ≤2.2 % between 2020 and 2030, benchmarked with China's earlier commitment to the Paris Agreement (Environment Bureau, 2017). Available estimates show that even meeting relatively moderate reduction goals would introduce a huge shock to Hong Kong's economy. For example, meeting the near-term targets approximating the 2.0 °C pathway is estimated to cost ≤2.5 % of Hong Kong's gross domestic product (GDP) by 2030, and the compliance costs would further increase to ≤10 % under the 1.5 °C scenario (Wang et al., 2020b). The stringency of the targets and the magnitude of the anticipated economic shocks necessarily lead to a question of feasibility.

Hong Kong's mitigation policy has strictly regulated the local power sector through conventional command-and-control (CAC) measures, such as a gradual phase-out of coal-fired power plants. Electricity generation and transmission is a dominant sectoral emission source, accounting for around two-thirds of Hong Kong's local greenhouse gas (GHG) emissions (Fig. 1). However, sole dependence on CAC regulations is costly, and an emissions trading scheme (ETS) needs increased policy attention. The ETS sets a cap on legally permitted GHG emissions and creates a market where firms can trade emission permits or allowances. In general, market-based interventions, such as the ETS, are more efficient than CAC regulations, since they do not require excessively high information costs and are open to various ingenious compliance options (Eden et al., 2018; Ma et al., 2019). Also, of the two main mitigation approaches, emissions trading—a *quantity* instrument allowing the price of emissions to vary—is theoretically more efficient and effective than

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carbon tax—a *price* instrument that does not restrict the quantity of emissions—as the former is less distortionary in market allocations and involves lower uncertainty in emission pathways (Burniauxi et al., 2009; Carl and Fedor, 2016; Jacoby and Ellerman, 2004).

Despite its potential benefit, Hong Kong has ruled out emissions trading from its potential mitigation options for two reasons (Central Policy Unit, 2017). One is Hong Kong's oligopolistic local electricity market, which weakens the local pool of potential market participants. At present, only two firms—China Light and Power and Hong Kong Electric—capture the entire market share, and these two sizeable players are not enough to ensure a solid carbon market. The other reason is Hong Kong's tiny carbon market itself, where operational costs may exceed efficiency gain. As a Special Administrative Region (SAR) symbolizing the "one country, two systems" principle, Hong Kong maintains highly autonomous administrative and economic systems, quasi-independent of China's national institutions. Under the Basic Law of the Hong Kong SAR, Hong Kong must attain compliance with its proposed carbon-neutrality target and schedule at the city level, without depending on China's internal adjustment mechanisms at the national level.

In contrast, Mainland China as the world's largest carbon emitter has actively tested and operated multiple ETS models to meet its mitigation targets. China first introduced a nationwide non-binding carbon-intensity reduction goal as part of the 12th Five Year Plan (2011–2015) and has set a binding target since the following five-year-plan period (Nam et al., 2014; Zhao et al., 2019). In 2020, China announced a more ambitious "double carbon" target, setting the nationwide carbon peak for 2030 and carbon neutrality for 2060 (Gu et al., 2022; Song et al., 2023). Emissions trading is a key policy instrument for China's mitigation strategy and has been implemented at two different levels. At a subnational level, eight ETS pilots have been in operation in seven province-level municipalities and one prefecture-level city since 2013 (Fig. 2). Two out of the eight pilots—Shenzhen and Guangdong (excluding Shenzhen)—are based in Guangdong Province. In 2022, the Shenzhen ETS, the first pilot launched in June 2013, imposed a cap of 26 $MtCO_2e$, comparable to roughly half the city's gross emissions, on 680 entities in 33 sectors (ICAP, 2024). The Guangdong ETS, launched in December 2013, is China's largest ETS pilot. In 2023, it covered 297 $MtCO_2e$ or 40 % of the local emissions, and liable entities included 391 local heavy emitters subject to an annual emission of $\geq$20 $ktCO_2e$ or an annual energy consumption of $\geq$10 ktce (ICAP, 2024; Zhao et al., 2019). In parallel with the eight ETS pilots, China also operates a national ETS covering the electricity sector only (Fang et al., 2021). The national ETS, launched in July 2021, plans to gradually increase its electricity-centered sectoral coverage to include other energy-intensive industries (Zhang et al., 2022). In 2022, China's national ETS concerned 2257 entities and covered around 5 $GtCO_2e$ or 40 % of the national CO_2 emissions (ICAP, 2024). An associated national carbon market is currently in operation, independent of the eight ETS pilots (Huang et al., 2022).

In this situation, introducing emissions trading to Hong Kong through its participation in China's existing ETS pilots seems more realistic than developing its independent carbon market (GSFCASG, 2022; Huang et al., 2019; Wang et al., 2020b). In particular, two nearby ETS pilots in Guangdong create a favorable condition for Hong Kong's carbon market development in several aspects. First, the Shenzhen ETS sets a good reference case for Hong Kong, with its small local carbon market, as it operates a city-level carbon market in contrast to the other seven province-level pilots. Second, carbon price differentials within China's Greater Bay Area (GBA), consisting of Hong Kong, Macau, and Guangdong Province, may call for cross-border cooperation (Fig. 3). In the absence of such cooperation, carbon leakage can lead to potential balloon effects, where city-level regulations may not result in net emissions reduction at the regional level. The final aspect relates to economic incentives, which can be strengthened through Hong Kong's participation in on-going ETS pilots. A GBA carbon market can be mutually beneficial: it will give Hong Kong an additional, efficient policy-compliance option and allow Guangdong-based firms to trade permits at higher prices. A regionally integrated carbon market can also promote cross-border investment in the renewable energy sector, which has weak economic bases in Hong Kong due to limited land endowments (Lam et al., 2017).

In this context, we examine the potential impacts of an integrated regional carbon market on Hong Kong and other GBA economies, focusing on efficiency improvement in terms of policy-compliance costs on their pathway to carbon neutrality. This is an important policy question for a small open economy like Hong Kong, but the empirical literature on this topic is sparse. It is often the case that Hong Kong is simply excluded from analysis due to its weak relevance to Mainland China's mitigation policy. This study is motivated to fill this gap.

From a policy perspective, this paper has great potential to contribute to an ongoing policy debate. In our model, we treat three key GBA stakeholder economies as separate regions for an in-depth impact analysis of local and regional ETS scenarios. This contrasts most other studies, which offer a weak regional perspective. A fundamental reason an ETS has received little attention in the policy circle is Hong Kong's tiny carbon market, but this challenge may be overcome through regional cooperation. We expect that Hong Kong's case will also convey crucial policy implications for many other city-scale economies which have their own mitigation targets but face serious resource constraints when it comes to implementation.

The remainder of this paper is structured as follows. In Section 2, we review the literature on the impacts of China's ETS and its linkage, and in Section 3, we introduce our methodology. In Section 4, we discuss key results and main findings, and Section 5 concludes this study.

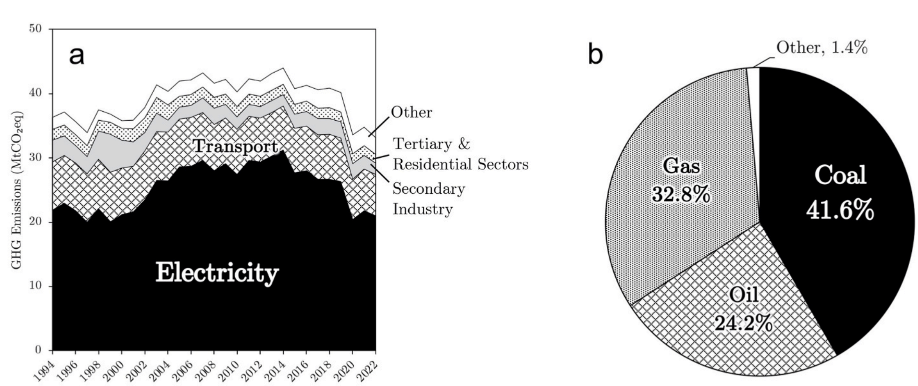

Fig. 1. GHG Emissions in Hong Kong: **(a)** Emissions by Sector, 1994–2022; **(b)** Emissions by Fuel Type, 2021.
Source: Created from IEA (2024) and Environment Protection Department (2024).

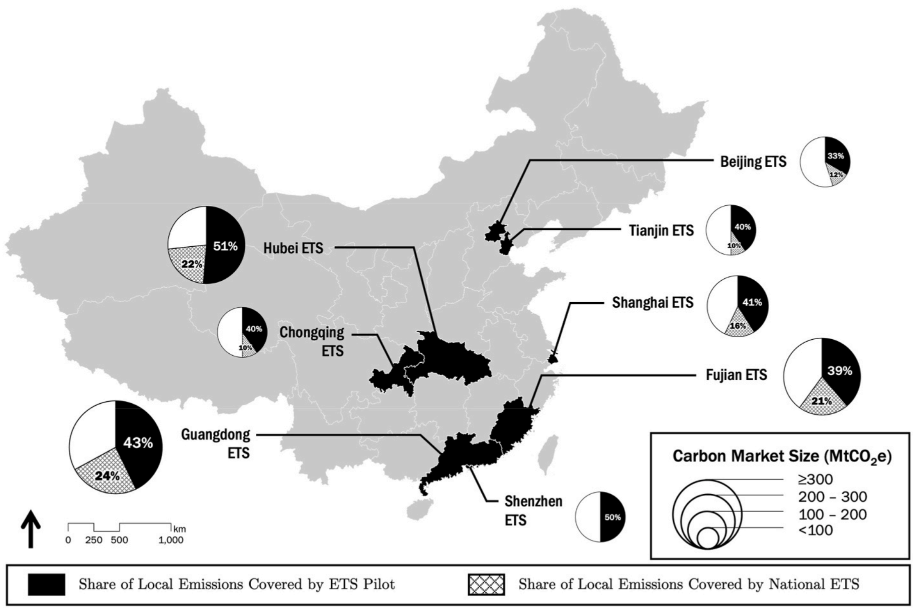

Fig. 2. Location of China's ETS Pilots, 2022.
Note: The black or shaded shares of pie graphs represent the portion of the local emissions covered by each ETS pilot or by China's national ETS. The size of each pie graph represents the size of each ETS, measured in covered emissions.
Source: Created by the authors from Zhao et al. (2019) and ICAP (2024).

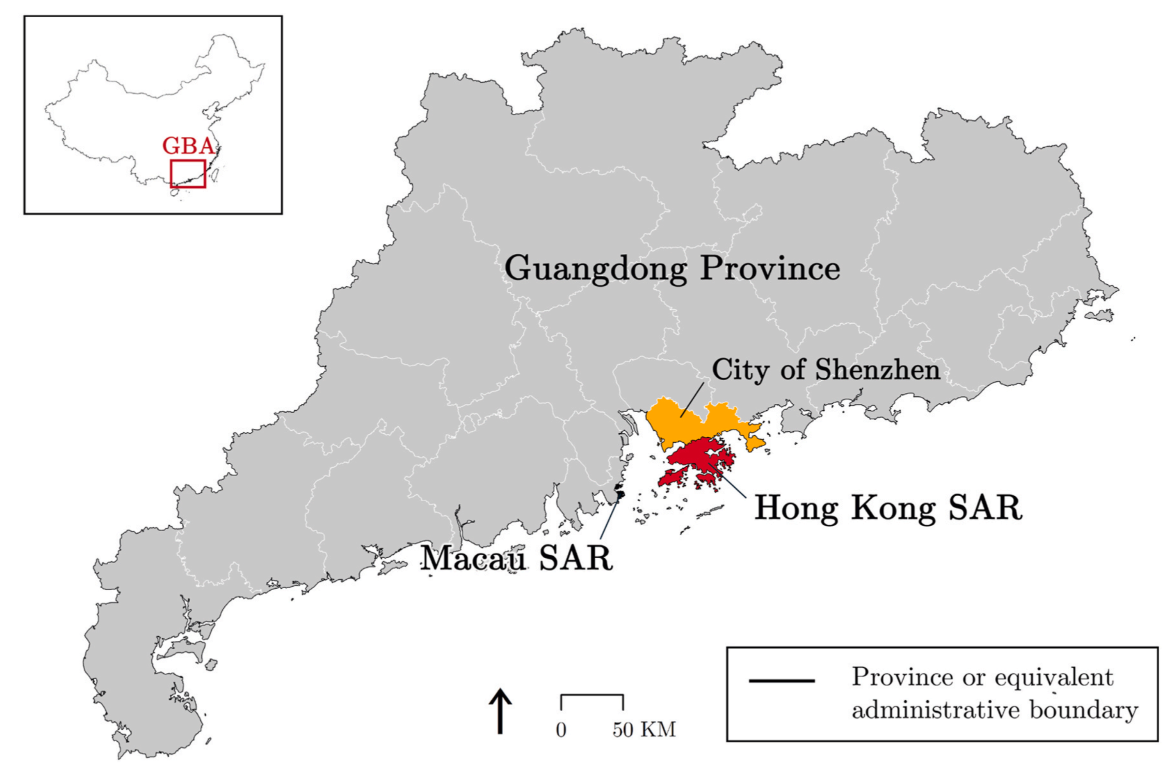

Fig. 3. China's Greater Bay Area. *Note*: "SAR" refers to the Special Administrative Region.

2. Literature review

Integrating or linking multiple ETS's can improve market efficiency by increasing the size of carbon markets and the number of market participants, enhancing the stability of carbon price, and increasing the liquidity of carbon market (Goers et al., 2012). An initial ETS integration case took place in 2007, when Norway, Iceland, and Liechtenstein adjusted their own systems to be consistent with the European Union (EU) ETS Phase II (Zhang et al., 2017). Inclusion of the three non-member countries contributed to the territorial expansion of the EU ETS. Linkage between California and Quebec ETS's is another example. In 2014, these two subnational economies in North America showcased the first direct bilateral ETS linking through joint auctions, serving as a benchmark for a bottom-up carbon-market integration. With the increased operation of regional, national, and subnational ETS's, bottom-up bilateral/multilateral carbon-market linkages have been attempted, complementing global top-down mitigation initiatives led by the United Nations Framework Convention on Climate Change (Gavard et al., 2016; ICAP, 2024).

Empirical studies on ETS integration have widely applied the computable general equilibrium (CGE) model to the counterfactual analysis of its economic impacts (Li et al., 2019, 2021). Many of them focus on China's carbon markets considering it to have the largest market potential, and examine the impacts of potential ETS linkage scenarios at both international and subnational levels (Table 1). These studies find that integrated carbon markets can bring overall efficiency improvement at the system level, but such efficiency gains may not be evenly distributed among participants. In particular, net-importers of carbon permits, which could face excessively high carbon prices in the absence of an integrated carbon market, tend to enjoy greater benefits from the ETS linking than net-exporters.

Overall, a bilateral global ETS linkage between China and the EU is found to be mutually beneficial and to help China attain significant efficiency improvement in complying with proposed mitigation targets. Key drivers underlying the results include the comparably large size of each carbon market and the complementarity in economic structure and industrial mix. For example, Hübler et al. (2014) estimate that the enlarged carbon market will allow China to improve overall economic efficiency by $\leq$ 0.1 % in meeting its 2030 mitigation target benchmarked to China's Copenhagen pledge. Alternatively, this result translates into China reducing policy-compliance costs by $\leq$6.8 % through the China-EU bilateral ETS linkage, if the costs are measured in terms of net-GDP loss under the carbon constraints. Liu and Wei (2014) also test the effects of the China-EU ETS linkage on the costs required to meet China's 2020 mitigation targets aligned with its Copenhagen pledge and arrive at a similar estimate. They find that the ETS linkage can help China avoid a 0.12 % loss of its baseline GDP.

However, a multilateral global ETS linkage may have mixed effects on China's economy, depending on its relative position in emissions trading. For example, Qi and Weng (2016) apply the China-in-Global Energy Model (C-GEM) and test the impacts of multilateral ETS linking scenarios involving 12 global regions of mixed income levels. Under these linking scenarios, China performs as a net-importer of carbon permits, and could maintain relatively high economic output levels in the face of a given carbon constraint. That is, China is estimated to meet its intended national determined contribution targets for 2030—proposed under the Paris Agreement—at substantially lower costs, avoiding the loss of its baseline GDP by 0.08 %. This contrasts the finding of another C-GEM-based study by Zhang et al. (2017). The global ETS linking scenarios they test involve six global regions, consisting of China and five high-income economies in Europe and Asia-Pacific. In these scenarios, China performs as a net carbon-permit exporter given the relatively low marginal abatement cost curve it faces. As a net permit exporter, China would have to cut its output level by a greater magnitude, which would translate into an additional welfare loss under the linking scenarios. This additional welfare loss is estimated to be 0.16 % of China's baseline GDP, a 52 % increase from the no-linkage level. These mixed results suggest that the design of a multilateral linkage can have significant effects on the distribution of its impacts across stakeholder economies.

In contrast to the multilateral global linking cases, subnational ETS linkage scenarios within China tend to beget relatively consistent results, in favor of economywide efficiency gains with their significant distributional impacts at subnational levels. As discussed earlier, China's carbon markets are currently segmented by sector and region: the national carbon market covers only the electricity sector and eight ETS pilots are still operated independently (ICAP, 2024). For example, Fan et al. (2016) estimate that a single unified carbon market within Mainland China would improve nationwide economic efficiency by $\leq$0.51 % point in baseline GDP, and reduce economic disparities between coastal and inland regions. Similarly, Cui et al. (2014) find that the linkage of the eight ETS pilots and a unified national carbon market would help reduce the policy-compliance costs to meet China's 2020 mitigation targets by 4.5 % and 23.7 %, respectively. Wang et al. (2020b) further extend their analysis to include Hong Kong—a quasi-autonomous Chinese economy having an administrative system independent of the Mainland's and a separate mitigation target—and examine the potential of China's extended national ETS inclusive of Hong Kong. They find that Hong Kong would save $\leq$78 % of the policy-compliance costs required to meet its 2030 mitigation goal without overburdening the Mainland's economy, although the benefits from the extended national ETS tend to be biased toward Hong Kong.

These findings extend to a smaller-scale integration of China's local carbon markets. For example, linking the Guangdong and Hubei provincial carbon markets—two of China's largest on-going ETS pilots—is estimated to bring a 47.2 % to 66.4 % reduction in policy-compliance costs at a regional level (comparable to 0.42 % to 0.94 % of baseline GDP), but this efficiency improvement is unevenly distributed to each province, favoring Guangdong (Feng et al., 2018; Liu et al., 2013). A key driver underlying this result is the relative role of each province in the regional carbon market. The linkage scenario lets Guangdong, specialized for high value-added industrial segments, perform as a net carbon-permit importer while assigning the role of net permit exporter to Hubei, which has weaker industrial bases. Thus, Guangdong could maintain a higher level of industrial production at the expense of Hubei's reduced industrial output, and the price that Guangdong pays for Hubei-imported permits would be more than offset by its increased industrial output value. A similar mechanism would also work for the Beijing-Tianjin-Hebei regional carbon market. In their static CGE analysis, Wang et al. (2020a) find that the ETS linkage could improve overall regional economic efficiency by $\leq$0.7 % of the baseline GDP, but Beijing and Tianjin as net permit importers would enjoy greater efficiency gains than Hebei, which has less competitive industrial bases.

Although the empirical literature reviewed in this section provides good insight into the potential impacts of ETS linkages on overall efficiency and their distribution among stakeholders, it fails to offer immediate answers to our research questions and leaves room for further improvement. First, empirical studies on China's carbon markets focus solely on Mainland China, excluding Hong Kong from their analysis. Wang et al. (2020b), which tests Hong Kong's participation in China's national ETS, is one of the few exceptions. This study conveys crucial policy implications regarding the need of an integrated carbon market from Hong Kong's perspective, but it neglects a more realistic, subnational level linkage scenario as an intermediate step. It takes a long time for China even to integrate regionally fragmented Mainland carbon markets and launch a more complete national ETS (ICAP, 2024; Zhao et al., 2019). It may take even longer for China's national ETS to accommodate Hong Kong, which has an independent administrative system. In this context, a subnational ETS linkage with Guangdong may be a more feasible near-term option for Hong Kong, and its potential impacts are a subject worthy of counterfactual analysis. Second, none of the studies reviewed pay attention to up-to-date carbon-neutrality targets. Both Mainland China and Hong Kong have recently announced their long-term mitigation goals with specific time schedules for carbon peak and neutrality. The increased stringency of the targets will necessarily increase the magnitude of the shock to be imposed on the economy; thus, the existing impact estimates focusing on older Copenhagen or Paris pledges need an update (Fleischhacker et al., 2019). Finally, four of the ten studies reviewed conduct a static analysis, neglecting the dynamic and cumulative dimensions of allocative efficiency losses under carbon constraints. However, an updated impact assessment would benefit from a dynamic analytic tool, which can consider a long-term pathway to carbon neutrality, reflecting proposed time schedules.

Table 1
CGE Studies of China's Integrated Carbon Markets.

	Temporal Dimension	Years Analyzed	Model Resolution		Integrated Carbon Markets Tested	Scope of Analysis	Carbon Constraints Imposed[a]	Policy-compliance Costs[b]	Efficiency Improvement from Integrated Carbon Markets[c]
			Chinese Regions	Sectors					
Cui et al. (2014)	Dynamic	2002–2020	31	137	China's national ETS	Mainland China only; Hong Kong is excluded.	42.5 % intensity reduction in 2020 (vs. 2005)	0.038–0.050 %	0.012 %
Fan et al. (2016)	Static	2007	30	17	China's national ETS	Mainland China only; Hong Kong is excluded.	≤10 % emissions reduction	–	≤0.51 %
Feng et al. (2018)	Static	2007	31	42	Hubei–Guangdong	Mainland China only; Hong Kong is excluded.	Hubei: ≤18.9 % emissions reduction; Guangdong: ≤21.9 % emissions reduction	0.4–4.6 %	Hubei: −0.39 to −2.28 Guangdong: 0.31–1.8
Hübler et al. (2014)	Dynamic	2005–2030	1	23	China–EU ETS	Mainland China only; Hong Kong is excluded.	45 % intensity reduction in 2020 (vs. 2005)	1.5–2.4 %	Mainland China: 0.1 %
Liu and Wei (2014)	Dynamic	2004–2020	1	15	China–EU ETS	Mainland China only; Hong Kong is excluded.	40 % intensity reduction in 2020 (vs. 2005)	0.08–0.22 %	Mainland China: 0.12 %
Liu et al. (2013)	Static	2007	31	42	Hubei–Guangdong	Mainland China only; Hong Kong is excluded.	Hubei: 8.1 % emissions reduction; Guangdong: 13.1 % emissions reduction	Hubei: ≤2.6 %; Guangdong: ≤2.1 %	Hubei: −1.44 Guangdong: 1.37
Qi and Weng (2016)	Dynamic	2007–2030	1	20	Global ETS[d]	Mainland China only; Hong Kong is excluded.	≤65 % intensity reduction in 2030 (vs. 2005)	–	Mainland China: 0.08 %
Wang et al. (2020a)	Static	2012	4	36	Beijing–Tianjin–Hebei (BTH)	Mainland China only; Hong Kong is excluded.	18 % intensity reduction in 2020 (vs. 2015)	–	BTH: 5.08–19.60
Wang et al. (2020b)	Dynamic	2021–2030	2	16	Mainland China–Hong Kong	Both Mainland China and Hong Kong are analyzed.	65 % intensity reduction (vs. 2005); 45 % emissions reduction (vs. 2010)	0.1–23.9 %	Mainland China: negligible Hong Kong: 0.1–1.8 %
Zhang et al. (2017)	Dynamic	2007–2020	1	20	Global ETS[e]	Mainland China only; Hong Kong is excluded.	45 % intensity reduction in 2020 (vs. 2005)	0.31–0.47 %	Mainland China: 0.16 %

Note:
[a] Carbon intensity refers to carbon emissions per unit GDP.
[b] Measured in % loss in baseline GDP.
[c] Measured in % gain in baseline GDP.
[d] Includes China, the US, the EU, Japan, Canada, Australia-New Zealand, South Korea, Mexico, Brazil, South Africa, Russia and India.
[e] Includes China, the US, the EU, Australia, Japan and South Korea.

3. Methodology

3.1. Greater Bay Area Economic Model

For our analysis, we develop a multi-region, multi-sector, recursive-dynamic CGE model, called the Greater Bay Area Economic Model (GBAEM) (see **Appendix** for technical details). The GBAEM includes eight regions in total, where Hong Kong (HKG), Shenzhen (SZH), the Rest of Guangdong (RGD), and the Rest of Mainland China (ROC) represent four separate regions, and 16 production sectors (Table 2). The GBAEM can run up to 2060 with a five-year interval, taking 2014 as the base year. The social accounting matrix (SAM) for the GBAEM is constructed from the Global Trade Analysis Project version 10 (GTAP10) dataset for the year 2014 (Aguiar et al., 2019), China's regional input-output tables for 2012 and 2017 (National Bureau of Statistics of China, 2017), and China's city-level multi-regional input-output tables for 2012 and 2015 (Zheng et al., 2021). The physical accounts relevant to carbon emissions and energy consumption are collected from GTAP-Power 10 Data Base (Maksym, 2020) and the International Energy Agency database (IEA, 2024). The GBAEM imposes conventional closure rules for market clearance, zero profit, and income balance, adopting standard behavioral assumptions for economic agents (Chen et al., 2022b; Rutherford, 1995).

In brief, the GBAEM consists of a set of hierarchical constant elasticity of substitution (CES) production nests (Fig. 4). Energy inputs and production factors (labor and capital) take a conventional CES structure (EVA nest), while non-energy intermediate inputs for each sector are subject to the Leontief, which is a special form of the CES function (INT nest). We apply Armington elasticities, and treat local domestic goods, non-local domestic goods, and foreign imports as imperfect substitutes. Eight electricity-generation technologies are considered—three thermal generation options (coal, oil, and gas) and five non-fossil technologies (hydro, nuclear, solar, wind, and other)—and electricity output is treated as a perfect substitute.

Carbon permits are modeled as a production input under a Leontief sub-nest. This structure imposes the condition that any industrial production involving the combustion of fossil fuels must be offset with carbon permits in proportion. When an emissions cap is imposed, each sector can respond in three different ways: purchasing carbon permits from other sectors, switching to less emission-intensive energy inputs, or reducing industrial outputs (i.e., cutting energy use). The decision as to the three responses is determined endogenously within the model, considering the relative price of each response. In essence, the price of carbon permits determined endogenously is thus a shadow price—a cost required to release a unit carbon constraint—and reflects the relative stringency of a given emissions cap. Accordingly, the carbon price is zero in the absence of carbon constraint and exists only when an emissions cap is imposed.

Table 2
Regional and Sectoral Aggregations in GBAEM.

	Code	Description
Regions	HKG	Hong Kong
	SZH	Shenzhen
	RGD	Guangdong, excluding SZH
	ROC	Mainland China, excluding SZH and RGD
	MAC	Macau
	JPN	Japan
	KOR	South Korea
	ROW	Rest of the World
Production Sectors	AGR	Primary industry
	MAN	Secondary industry, excluding energy production sectors
	TRN	Transport services
	SER	Tertiary industry, excluding TRN
	COA	Coal mining
	CRU	Crude oil extraction
	REFINE	Oil refinery
	GASS	Natural gas production
	ECOA	Power generation from coal
	EOIL	Power generation from oil
	EGAS	Power generation from natural gas
	EHYD	Power generation from hydro
	ENUC	Power generation from nuclear
	ESOL	Power generation from solar
	EWIN	Power generation from wind
	EOTH	Power generation from other technologies

3.2. Scenarios

Five scenarios in total—one reference and four policy case scenarios—are developed for counterfactual analysis (Table 3). The business-as-usual (BAU) scenario is the reference case scenario, which further extends the current legislation to the future without tightening existing mitigation targets. The GBAEM is calibrated to simulate the baseline GDP and carbon emission schedules under the BAU scenario. The baseline GDP schedule is estimated from official historic data—including the Shenzhen Bureau of Statistics (2024), the Statistics Bureau of Guangdong Province (2024), and the World Bank (2024)—and available long-term GDP projections—including Zhang et al. (2021) and the Organisation for Economic Co-operation and Development (2024). The baseline CO_2 emissions inventory is developed with reference to the BAU scenarios for GAINS-Asia (IIASA, 2024), C-REM 4.0 (Peng et al., 2025), and the Hong Kong Energy Policy Simulator (Jiang et al., 2019), as well as historic data from the GTAP 10 database (Aguiar et al., 2019), the International Energy Agency database (IEA, 2024), the Multi-resolution Emission Inventory model for Climate and Air Pollution Research database (Center for Earth System Science, 2023), the China City Greenhouse Gas Working Group (2022), and the Environment Protection Department (2024).

The four policy scenarios apply the identical emission reduction schedule for each region but depict four different subnational ETS linkage options. The nature of the emission constraint imposed under the policy scenarios is in essence an economy-wide emissions cap without sectoral dimensions. First, Pol_1 is a no-linkage scenario, where each of Hong Kong, Shenzhen, and the Rest of Guangdong operates an independent ETS to meet its own carbon-neutrality targets. Second, Pol_2 is a restricted GBA ETS linkage scenario, where Hong Kong and Shenzhen integrate their carbon markets, but the Rest of Guangdong independently operates its own carbon market. Third, Pol_3 assumes an extended GBA ETS linkage scenario, where Hong Kong, Shenzhen, and the Rest of Guangdong operate a fully integrated regional market. Finally, Pol_4 portrays China's extended national ETS, where Hong Kong, Shenzhen, the Rest of Guangdong, and the Rest of Mainland China operate a single, integrated national carbon market.

The emissions reduction schedule under the four policy scenarios benchmarks China's proposed national and regional carbon-neutrality targets (Fig. 5). As discussed earlier, Hong Kong has set a carbon-neutrality goal for 2050, and Mainland China aims to achieve net-zero emissions by 2060 with a carbon peak before 2030. Each of the three Mainland regions (SZH, RGD, and ROC) is assumed to comply with the national goal at the local level, and to follow a quasi-linear reduction schedule after a carbon peak. Even in the absence of sector-specific emissions constraints, this emissions reduction schedule under the policy case scenarios ensures compliance with proposed long-term sectoral targets. For example, Hong Kong's climate action plan (Environment Bureau, 2021) outlines net-zero emissions to be achieved by 2050 in its major "direct" sectoral contributors, including the electricity, transport, and waste-management sectors. The emissions schedule under all policy-case scenarios considered for this study reflects these long-term mitigation targets. The same plan also proposes long-term targets for "indirect" sectoral contributors, such as a 20 % to 40 % energy efficiency improvement in the building sector—Hong Kong's largest energy-demand sector, which consumes 90 % of local electricity—to be

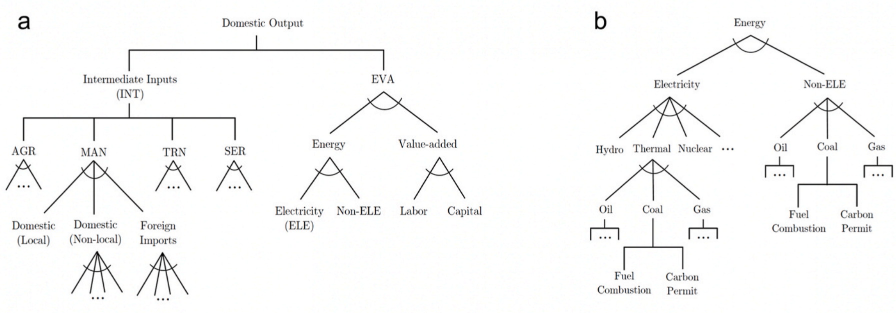

Fig. 4. Simplified Model Structure of the GBAEM: **(a)** Non-energy Production Nest; **(b)** Energy Production Nest.

Table 3
Scenarios for Model Simulation.

Scenario	Emission Caps for Carbon Neutrality	Nature of Regional Carbon Markets
BAU	Not imposed[a]	N/A
Pol_1	Imposed	Independent[b]
Pol_2	Imposed	HKG integrated with SZH[c]
Pol_3	Imposed	HKG integrated with SZH and RGD (GBA regional carbon market)[c]
Pol_4	Imposed	HKG integrated with SZH, RGD and ROC (national carbon market)[c]

Note:
[a] In the model, carbon is priced as a shadow price, and thus carbon price is zero under BAU, where no binding carbon caps are imposed.
[b] Each region operates an independent carbon market with a unique region-specific carbon price.
[c] Integrated carbon markets share a single carbon price within the region.

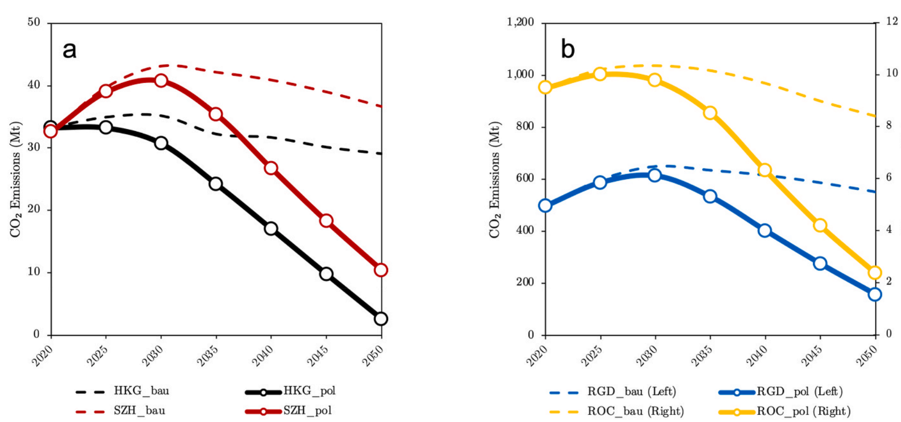

Fig. 5. Regional Emission Schedule under the BAU and Policy Scenarios: **(a)** HKG and SZH; **(b)** RGD and ROC.

achieved by 2050 from the 2015 level (Environment Bureau, 2021).[1] In response, the GBAEM adopts an autonomous energy efficiency improvement (AEEI) concept for each region—annual AEEI rates of 1 % for Hong Kong's non-energy sectors and of 3 % for Mainland China—following a standard modeling approach (e.g., Chen et al., 2022; Wang et al., 2020b). The AEEI of 1 % translates into a cumulative energy efficiency improvement of 30 % in Hong Kong's non-energy sectors for the 35 years between 2015 and 2050, in accordance with the proposed 20 % to 40 % reduction target.[2]

In addition, the emissions caps under the policy-case scenarios incorporate China's official plan for carbon capture, utilization and storage (CCUS) capacity building (ADB, 2022; Ministry of Science and Technology, 2019) and are relaxed by the CCUS capacity allocated to each region (see Section 4.2 of **Appendix** for further details). The national CCUS capacity is allocated to each region in proportion to regional baseline emissions, applying a common market penetration trend (IEA, 2020). However, we limit our analysis to fuel-related emissions, and our emissions accounting excludes the effects of natural carbon sinks or other land use changes. We also do not consider negative emission technologies under discussion, given the high uncertainty involved in their future implementation scale and cost (IEA, 2023).

4. Results[3]

4.1. GBA ETS linkage and overall efficiency gains

To measure efficiency, we use two indicators. One is policy-compliance costs, measured as a net GDP loss under carbon constraints compared to the baseline case. Complying with a stringent

[1] A 20 % to 30 % improvement for residential buildings and a 30 % to 40 % improvement for commercial buildings.
[2] Cumulative energy efficiency improvement (vs. no-improvement case) $= 1-(1-0.01)^{35} = 0.3$.

[3] Monetary values presented throughout this paper are measured in constant 2014 US dollars, unless mentioned otherwise.

mitigation target incurs some degrees of efficiency loss, since it restricts firms' choice of production technologies or imposes additional costs on inputs for production (Wang et al., 2020b). Under a carbon constraint, firms are forced to switch to less emission-intensive fuels or purchase carbon permits; either response will result in increased production costs. Alternatively, firms may choose to cut energy use to reduce emissions, and this decision will then cause a negative shock to the economy (Nam et al., 2013). Such efficiency loss arising from increased production costs or reduced industrial output can be considered a policy-compliance cost required to meet a given climate mitigation target (Nam et al., 2014). Adopting this concept, we define as the policy-compliance costs a net loss of GDP under policy case scenarios from the baseline GDP levels achievable in the absence of the policies. In particular, we focus on how a given ETS linkage scenario affects the costs required to meet a carbon-neutrality target.

The other efficiency indicator used is the net change in carbon intensity under an additional emissions cap. Carbon intensity is defined as the carbon emissions required to produce a unit GDP (often measured in kgCO_2/US$). While policy-compliance costs measure an aggregate efficiency loss in absolute terms, carbon intensity pays attention to cost effectiveness in relative terms. Given their nature—absolute vs. relative measurements—these two indicators may not always agree in terms of the results. Although a stringent emissions cap may require an economy increased compliance costs (i.e., reduced aggregate efficiency), it may help reduce carbon intensity (i.e., increased cost effectiveness) by penalizing emission-intensive sectors (Nam et al., 2014).

When efficiency is measured in terms of policy-compliance costs, a regional ETS linkage will bring substantial efficiency improvement to China's GBA region, and the level of efficiency improvement is positively associated with the size of the integrated carbon market (Table 4). As explained earlier, policy-compliance costs are defined as a magnitude of the baseline GDP loss required to meet a given policy-imposed emissions cap. Compliance that entails less GDP loss is regarded as having higher economic efficiency and vice versa. Proposed mitigation targets for carbon neutrality are costly, and each year between 2025 and 2050, the required policy-compliance costs can be as large as ≤16.9 % of the GBA region's baseline GDP under the `Pol_1` scenario. These costs, however, decline substantially under ETS linkage scenarios. Under `Pol_2`, where Hong Kong and Shenzhen form an integrated carbon market, the costs decrease to ≤16.2 % of the region's baseline GDP, ≤4.2 % below the `Pol_1` level. The costs decline further to ≤14.9 % of the region's baseline GDP under `Pol_3`, where Hong Kong forms an extended GBA carbon market with Shenzhen and Guangdong. That is, an extended GBA carbon market established among `HKG`, `SZH`, and `RGD` (`Pol_3`) presents efficiency improvement of ≤11.6 % compared with the no-linkage case (`Pol_1`) and of ≤8.9 % compared with the Hong Kong–Shenzhen ETS linkage case (`Pol_2`). An extended GBA ETS linkage brings even greater efficiency improvement at the national level, while its full integration into China's national ETS has negligible net effects (Table 5). The Hong Kong-Shenzhen ETS linkage (`Pol_2`) is estimated to help save policy-compliance costs at the national level by ≤1.2 %, compared with the non-ETS linkage case (`Pol_1`). The extended GBA carbon market including the entire Guangdong Province (`Pol_3`) has substantially greater effects, improving national-level efficiency by ≤3.7 % compared with the non-linkage case (`Pol_1`) or by ≤3.5 % compared with the Hong Kong-Shenzhen ETS linkage case (`Pol_2`). However, the impacts of the full integration of the GBA carbon markets into China's national ETS (`Pol_4`) remain marginal, compared with the GBA-only integration case (`Pol_3`). The reason for the marginal effects seems to be related to strong complementarity that exists within the GBA region, such as Hong Kong, which is specialized for finance and high value-added producer services, Shenzhen, which is specialized for high-technology manufacturing, and the rest of Guangdong, which is specialized for other secondary segments (Yeh et al., 2015). Such intra-regional economic complementarity may strengthen inward orientation in reallocating local emissions caps while reducing the need for the GBA region's carbon-permit trading with the rest of China (Nam, 2021).

From a carbon-intensity perspective, the extended GBA carbon market presents the largest carbon-intensity reductions (Table 6). Under `Pol_3`, carbon intensity in the GBA region, which is reduced by ≤67.4 % compared with the `BAU` levels, maintains the lowest levels: ≤4.3 %, ≤3.6 %, and ≤10.8 % below the `Pol_1`, `Pol_2`, and `Pol_4` levels, respectively. This suggests that `Pol_3` imposes an effective penalty on emission-intensive sectors without overly sacrificing the region's aggregate economic performance—relatively large emissions reductions relative to GDP loss, compared with other policy case scenarios. That is, the largest carbon-intensity reductions are attained under `Pol_3` primarily because the extended GBA carbon market helps take full advantage of intra-regional complementary (vs. `Pol_1` or `Pol_2`) without exporting local emissions to outside the region (vs. `Pol_4`).

Carbon intensity under the policy case scenarios also presents a significant reduction at the national level, but the national impacts of GBA carbon markets are limited (Table 7). National carbon intensity under `Pol_1` is ≤76.8 % below the `BAU` levels, but it shows only a marginal difference from other policy case scenarios—only ≤0.4 % above the `Pol_2`, `Pol_3`, or `Pol_4` levels. As discussed earlier, this seems to reflect the strong economic complementarity that exists within the GBA region.

4.2. Cross-regional distribution of improved efficiency

The benefits from a regional ETS linkage are unevenly distributed across the three GBA stakeholder regions, although all of them gain from the linkage. In terms of savings in policy-compliance costs, Hong Kong is the greatest winner, regardless of the linkage scenario (Table 8). Independent pursuit of carbon neutrality without any ETS linkage is excessively costly to Hong Kong. Under `Pol_1`, Hong Kong pays ≤21.0 % of its baseline GDP for compliance with its 2050 net-zero emission targets. The policy-compliance costs tend to increase over time from 1.1 % of the baseline GDP in 2025 to 21.0 % in 2050, since increasingly stringent emissions caps are imposed on the region's pathway to carbon neutrality. In particular, the costs spike during the last two periods, from 13.6 % in 2045 to 21.0 % in 2050, suggesting that even a comparable amount of absolute emissions reduction can be felt more stringent approaching the target year of net-zero emission. In fact, the carbon price for Hong Kong near the targe year spikes almost eight-fold from US $61/t$CO_2$ in 2045 to US$470/t$CO_2$ in 2050 (Table 9). This contrasts earlier periods, where the carbon price increases at a more moderate rate, rising by a factor of 2.6 to 3.9 every five years.

These excessively large compliance costs for Hong Kong decline substantially under ETS linkage scenarios. For example, the Hong Kong-Shenzhen ETS linkage (`Pol_2`) helps Hong Kong reduce its policy-compliance costs required in the absence of the linkage (`Pol_1`) by ≤23.0 %. The main reason for this efficiency gain is that the integration

Table 4
Policy Compliance Costs for China's GBA Region[a].

	`Pol_1`		`Pol_2`		`Pol_3`		`Pol_4`	
	US $bn[b]	%[c]	US $bn[b]	%[c]	US $bn[b]	%[c]	US $bn[b]	%[c]
2025	12.0	0.5	11.9	0.5	10.9	0.4	4.9	0.2
2030	28.7	0.9	28.1	0.9	26.3	0.9	14.2	0.5
2035	83.7	2.4	82.1	2.3	74.8	2.1	60.3	1.7
2040	254.9	6.4	247.8	6.2	229.8	5.8	222.5	5.6
2045	495.2	11.1	474.4	10.6	437.7	9.8	429.8	9.6
2050	828.6	16.9	793.8	16.2	732.4	14.9	720.1	14.7

Note:
[a] China's GBA region includes `HKG`, `SZH`, and `RGD`.
[b] GDP loss under each policy case scenario, compared with baseline GDP in each year.
[c] GDP loss as % of baseline GDP.

Table 5
Policy Compliance Costs for China's National Economy[a].

	Pol_1		Pol_2		Pol_3		Pol_4	
	US$bn[b]	%[c]	US$bn[b]	%[c]	US$bn[b]	%[c]	US$bn[b]	%[c]
2025	28.5	0.1	28.4	0.1	27.4	0.1	20.0	0.1
2030	67.8	0.3	67.3	0.3	65.5	0.3	50.2	0.2
2035	378.4	1.4	376.8	1.4	369.5	1.4	350.5	1.3
2040	1537.5	5.2	1529.6	5.2	1510.8	5.1	1498.2	5.1
2045	3369.3	10.1	3345.3	10.1	3307.7	10.0	3292.7	9.9
2050	4953.7	13.5	4892.7	13.4	4830.4	13.2	4797.9	13.1

Note:
[a] China's national economy includes the participants in its extended national carbon market (HKG, SZH, RGD, and ROC).
[b] GDP loss under each policy case scenario, compared with baseline GDP in each year.
[c] GDP loss as % of baseline GDP.

Table 6
Carbon Intensity for China's GBA Region[a] (Unit: $kgCO_2$/US$)

	BAU	Pol_1	Pol_2	Pol_3	Pol_4
2020	0.294	0.294	0.294	0.294	0.294
2025	0.281	0.276	0.276	0.276	0.278
2030	0.258	0.245	0.245	0.244	0.248
2035	0.219	0.187	0.187	0.185	0.190
2040	0.188	0.130	0.130	0.129	0.134
2045	0.161	0.083	0.083	0.081	0.086
2050	0.138	0.045	0.044	0.043	0.048

Note:
[a] China's GBA region includes HKG, SZH, and RGD.

Table 7
Carbon Intensity for China's National Economy[a] (Unit: $kgCO_2$/US$).

	BAU	Pol_1	Pol_2	Pol_3	Pol_4
2020	0.674	0.674	0.674	0.674	0.674
2025	0.570	0.560	0.560	0.560	0.560
2030	0.490	0.463	0.463	0.463	0.463
2035	0.415	0.351	0.351	0.351	0.350
2040	0.350	0.234	0.234	0.234	0.234
2045	0.291	0.139	0.139	0.138	0.138
2050	0.247	0.057	0.057	0.057	0.057

Note:
[a] China's national economy includes the participants in its extended national carbon market (HKG, SZH, RGD, and ROC).

of the two local carbon markets relaxes the stringent carbon constraint Hong Kong faces and reallocates the pooled emissions caps in such a way that the aggregate compliance costs can be minimized. The two regions share a single carbon price under Pol_2, and the price is located somewhere between the two prices they faced under Pol_1. When the GBA carbon market further extends to include RGD, Hong Kong enjoys even greater efficiency improvement. Under Pol_3, Hong Kong can decrease its policy-compliance costs by ≤38.2 % compared to the no-linkage case (Pol_1) and by ≤12.2 % compared to a smaller-scale linkage case (Pol_2). The integration of the GBA carbon market into China's national ETS also presents a substantial efficiency gain from Hong Kong's perspective, allowing the economy to save additional policy-compliance costs by ≤7.1 % under Pol_4, compared with under Pol_3.

Shenzhen is also better off under all three ETS linkage scenarios. In the absence of the ETS linkage (Pol_1), Shenzhen loses ≤19.8 % of its baseline GDP on its pathway to carbon neutrality. These costs in relative terms are slightly smaller than the costs Hong Kong pays under the same scenario. Under Pol_2, the costs are consistently below the Pol_1 levels by ≤9.3 %, suggesting that the Hong Kong-Shenzhen ETS is mutually beneficial while Hong Kong gains more from the linkage than Shenzhen. The costs under Pol_3 are comparable to ≤17.4 % of Shenzhen's baseline GDP or ≤12.2 % below the Pol_1 levels. The costs under Pol_4 further go down to ≤17.0 % or ≤13.9 % below the Pol_1 levels.

Guangdong (RGD) may be somewhat better off under ETS linkage scenarios, but the overall effects of the linkage tend to be relatively marginal. In the absence of any ETS linkage (Pol_1), Guangdong bears a ≤15.0 % loss of its GDP to meet its climate mitigation target. This cost is moderately reduced to ≤14.9 % of the GDP under Pol_2 and to ≤14.2 % of GDP under Pol_3. Guangdong gains most under Pol_4, but the difference in impacts is negligible between Pol_3 and Pol_4 (≤US $445 billon vs. ≤US$444 billion).

Finally, the ETS linkage scenarios tested have only marginal impacts on the economy of Mainland China. The marginal impacts may speak to the large size of China's national economy, which is around nine times the economies of Guangdong and Hong Kong combined. In addition, the complementarity established within the GBA may also partly explain the result, since it strengthens the incentives for intra-regional emissions trading rather than trading with non-GBA firms.

Carbon intensity in each region shows a somewhat different picture (Table 10). In Hong Kong, carbon intensity is lowest under Pol_1 (≤88.1 % below the BAU levels), while it increases by a factor of ≤2.8 under the three ETS linkage scenarios. In Shenzhen and Guangdong (RGD), carbon intensity is lowest under Pol_2 (≤79.2 % below the BAU levels) and under Pol_3 (≤69.2 % below the BAU levels), respectively. This pattern is determined by the relative magnitude of changes in local output and emission levels under the ETS linkage scenarios. By definition, lower (or higher) policy-compliance costs mean smaller (or larger) GDP losses under carbon constraints, leading to higher (or lower) output levels. Each region can maintain a higher (or lower) output level by relaxing (or tightening) its carbon constraint through carbon permit purchase (or sales), resulting in a smaller (or larger) emissions cut. That is, there is a trade-off between increased (or reduced) output levels and reduced (or increased) emission cuts under an ETS linkage scenario. If increased output from the non-linkage levels exceeds reduced emission cuts in relative terms, carbon intensity will decline; if the opposite is the case, carbon intensity will increase. In this sense, carbon intensity may be seen to represent the relative stringency of a "net" carbon constraint, where the portion of the emissions exported to other regions as an outcome of ETS linkages is subtracted from the initial emissions cap.

4.3. Emissions reduction by region and sector

The overall picture of emissions reduction in each region largely overlaps with that of the policy-compliance costs discussed earlier, confirming that Hong Kong gains most from regional ETS linkages (Table 11). Hong Kong is better off pursuing any of the three linkage scenarios compared with the non-linkage case (Pol_1), and the physical emissions reduction required for its compliance decline with the increase in size of the carbon market it participates in. In particular,

Table 8
Policy Compliance Costs for Each Chinese Region.

	Pol_1		Pol_2		Pol_3		Pol_4	
	US$bn[a]	%[b]	US$bn[a]	%[b]	US$bn*	%[b]	US$bn[a]	%[b]
Hong Kong (HKG)								
2025	3.8	1.1	3.8	1.1	3.8	1.1	3.5	1.0
2030	8.7	2.3	8.5	2.3	8.4	2.2	7.8	2.1
2035	16.9	4.1	16.3	4.0	15.8	3.9	14.9	3.6
2040	40.7	9.1	37.0	8.3	34.7	7.8	33.9	7.6
2045	65.9	13.6	50.7	10.5	44.5	9.2	43.1	8.9
2050	109.6	21.0	102.8	19.7	67.7	13.0	60.6	11.6
Shenzhen (SZH)								
2025	6.6	1.0	6.5	1.0	5.9	0.9	0.5	0.1
2030	16.2	2.1	15.8	2.0	15.6	2.0	4.5	0.6
2035	35.6	3.9	34.6	3.8	33.4	3.7	20.3	2.2
2040	82.9	8.1	79.5	7.8	79.8	7.8	74.0	7.2
2045	143.7	12.5	138.0	12.0	126.0	11.0	119.9	10.5
2050	250.5	19.8	227.2	18.0	220.1	17.4	215.6	17.0
Rest of Guangdong (RGD)								
2025	1.6	0.1	1.6	0.1	1.2	0.1	0.9	0.1
2030	3.8	0.2	3.8	0.2	2.3	0.1	1.9	0.1
2035	31.2	1.4	31.2	1.4	25.5	1.1	25.1	1.1
2040	131.3	5.2	131.3	5.2	115.3	4.6	114.6	4.5
2045	285.7	10.1	285.7	10.1	267.1	9.4	266.8	9.4
2050	468.5	15.0	463.8	14.9	444.6	14.2	443.9	14.2
Rest of Mainland China (ROC)								
2025	16.5	0.1	16.5	0.1	16.5	0.1	15.1	0.1
2030	39.1	0.2	39.2	0.2	39.2	0.2	36.0	0.2
2035	294.7	1.3	294.7	1.3	294.7	1.3	290.1	1.3
2040	1282.6	5.0	1281.8	5.0	1281.0	5.0	1275.7	5.0
2045	2874.0	10.0	2870.8	10.0	2870.0	10.0	2862.9	10.0
2050	4125.1	13.0	4098.8	12.9	4098.0	12.9	4077.8	12.9

Note:
[a] GDP loss under each policy case scenario, compared with baseline GDP in each year.
[b] GDP loss as % of baseline GDP.

Table 9
Carbon Prices under Policy Scenarios (Unit: 2014 US$/t$CO_2$).

	Pol_1				Pol_2				Pol_3				Pol_4			
	HKG	SZH	RGD	ROC	HKG	SZH	RGD	ROC	HKG	SZH	RGD	ROC	HKG	SZH	RGD	ROC
2025	0.7	0.3	0.3	0.0	0.4	0.4	0.3	0.0	0.3	0.3	0.3	0.0	0.1	0.1	0.1	0.1
2030	1.9	0.7	0.7	0.1	0.9	0.9	0.7	0.1	0.7	0.7	0.7	0.1	0.2	0.2	0.2	0.2
2035	5.0	1.9	1.5	0.8	2.3	2.3	1.5	0.8	1.6	1.6	1.6	0.8	0.9	0.9	0.9	0.9
2040	19.6	5.8	4.1	3.7	7.3	7.3	4.0	3.7	4.4	4.4	4.4	3.7	3.8	3.8	3.8	3.8
2045	60.7	10.5	8.1	7.7	14.9	14.9	8.1	7.7	8.9	8.9	8.9	7.7	7.8	7.8	7.8	7.8
2050	470.1	32.0	20.6	18.5	54.2	54.2	21.0	18.5	23.1	23.1	23.1	18.5	18.7	18.7	18.7	18.7

Pol_4, which depicts China's fully integrated national carbon markets, allows Hong Kong to minimize its mitigation burden through imported carbon permits.

Under Pol_1, Hong Kong confronts an excessively stringent policy shock and needs to independently abate almost all of its baseline emissions ($\leq$26.6 Mt). Under Pol_2, Hong Kong-based firms may feel an identical emissions cap to be less stringent, as they have an additional, more cost-effective compliance option. That is, they can simply purchase carbon permits from Shenzhen-based firms, instead of abating emissions through less use of energy or fuel switching. Theoretically, the relative stringency of local mitigation targets, which is reflected in pre-linkage unit carbon prices under Pol_1 given in Table 9, determines each region's position under the ETS linkage. Those regions facing more stringent carbon constraints become net-importers of carbon permits and partly shift their mitigation burden to other participants, and vice versa. Accordingly, the gap in pre-linkage carbon prices ($\leq$US$470/t$CO_2$ in Hong Kong vs. $\leq$US$32/t$CO_2$ in Shenzhen) explains why part of Hong Kong's physical emissions cap is transferred to Shenzhen under Pol_2, and its actual emissions cut is reduced to $\leq$24.6 Mt from $\leq$26.6 Mt. The other two policy scenarios further increase the size of the carbon market that Hong Kong can access and relax the stringency of the shock that it faces by even greater magnitude. Under Pol_3, Hong Kong shifts part of its mitigation burden to Guangdong, as well as to Shenzhen, and abates only $\leq$21.2 Mt of its baseline emissions. Under Pol_4, Hong Kong's mitigation burden slightly declines, thanks to its access to the entire Mainland's carbon market, but the difference is marginal compared with its burden under Pol_3.

The same logic underlies the results for the other regions. First, emissions reduction required for Shenzhen's compliance under Pol_1 ($\leq$29.5 Mt) further increases to $\leq$30.4 Mt under Pol_2; but it is reduced to $\leq$27.1 Mt under Pol_3 and further to $\leq$26.7 Mt under Pol_4. The Hong Kong–Shenzhen ETS linkage (Pol_2) makes Shenzhen cut more of its local emissions in exchange for the carbon permits exported to Hong Kong, as Shenzhen' mitigation targets are less stringent than Hong Kong's. In the extended GBA (Pol_3) or fully integrated national carbon markets (Pol_4), however, Shenzhen becomes a net permit importer and shifts part of its mitigation burden to the rest of Guangdong or Mainland China, which face relatively moderate carbon constraints. In contrast to the two city-level economies of Hong Kong and Shenzhen, both RGD and ROC, which have much larger province- or national-level

Table 10
Carbon Intensity for Each Chinese Region (Unit: $kgCO_2$/US$).

	BAU	Pol_1	Pol_2	Pol_3	Pol_4
Hong Kong (HKG)					
2020	0.107	0.107	0.107	0.107	0.107
2025	0.102	0.098	0.099	0.101	0.102
2030	0.093	0.084	0.087	0.091	0.092
2035	0.078	0.061	0.071	0.075	0.075
2040	0.071	0.042	0.049	0.055	0.056
2045	0.062	0.023	0.028	0.033	0.034
2050	0.056	0.006	0.011	0.018	0.017
Shenzhen (SZH)					
2020	0.082	0.082	0.082	0.082	0.082
2025	0.078	0.077	0.077	0.077	0.077
2030	0.071	0.068	0.067	0.070	0.070
2035	0.060	0.052	0.049	0.055	0.055
2040	0.051	0.035	0.033	0.038	0.038
2045	0.044	0.021	0.020	0.024	0.024
2050	0.037	0.009	0.008	0.012	0.012
Rest of Guangdong (RGD)					
2020	0.413	0.413	0.413	0.413	0.413
2025	0.387	0.380	0.380	0.380	0.383
2030	0.354	0.335	0.335	0.332	0.338
2035	0.298	0.254	0.254	0.248	0.256
2040	0.256	0.176	0.176	0.171	0.179
2045	0.218	0.113	0.113	0.108	0.116
2050	0.185	0.062	0.062	0.057	0.065
Rest of Mainland China (ROC)					
2020	0.730	0.730	0.730	0.730	0.730
2025	0.612	0.600	0.600	0.600	0.600
2030	0.523	0.494	0.494	0.494	0.493
2035	0.443	0.374	0.374	0.374	0.373
2040	0.372	0.249	0.249	0.249	0.248
2045	0.309	0.146	0.146	0.146	0.146
2050	0.262	0.059	0.059	0.059	0.058

economies, are only marginally affected by the ETS linkage scenarios. Nonetheless, RGD performs as a net permit exporter to the two other GBA economies under Pol_3, but flips its role to a net permit importer under Pol_4, by transferring part of its physical mitigation burden to ROC with less stringent carbon constraints.

In all regions, a large fraction of the local emissions cut is attained from the electricity sector, although detailed cross-sectoral distribution patterns depend on the regional industry mix (Fig. 6). In Hong Kong, the electricity sector alone accounts for $\geq$79.8 % of the emissions cut, regardless of scenarios and time periods. In particular, during the earlier periods, when relatively moderate emissions caps are imposed, the city's entire emissions cut is from the electricity sector. After the sector's abatement potential is exhausted in later periods, the tertiary industry contributes to a fraction of the required emissions reduction that exceeds the electricity sector's abatement capacity. The share of the electricity sector is much higher under the three ETS linkage scenarios than under Pol_1, as Hong Kong's reduced physical mitigation burden in integrated carbon markets (thanks to imported carbon permits) lowers the need to involve the tertiary sector. Other regions also show a similar pattern, where the local electricity sector plays a dominant role in emissions reduction and the sector's depleted abatement potential with increased regulatory stringency gradually creates room for other sectors. The tertiary industry is a paramount sectoral complement to the electricity sector for compliance in Hong Kong and Shenzhen, which have service-intensive urban economies; in contrast, the secondary industry plays almost as important a role as the tertiary industry for mitigation in RGD and ROC with a strong manufacturing sector.

The electricity sector becomes the priority target of emissions reduction, as its large share in local emissions and high dependence on coal offer a sizeable, low-cost abatement opportunity. In 2021, for example, electricity and heat generation accounted for over half the local anthropogenic carbon dioxide (CO_2) emissions in Mainland China and for over two-thirds of them in Hong Kong (IEA, 2024). At the same time, the sector intensively uses coal, which accounted for 63 % of the total CO_2 emissions in Mainland China and for 42 % in Hong Kong in 2021 (*ibid.*). Reducing the use of coal, which has a higher emission factor, can be less costly than cutting other fossil-fuel consumption, as a unit coal reduction translates into a larger emissions cut than a unit reduction of oil or natural gas. That is, coal-based compliance with an emission cap helps minimize a negative shock to aggregate energy demand and economic output.

This explains why almost the entire emissions cut required for compliance is from the electricity sector, regardless of region, when relatively moderate emissions caps are imposed during earlier periods (Fig. 7). As a target year of carbon neutrality approaches, however, the growing stringency of the mitigation targets increasingly exhausts the sector's low-cost abatement opportunities and creates room for other sectors to play. During later periods, part of the emissions cut needs to come from other industries if the entire cut cannot be attained at reasonable costs within the electricity sector. Overall, compliance with proposed mitigation targets harshly hits the local power sector and phases out conventional thermal plants from the local electricity output mix. Only Hong Kong may be able to create a buffer for thermal generation under an ETS linkage scenario in exchange for imported carbon permits.

4.4. Synthesis and further discussion

Our analysis results yield three clear macro pictures. First, compliance with proposed carbon-neutrality targets is extremely costly and introduces a huge shock to the regional economy. The magnitude of the shock is particularly large in Hong Kong, which cannot take advantage of China's internal adjustment mechanisms on its pathway to carbon neutrality. Second, the compliance costs, however, can be significantly reduced through regional ETS linkages. In particular, an extended GBA carbon market involving Hong Kong and the entire Guangdong Province is worthy of attention, given its intra-regional economic complementarity. Under this ETS linkage scenario, the GBA region can meet its region-wide mitigation goal at a $\leq$11.6 % lower cost without significant adverse impacts on the rest of China. Finally, a regional carbon market is mutually beneficial to all three GBA stakeholders, but the benefits are not evenly distributed—Hong Kong gains a lot more from it than Shenzhen or the rest of Guangdong. This Hong Kong-biased benefit can potentially weaken economic incentives for a regional carbon market on the Mainland's side.

Table 11
Carbon Emissions Reduction from BAU Levels (Unit: Mt).

	Pol_1				Pol_2				Pol_3				Pol_4			
	HKG	SZH	RGD	ROC	HKG	SZH	RGD	ROC	HKG	SZH	RGD	ROC	HKG	SZH	RGD	ROC
2025	1.7	0.8	11.3	201.5	1.5	0.8	11.3	201.5	0.7	0.7	12.6	201.5	0.2	0.3	7.9	207.1
2030	4.4	2.5	36.1	595.5	3.3	3.0	36.1	595.5	1.8	1.3	41.7	595.5	1.4	0.9	29.3	608.1
2035	8.0	7.0	101.9	1700.2	4.3	8.8	101.9	1700.2	2.7	4.6	113.1	1700.2	2.4	4.1	95.1	1718.4
2040	14.7	15.0	213.6	3548.4	11.8	16.3	213.6	3548.4	9.1	13.3	223.5	3548.4	8.7	12.7	204.0	3568.1
2045	20.4	22.4	312.7	5167.2	18.2	23.4	312.7	5167.2	15.5	19.9	323.7	5167.2	15.1	19.4	304.0	5186.7
2050	26.6	29.5	395.8	6784.5	24.6	30.4	395.8	6784.5	21.2	27.1	406.9	6784.5	21.2	26.7	387.0	6803.9

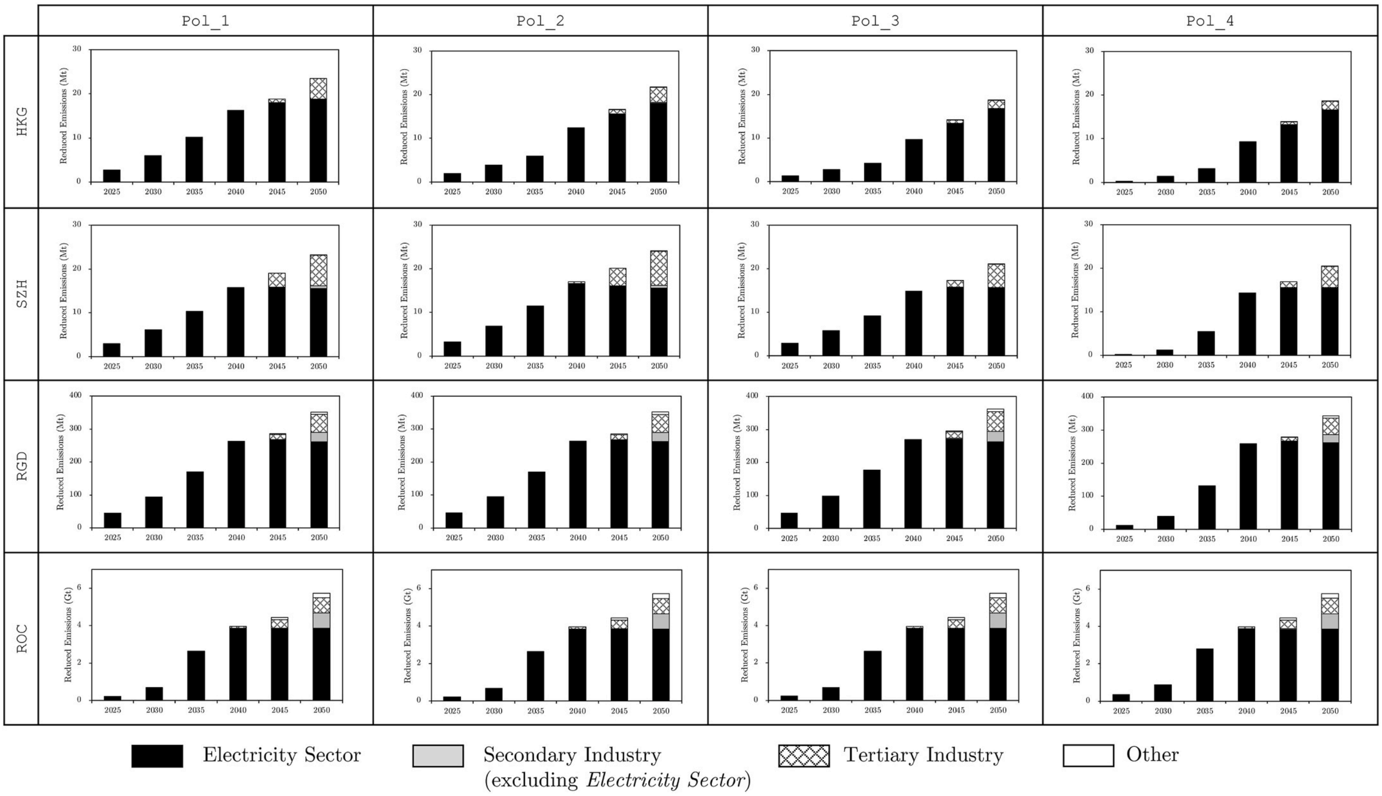

Fig. 6. Carbon Emissions Reduction under Policy Scenarios (vs. BAU levels).

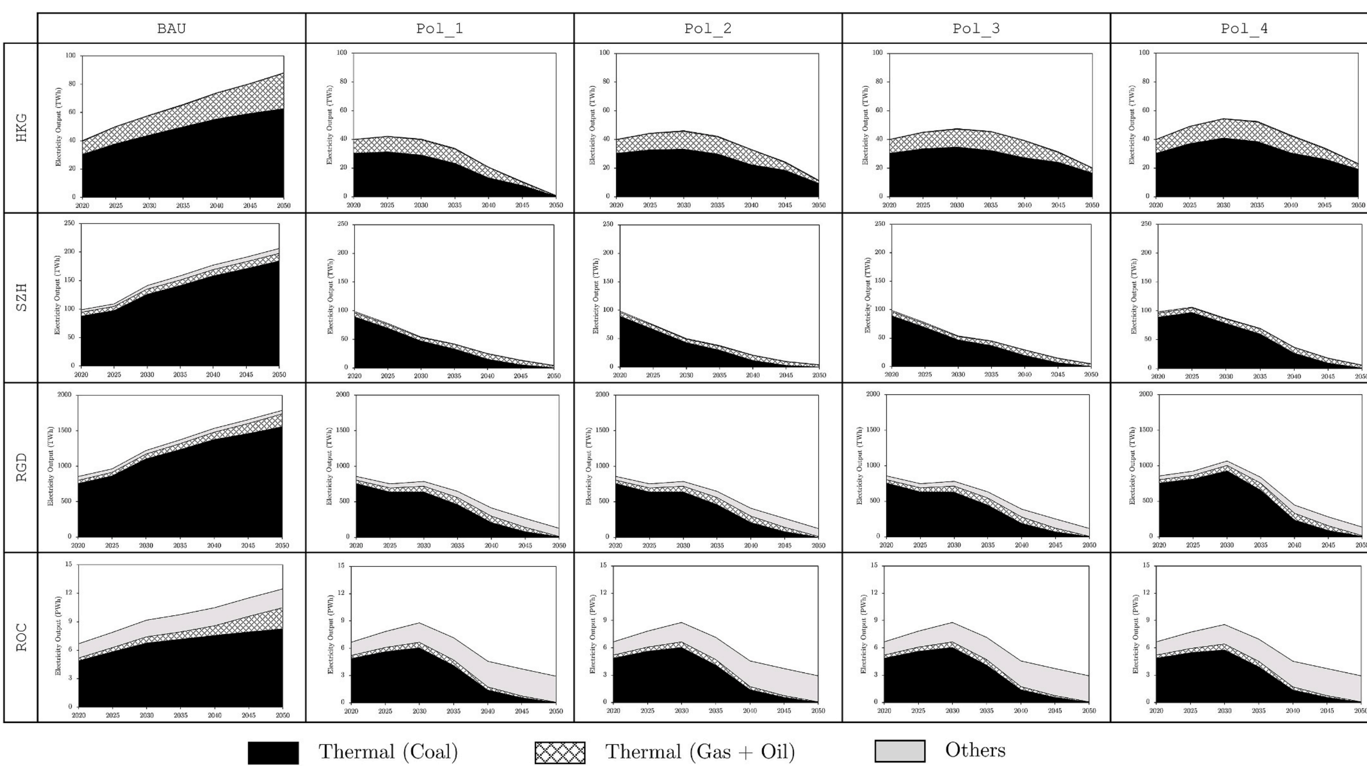

Fig. 7. Local Electricity Output Mix.

These results convey several policy implications for regional cooperation. The most important message from the results is that it is Hong Kong that needs to be more proactive than any other potential stakeholder in making the GBA carbon market happen in reality. Shenzhen and the rest of Guangdong likely have much weaker incentives for the ETS linkage, given the Hong Kong-biased benefits.

Furthermore, their ultimate integration into China's national ETS is scheduled according to the central government's green-development roadmap. From their perspective, this determined future reduces the urgency or attractiveness of the GBA carbon market as an alternative, efficient compliance option. In this context, a recycling mechanism for the revenues from carbon pricing may matter in increasing the feasibility of the GBA ETS linkage. If the mechanism is designed to help balance the benefits across GBA municipalities, it can help strengthen economic incentives for Shenzhen and the rest of Guangdong. For example, the GBA municipalities can consider establishing a unified regional tax-collection body and redistributing tax revenues from initial allowance auctioning/permit allocations and secondary market transactions to stakeholder municipalities in such a way as to offset the imbalance in their gains from the ETS linkage.

In addition, approaching the regional carbon market from a cross-border investment and carbon-leakage perspective may be appealing to Guangdong Province. In fact, Guangdong Province and Hong Kong have extended their regional-level cooperation on environmental agendas, such as air-quality monitoring and regulations, and associated initiatives for cross-border cooperation have been supported by China's central government under the leadership of the GBA Development Office (Constitutional and Mainland Affairs Bureau, 2018; Nam, 2021). In this respect, a normative stance may complement the economic incentives for the GBA carbon market.

In addition, Hong Kong can take a two-track approach to enhancing a regional carbon market— the voluntary markets based on economic incentives, as well as the compliance markets based on environmental norms. Its tapping into voluntary carbon-market opportunities may begin with those GBA entities that are not constrained by the compliance markets. In 2022, for example, over a third of Guangdong's local emissions were not covered by either local ETS pilots or the national ETS (ICAP, 2024). Hong Kong as a global financial hub already has the competitive key institutional and physical infrastructure, and has great potential to position itself as a center for international voluntary carbon markets (Financial Services Development Council, 2023). On its path to this role, Hong Kong may first focus on regional opportunities, in cooperation with Guangdong Province, and then consider extending its market reach at the national and international levels (GSFCASG, 2022).

5. Conclusions

Apart from China's national level mitigation targets, Hong Kong sets an independent city-level carbon-neutrality target for 2050. Hong Kong's proposed carbon-neutrality target would put a harsh constraint on its economy and is estimated to require policy-compliance costs as large as $\leq$21.0 % of its baseline GDP. This magnitude of the shock may be too large for the city-sized economy to manage independently, and its alleviation would require an extended application of market-based mechanisms through regional cooperation. In particular, an ETS linkage within China's GBA is worthy of attention, as it can help establish an efficient internal adjustment mechanism for the compliance with joint mitigation targets at a regional level, overcoming the limitation of Hong Kong's tiny carbon markets.

An integrated regional carbon market through an ETS linkage brings substantial efficiency improvement at both regional and local levels. For example, an extended GBA carbon market involving Hong Kong and the entire Guangdong Province can reduce policy-compliance costs by $\leq$11.6 % in each year between 2025 and 2050, without imposing any significant negative shock on other parts of the Chinese national economy. A key driver underlying this regional level efficiency gain is the strong economic complementarity that exists within the region. We find that a regional carbon market is mutually beneficial, and all three GBA stakeholder economies are better off with it. In particular, Hong Kong will be the largest winner of an ETS linkage, although it also helps Shenzhen and the rest of Guangdong comply with their mitigation targets at $\leq$13.9 % and $\leq$5.2 % lower costs, respectively. Hong Kong can reduce its compliance costs for carbon neutrality by $\leq$23.0 % (vs. no-linkage scenario) if it forms an integrated carbon market with Shenzhen. The cost savings will further increase to $\leq$38.2 % if Hong Kong cooperates with the entire Guangdong Province to create an extended regional carbon market. Accordingly, Hong Kong has a great incentive to promote cross-border cooperation towards an integrated regional carbon market.

Our results speak to the need for a regional carbon market in China's GBA region. It helps save substantial economic costs required for the region's compliance with proposed climate mitigation targets, benefiting all participating GBA municipalities. At present, China plans to gradually move toward a fully integrated national carbon market, which ultimately will cover the entire Guangdong Province and non-electricity sectors. However, Hong Kong, which will benefit most from the integrated carbon market, is excluded from this plan. Without the market, Hong Kong will have to bear an excessively large compliance cost, and the feasibility of its proposed carbon-neutrality target may be questioned. In this context, Hong Kong needs to be more proactive in terms of cross-border cooperation for ETS linkages and to take the initiative in forming a regional carbon market. It seems realistic that Hong Kong should first try an ETS linkage with Shenzhen as a testbed and gradually extend the linkage to form an extended GBA carbon market and to participate in China's national ETS.

CRediT authorship contribution statement

Ji Zheng: Writing – original draft, Software, Methodology, Formal analysis. **Xin Li:** Writing – review & editing, Validation, Investigation, Conceptualization. **Kyung-Min Nam:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Compliance with ethical standards

This manuscript does not contain any studies involving human participants performed by any of the authors.

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Declaration of competing interest

The authors have no relevant financial or non-financial interests to disclose.

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Appendix: Technical Note on GBAEM

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Data availability

The authors do not have permission to share data.

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