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# Structural analysis of embodied greenhouse gas emissions from key urban materials: A case study of Xiamen City, China

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ABSTRACT

The indirect greenhouses gas emission (GHG) embodied in the key urban materials purchased outside the city boundary (Scope 3) are often ignored in traditional city GHG studies, mostly concentrating on the emissions occurring inside the city (Scope 1) and emissions by the purchased electricity out of boundary (Scope 2). And there is little research on the structural analysis of the upstream supply chain for Scope 3. However, a comprehensive urban GHG accounting system is the basis for cities to make appropriate mitigation measures. Identifying the main embodied GHG that dominate the emissions in upstream supply chains can help focus attention on the largest emitters and offer insights into where climate mitigation efforts should be directed. Thus, in this study the Economic Input Output – Life Cycle Assessment (EIO-LCA) approach was used to evaluate the embodied GHG emissions from Scope 3 and to explore the related GHG emissions structure in the upstream supply chain based on the final demand for the key urban materials. And food, water, steel, cement, and fuel were selected as the representative urban materials based on the characteristic of Xiamen City. Our results demonstrate that the total embodied GHG emissions were 13,201.31 kt $CO_2$e, very close to the direct GHG emissions from end-use sectors inside Xiamen city. Among the embodied GHG emissions, imported steel, fuels, cement, food, and water accounted for 56, 26, 13, 4, and 1% of the emissions, respectively. The main embodied GHG emissions contributors were found in the upstream supply chain and some related policy implications were presented. Compared to other cities, Xiamen had a relatively low per capita embodied GHG emission, which was 5.24 t $CO_2$e lower than eight U.S. cities.



## 1. Introduction

Cities are recognized as key contributors to global climate change (IEA, 2008; Li et al., 2013), as well as a critical part of the solution by addressing both GHG mitigation and climate risk adaption (Alberti and Susskind, 1996; Chavez and Ramaswami, 2011). Currently, cities cover less than 1% of the Earth's surface but host 50% of the world population (Sovacool and Brown, 2010; UN-HABITAT, 2011), consume at least 75% of the world's energy, and discharge an even larger portion of anthropogenic GHG emissions (Grimm and Faeth, 2008; Satterthwaite, 2008). China's urban population has sharply increased from less than 200 million to more than 700 million in the past three decades. More than half of China's population is currently living in urban areas (National Bureau of Statistics of China, 2013). Large-scale urbanization in China has led to unprecedented urban expansion and infrastructure development, which requires significant product, energy materials and other resource input and results in huge waste streams and emissions such as $CO_2$ emissions (Feng and Hubacek, 2016). Consequently, the city-level GHG emissions accounting, providing insight into the nature of current emissions, is the basis for

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decision-makers to implement appropriate abatement policies.

The World Resources Institute and the World Business Council for Sustainable Development (WRI/WBCSD) defined the emission boundary of a city using three Scopes, describing in-boundary and trans-boundary GHG emissions (WBCSD and WRI, 2009). Scope 1 includes all direct GHG emissions resulting from in-boundary fossil fuel combustion (*e.g.*, natural gas, fuel oil, gasoline, or diesel), non-energy industrial processes, and waste. Indirect GHG emissions from imported electricity used within the community are included in Scope 2. Scope 3 includes all other indirect GHG emissions linked to the supply chain life cycle of materials and energy carriers used within the boundary but that are produced outside. There are a broad range of research focused on urban GHG accounting (Glaeser and Kahn, 2010; Hillman and Ramaswami, 2010; Phdungsilp, 2010; Sovacool and Brown, 2010; Zhou et al., 2010; Liu et al., 2012; Makido et al., 2012; Yu et al., 2012), which provides important insights for urban decision makers to facilitate practical GHG emission abatement. However, these studies on urban GHG emissions only consider 'Scope 1'and 'Scope 2', which only describe a partial accounting of in-boundary energy use and associated GHG emissions (Brown et al., 2009; Dhakal, 2009; Kennedy et al., 2009; Parshalla et al., 2009; Bi et al., 2011), and they ignore the total embodied or life cycle emissions which ultimately result from urban consumption, leading to an emission leakage (Li et al., 2013; Niels, 2010). Thus, only accounting for GHG emissions strictly within a city's boundaries can provide an incorrect and even misleading picture. Indeed, in some cases it may even create unintended incentives to simply move GHG emissions outside the boundary (Ramaswami et al., 2008, 2012; Hillman and Ramaswami, 2010; Peters, 2010; Chavez and Ramaswami, 2011). Dhakal (2010) showed that the total emissions for which cities are held responsible will normally increase if embodied emissions are assigned to the final consumer. This is most likely to be true for post-industrial cities in developed countries with lower manufacturing output and a larger services sector.

Both GPC (Global Protocol for Community-Scale Greenhouse Gas Emission Inventories) and PAS 2070 recommended the inclusion of Scope 3 or supply-chain emissions from certain products or services only (WRI and ICLEI, 2014; BSI, 2013). These "are either of exceptional importance to life in cities (e.g. water), or are known to make a material contribution to the GHG emissions of cities …" (BSI, 2013). Explicitly mentioned in the PAS 2070 are water provision, food and drink, and construction materials (p. 11). In this study, we aim at only accounting the embodied GHG from Scope 3 in city scale and exploring the structural analysis in the upstream supply chain from Scope 3 based on the industry transactions in input-output table. Currently, there are many studies on the embodied GHG emissions at a city scale: The city of Denver is the first known city to have included trans-boundary GHG emissions (including production of cement and food for in-boundary use) in their urban GHG emissions estimates, described by Ramaswami et al. (2008). Since then, life cycle upstream GHG emissions from critical urban materials used within cities have been increasingly considered in accounting efforts (Ngo and Pataki, 2008; Kennedy et al., 2009). Hillman and Ramaswami (2010) developed a demand-centered, hybrid life cycle-based methodology used across eight U.S. cities to elucidate that key urban materials in Scope 3 contribute to 18% of all GHG emissions. Schulz (2010) estimated the state city Singapore's embodied GHG emissions and found that the indirect GHG emissions embodied in trade exceeded direct emissions. Chen et al. (2013) simulated Beijing's economic network and calculated the embodied $CO_2$ emissions by three scale input-output modeling. Guo et al. (2012a) investigated the embodied $CO_2$ emissions induced by the fossil fuel combustion of Beijing economy in 2007. Those research results have proved the importance of embodied GHG emissions in the city economy system. Yet few studies have explored the inter distribution structure for the embodied GHG emissions of the whole supply chain from a life cycle perspective. Identifying the main embodied GHG emissions that dominate the emissions in upstream supply chains can help focus attention on the largest emitters and offer insights into where climate mitigation efforts should be directed.

In fact, Input-Output (IO) analysis has been adopted to estimate the embodied energy, GHG emissions, pollutants and land appropriation associated with products sold in national or international markets (Yan and Yang, 2010; Ackerman et al., 2007; İpek Tunç et al., 2007; McGregor et al., 2008; Peters and Hertwich, 2008; Chen and Chen, 2011b; Guo and Chen, 2013; Liu et al., 2014; Vetőné Mózner, 2013). With this method, Chen and his group have carried out a range of studies on the embodied GHG emissions and natural resources, such as energy sources, pollutants, exergy, solar and cosmic emergy, at global (Chen and Chen, 2011a,b; Chen et al., 2010a), national (Chen and Chen, 2010; Chen et al., 2010b,c; Chen and Zhang, 2010; Zhang and Chen, 2010; Zhang and Chen, 2014) and city (Chen et al., 2013; Guo et al., 2012a,b; Li et al., 2014; Li et al., 2013; Zhou et al., 2010) scale. Research has shown that estimating the full extent of Scope 3 (supply chain) emissions is only possible by employing a top-down method such as IO analysis (Wiedmann et al., 2015; Hillman and Ramaswami, 2010; Lin et al., 2013; Chen and Chen, 2011a; Zhou et al., 2010). Although a traditional Economic Input-Output (EIO) approach can calculate the embodied GHG emissions induced by the final demand of one sector, the GHG emissions distribution among the sectors in the production chain cannot be accounted for (Leontief, 1970; Miller and Blair, 1984). In EIO-LCA model, the emission coefficient matric is improved into a diagonal matric from a row in traditional IO. Therefore, the Economic Input-Output Life-Cycle Analysis (EIO-LCA) model was introduced to explore the embodied GHG distribution among the upstream supply chain in our study. Or rather, EIO-LCA model is used to evaluate the GHG emissions of typical products from life cycle perspective in the economy system (Lave et al., 2002). EIO-LCA combines life cycle assessment and the economic input-output method, which was theorized and developed by the economist Wassily Leontief in the 1970s (Leontief, 1936, 1970). The EIO-LCA model is applied to estimate the materials and energy resources required for, and the environmental emissions resulting from, activities in an economy (Hendrickson and Horvath, 1998; Bjorn et al., 2005; Norman et al., 2007; Blackhurst et al., 2010). It allows the determination of the overall material input (direct and indirect) required to produce a given quantity of products and has the advantages of tracing out the full direct and indirect implications of a material, process, or product (Lave, 1995).

Xiamen was identified as a low carbon pilot city as part of the National Development Reform Commission's (NDRC's) low carbon pilot project. As a typical coastal city in China, Xiamen's economy relies heavily on the import and there is a severe water-shortage and very limited resources and energy. As such, many key urban materials consumed by local residents are imported from other cities, such as food, water, construction materials, and fossil fuels, which leads to carbon emission leakage of the city by transferring the carbon emission responsibilities to importing cities. To overcome the limitations of previous studies, this paper aimed to help solve the emission leakage problem induced by the embodied energy of key urban materials and therefore help guide appropriate low-carbon policies by achieving the following goals: 1) constructing an EIO-LCA model and developing a sector GHG emissions matrix based on the Fujian Province IO table from 2007, 2) exploring the total embodied GHG emissions of critical urban materials used in Xiamen from the life cycle perspective, based on the

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