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Embodied greenhouse gas emission by Macao

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HIGHLIGHTS

- A systematic accounting procedure is presented to inventory a city's GHG emissions.
- A comprehensive review of GHG emissions is performed for Macao.
- Indirect GHG emissions dominate Macao's embodied GHG emissions.
- Macao induced large amount of GHG emissions in other regions through trade.
- The variation in GHG emission structure against socio-economic changes is revealed.

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ABSTRACT

Comprehensive inventory of cities' greenhouse gas emissions (GHG) is the basis for cities to make appropriate mitigation plans. However, previous studies on cities' GHG emissions consider emissions occurring within the city boundary (Scope 1) and out of boundary electricity emissions (Scope 2), but neglect indirect emissions associated with commodities consumed by cities (Scope 3), resulting in emission leakage. To cope with this problem, a systematic accounting covering all 3 scopes is presented in a case study of Macao for the years 2005–2009, based on the latest embodied emission intensity databases for China and for the world. The results show that total emissions are dominated by indirect emissions mainly embodied in imports, which is 3–4 times direct emissions during the period concerned. It is verified that accounting under Scopes 1 and 2 cannot capture the full picture of cities' emissions, especially cities like Macao which are dominated by service industry and inevitably sustained by massive materials and services from other regions. Our study suggests that Macao should adjust its current GHG mitigation policies which consider only its emissions occurring within its border, as Macao is a net GHG emissions importer. This work is the first assessment of Macao's embodied GHG emissions.

1. Introduction

Though they cover less than 1% of the Earth's surface, cities host half of the world's population (Sovacool and Brown, 2010), consume at least 75% of the world's energy and emit even larger share of the anthropogenic Greenhouse Gas (GHG) emissions (Satterthwaite, 2008). Moreover, it is estimated that the share of GHG emissions induced by energy consumption in cities continues rising steadily due to rapid urbanization in developing countries (IEA, 2008). Therefore, cities play a key role in tackling global climate change, as well as in energy conservation.

Currently, cities are the main targets for GHG emission control and significant efforts are made to reduce cities' GHG emissions. In the context of politics, groups like "Cities for Climate Protection" (CCP) campaign and "Large Cities Climate Leadership Group" (C40 group) are setting goals and taking actions to mitigate urban GHG emissions (Betsill and Bulkeley, 2007; Kennedy et al., 2010). Moreover, a wide range of research has focused on investigating cities' GHG emissions (Schmidt Dubeux and Rovere, 2007; Glaeser and Kahn, 2010; Hillman and Ramaswami, 2010; Kennedy et al., 2009, 2010; Koehn, 2008; Phdungsilp, 2010; Makido et al., 2012; Liu et al., 2012; Yu et al., 2012; Zhou et al., 2010), which provides important insights to facilitate practical policy making for GHG emission abatement.

Obtaining a reliable inventory is the basis for planning effective GHG reduction (Kennedy et al., 2009). Particularly, GHG inventory can provide insight into the nature of current emissions, and more

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importantly, help decision-makers to implement appropriate abatement policies. Consequently, inventories of GHG emissions by economies at different scales have been established by applying different methodologies within various frameworks. At the international scale, Hertwich and Peters (2009) conducted a global, trade-linked analysis on greenhouse gas emissions associated with the final consumption of goods and services for 14 aggregate world regions. In another study, Chen and Chen (2011b) presented a study on embodied carbon dioxide emissions induced by world's fuel combustions and pointed out that CO_2 emission leakages are associated with international trade. Research on embodied GHG emissions accounting at national scale is prevalent, owing to the concerns on trade balance. For instance, considering that international trade will impact the picture of responsibilities of different countries for the GHG emissions, Mäenpää and Siikavirta (2007) carried out an analysis on GHG embodied in the international trade and final consumption of Finland. Their results suggested that the change of trade's magnitude contributed to increasing positive GHG trade balance. From the perspective of Consumption-Based Principle (CBP), Muñoz and Steininger (2010) quantified the CO_2 emissions for Austria on the basis of input–output analysis. As China plays a vital role in world's economy and global trade, China's embodied GHG emissions associated with international trade and interprovincial trade are also explored by some existing literature (e.g., Guo et al., 2012; Xu et al., 2011, Yan and Yang, 2010), which indicated that trade is responsible for the large amount of GHG transfer.

Although city-level GHG emissions accounting has been conducted by many researchers as aforementioned, comprehensive and complete analysis on urban scale's embodied GHG emissions is comparatively rare. Based on the life cycle analysis, Schulz (2010) estimated the state city Singapore's embodied GHG emissions and found that the indirect GHG emissions embodied in trade exceeded direct emissions. Recently, Chen et al. (2013) simulated Beijing's economic network and calculated the embodied CO_2 emissions by three-scale input–output modeling. The complex nature of goods and services flowing through the city boundary not only makes it complicated to compile the city's emission inventory (Xi et al., 2011) but also causes accounting errors (Bi et al., 2011). In order to cope with this problem, the World Resources Institute and the World Business Council for Sustainable Development (WRI/WBCSD) suggest that the emission boundary of a city be defined by 3 scopes (WRI/WBCSD, 2009) for the purpose of GHG emission accounting. Scope 1 includes only direct emissions such as fuel combustion, industrial processes and fugitive emissions within the city's territorial boundaries. Indirect GHG emissions related to electricity supplied by upstream power plants are included in Scope 2. Scope 3 is defined as other out-of-boundary emissions embodied in upstream production attributable to the city. It is obvious that to capture a holistic picture of a city's GHG emissions, appropriate methodology used to calculate city's GHG emissions should cover all the three scopes. However, most studies covering emissions consider only Scopes 1 and 2 (Bi et al., 2011; Dhakal, 2009; Kennedy et al., 2009; Xi et al., 2011), while the emissions embedded in food, water and other products flowing into the city are ignored. As a result, the neglect of emissions under Scope 3 in previous studies leads to emission leakage. In fact, input–output analysis which has been adopted to reattribute embodied emissions associated with material and service exchanges in international trade (Chen and Chen, 2010, 2011a, 2011b, 2013; Davis and Caldeira, 2010; Guo and Chen, 2013; Muñoz and Steininger, 2010; Pan et al., 2008; Peters and Hertwich, 2008; Zhang and Chen, 2010). And this approach can also be used to account for emissions under Scope 3. Yet few studies have employed this method to benchmark city-level GHG emissions to facilitate suitable policymaking because of data unavailability.

On January the 14th, 2008, the United Nations formally confirmed that the Kyoto Protocol is applicable to Macao, which means Macao has become an individual member of the global GHG emission mitigation plan ever since then. Considering the significant importance of Macao's GHG emissions, efforts have also been devoted to evaluate the GHG emissions by Macao. For instance, *Macao Environment Report 2008–2009*, published by Macao Environmental Protection Agency, briefly reports the main GHG emissions by Macao in 2009 and points out that the amount of GHG emissions released by Macao decreased by comparing with that of 2008 due to the financial crisis (DSPA, 2010). The quantity of GHG emissions is also calculated for the key energy sector in Macao. For instance, Li and Chen (2013) comprehensively analyzed the GHG emissions caused by Macao's energy consumption from 2000 to 2010. Lai et al. (2011) applied the vector error correction model to illustrate the casual relationship between Macao's electricity consumption and economic growth. Based on the work of Lai et al. (2011), To et al. (2011) estimated the GHG emissions induced by Macao's electricity consumption by applying life cycle analysis. Although these studies have contributed greatly to the assessment of Macao's GHG emissions and implementation of emission reduction policies, they have their limitations. Firstly, most studies focus only at GHG emissions in Scope 1 and/or 2. Secondly, previous research evaluated only the GHG emissions by important sectors such as energy, transportation rather than the whole economy. As a result, these studies are still not sufficient to capture the full picture of Macao's GHG emissions.

To overcome the limitations of previous studies on Macao, this paper aims to help solve the emission leakage problem and therefore help to guide appropriate low-carbon policies by achieving the following goals: (1) based on the most recent data sources, exploring the total and per capita embodied GHG emissions of Macao by applying systematic analysis, and thereby, figuring out Macao's emission responsibility; (2) accounting for the GHG emission balances between import and export as well as comparing direct and indirect GHG emissions; (3) revealing the variation in GHG emission structure against Macao's socio-economic changes; (4) analyzing sectoral energy consumption and GHG emissions in order to provide insights into the economic sectors' impact on the total economy.

This study takes into account all the three major GHGs: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Following IPCC (2006), this paper presents the quantity of each GHG in the equivalent CO_2 (CO_2e) emission by applying global warming potential (GWP), in the ratio 1:21:310 for CO_2:CH_4:N_2O. This paper is organized as follows: Section 2 presents background information on Macao. Methodology and data sources are elaborated in Section 3. Section 4 presents in-depth analysis of the results and discusses the emission inventory and its relation to various economic sectors. Section 5 discusses the advantages and barriers for Macao to reduce GHG emissions. Finally, conclusions are drawn in Section 6.

2. Overview of Macao

Macao is located on the south-east coast of Mainland China. It consists of Macao Peninsula, Taipa Island, Luhuan Coloane Island and Taipa-Coloane Reclamation Area. Macao comprised an area of only 10.3 km^2 in the 17th century, but gradually expanded to 29.5 km^2 (DSEC, 2009d) by reclamation. Its land area equals only 1/6 of that of Washington D.C or 1/23 of that of Singapore. With a population of 544,100 in 2009 (DSEC, 2009d), Macao is considered to be one of the most densely populated regions in the world (about 18,400 persons/km^2). Macao has no arable land, forest, or mineral mines; as a result, natural resources are scarce in Macao.