Carbon Footprints

Perspective

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Experiences and challenges in the development of carbon footprinting in megacities - taking Shanghai as an example

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Abstract
Using Shanghai as a case study, this article discusses the practices and methods of carbon footprint measurement in megacities, analyzing its evolution and significance in supporting densely populated megacities worldwide to achieve carbon neutrality. The study emphasizes thorough greenhouse gas emission accounting in high-density urban areas characterized by intensive economic activity and population concentration. Globally, nations, including China, are enhancing carbon management strategies by introducing new standards under the regulatory guidance of organizations such as the National Development and Reform Commission. However, notable obstacles remain, including the lack of a centralized database, insufficient product-specific approaches to managing emissions, and the absence of standardized certification systems for labeling products based on their environmental impact. To address these challenges, Shanghai is promoting a low-carbon transition across industries and encouraging the city's green development by fostering a collaborative industrial framework. This includes the CN100 program, which mobilizes leading companies to reduce the carbon footprint of supply chains and industrial processes.

Keywords: Carbon neutrality, megacities, carbon footprint

In recent years, to accelerate the progress toward the global carbon neutrality goal, countries have initiated research and development in new energy technologies, industrial energy-saving upgrades, low-carbon

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building renovations, and sustainable urban lifestyles, aiming to establish a new green and low-carbon approach to development[1]. Among them, measuring the carbon footprint of products is an important initiative for assessing and documenting the greenhouse gas emissions of enterprises, compiling a regional greenhouse gas emission inventory, and constructing a green and low-carbon supply chain system[2]. In real life, it holds greater value to carry out carbon footprint measurements in megacities with intensive economic and population activities[3].

Since the mid-20th century, observed climate change has been driven primarily by human activities. Relevant studies have shown that significant expansion of urban land has led to substantial reductions in vegetation cover and in the carbon-neutralizing capacity of forests, and that the burning of fossil fuels has increased atmospheric levels of heat-trapping greenhouse gases (GHGs), thereby accelerating carbon emissions, surface temperature increases, and global warming. Human-induced emissions of GHGs have contributed to an approximate temperature increase of 1.1 degrees Celsius since 1850-1900. The global average temperature in 2023 is the highest on record, surpassing the average surface temperature of the late 19th century. According to NASA, the average global surface temperature in 2023 is about 1.36 degrees Celsius above the pre-industrial average of the late 1800s. Global warming has already led to an increase in extreme weather events, the melting of glaciers and ice caps, rising sea levels, and ocean acidification. From 2000 to 2004, global glaciers lost an average of 227 billion tons of ice per year, and between 2015 and 2019, this loss increased to 298 billion tons per year. Glacial melting is responsible for 21% of the observed sea level rise during this period. As urbanization progresses, the development of commercial districts, factories, and other mixed-use areas generates significant carbon emissions and releases large amounts of waste heat into the atmosphere, contributing to the greenhouse effect and urban heat island effect. The rapidly accelerating urbanization process has also prompted many cities, previously focused on horizontal development, to adopt models that combine both horizontal and vertical expansion. Excessive urbanization, characterized by high building volume ratios, can hinder heat dissipation and exacerbate the urban heat island effect. Megacities, with their dense population, high levels of economic activity, and substantial demand for global resources, have far-reaching environmental impacts. These cities not only produce significant direct carbon emissions locally, but also generate indirect emissions globally through their consumption patterns.

Product Carbon Footprint is a specific application of product environmental footprinting in the context of climate change mitigation, based on the life cycle concept. It aims to minimize and reduce the potential transfer of greenhouse gases throughout the entire life cycle of a product. This is achieved by identifying the carbon impacts at each stage, from raw material acquisition, energy and material production, product manufacturing and use, to the product's end-of-life and final disposal[4]. As the urgency of climate governance grows, measuring the carbon footprint of products has become a significant factor in influencing green consumption and trade, as well as an important tool for advancing climate governance. To enhance carbon footprint measurement and management, the National Development and Reform Commission (NDRC) issued the "Opinions on Accelerating the Establishment of Product Carbon Footprint Management System" in November 2023. Among other measures, this document outlines comprehensive accounting rules and standards for key products, builds a carbon footprint database for key industries, and implements a carbon labeling certification system.

The Chinese government has initiated product carbon footprinting from multiple angles, including data collection, model construction, policy guidance, and management organization. Firstly, this initiative provides a data basis for key enterprises to efficiently promote energy conservation and carbon reduction[5]. By clarifying the carbon footprints of key products in industries such as iron and steel, chemicals, textiles, and electronics, the government aims to identify high-carbon-emission points in industrial production and distribution. These insights allow businesses to benchmark against both domestic and international low-carbon standards, driving technological process reforms, strengthening energy-saving and carbon-reducing management, and enhancing the overall greening transformation of upstream and downstream enterprises. China's research team has developed the Carbon Emission Factors Database (CEADs), which is a world-leading database that integrates both domestic and international standard databases, commercialized databases, enterprise research data, and literature. This database focuses on accumulating China's localized data, offering a unified, full-caliber, and verifiable carbon accounting platform for national, regional, and urban levels. Furthermore, as part of the Chinese government's plan, a national greenhouse gas emission factor database is expected to be largely completed by 2025 and will be regularly updated. This database will provide benchmark data for localities and enterprises, supporting more consistent and comparable carbon accounting for businesses and products. Deloitte China has developed the EEIO Carbon Footprint Factor Database, based on economic value, which covers the three major sectors of the national economy. This database is subdivided into 153 sub-industries and provides corresponding emission factors for all industries and products. It is based on official data released by the National Bureau of Statistics and is characterized by its reliability, broad coverage of all industrial sectors, in-depth analytical functions, and diverse application scenarios. Secondly, the Chinese government is adapting to new international trade rules. In response to global carbon reduction trends, particularly in Europe and the United States, China has introduced a series of regulations and policies related to product carbon footprints[6]. These measures aim to enhance the low-carbon competitiveness of domestic enterprises. The EU's Carbon Border Adjustment Mechanism (CBAM) restricts the import of carbon-intensive products to prevent these goods from undermining the EU's greenhouse gas emission reduction efforts. The first phase of CBAM applies to imports of iron, steel, cement, aluminum, fertilizers, electricity, and hydrogen, as well as indirect emissions under certain conditions. This mechanism sets higher requirements for the carbon footprint accounting of relevant products in China. China has also established carbon emissions trading markets in various regions, using market mechanisms to control greenhouse gas emissions and promote corporate emissions reductions. Additionally, the country has implemented the Interim Regulations on the Administration of Carbon Emission Trading to provide a regulatory framework for the carbon market, clarifying key aspects of carbon emissions trading and related activities, as well as the legal responsibilities of all stakeholders. Lastly, China is focused on cultivating green and low-carbon industrial clusters. As the global push for carbon neutrality intensifies, leading enterprises in various industries are strengthening their own emissions reductions. They are also developing industry-specific carbon footprint accounting rules, implementing green and low-carbon procurement strategies across supply chains, and establishing low-carbon industrial clusters. These clusters are driven by leading enterprises, spearheading the transformation to low-carbon practices[7]. Companies are increasingly releasing specialized ESG reports to highlight their commitment to corporate social responsibility and improve their brand image. More products are now obtaining low-carbon certifications to meet market demand and consumer preference for environmentally friendly products.

Shanghai, as an outward-oriented city benchmarked against international metropolises such as New York, London, Paris, and Tokyo, is an important urban sample in China. As the window to the Chinese economy, Shanghai is a key model for China's low-carbon economic transformation with its open economy, robust financial services, advanced manufacturing, and vibrant international trade. With a population exceeding 25 million, Shanghai serves as a key economic and shipping hub. In 2023, the city's GDP reached 4.72 trillion yuan, the total financial market transactions surpassed 330 trillion yuan, the container throughput of the Port of Shanghai hit 49.158 million TEUs, and the annual electricity consumption totaled 184.9 billion kilowatt-hours. The city boasts well-established manufacturing industries, including iron and steel, chemicals, and automobile manufacturing. Simultaneously, it is accelerating the growth of strategic emerging industries such as artificial intelligence and biomedicine while laying the groundwork for future industries like brain-inspired intelligence, 6G networks, and quantum technology[8]. The intelligent evolution of these industries, combined with the continuous improvement of residents' quality of life, is expected to exert considerable pressure on energy consumption and carbon emissions. Maintaining the smooth operation of a megacity while actively and steadily transforming its development model presents a formidable challenge for urban planners and managers.

To promote the development of a green and low-carbon supply chain, Shanghai became the first city in China to introduce the “Shanghai Municipality Accelerates the Establishment of Product Carbon Footprint Management System to Create Green and Low-Carbon Supply Chain Action Program”. This program specifies key initiatives, such as building a product carbon footprint management system, expanding the application scenarios of product carbon footprints, and promoting the green and low-carbon transformation of critical supply chain processes. Currently, efforts are underway to develop product carbon footprint accounting rules aligned with international standards, create a representative product carbon footprint database for key industries, launch pilot programs for product carbon footprint labeling and certification, enhance green financial service platforms, and provide comprehensive services and support for green and low-carbon supply chains. In addition, Shanghai actively supports key industry leaders in forming the Green and Low Carbon Supply Chains Alliance (CN100). This alliance, comprising 31 prominent companies such as Baowu, China Motor Bus, China National Energy Corporation, Siemens, Tesla, BASF, Vision Energy, Ningde Times, and Shanghai Electric, aims to collaboratively improve supplier management and promote the green and low-carbon transformation of supply chains. For example, in the iron and steel sector, Baowu Group drives sustainability across its network of 280,000 upstream and downstream enterprises. At its Shanghai base, Baowu is improving energy efficiency in key processes to meet benchmark standards, utilizing residual heat and energy, and upgrading energy-saving and carbon-reduction measures in production processes and energy-intensive equipment. The company aims to achieve annual energy savings of 1%. Baosteel is working toward meeting the national requirement of a 10% scrap steel recycling rate while gradually transitioning to a short-process electric furnace steelmaking system, retaining some long-process lines to ensure supply during the transition. In the automotive field, SAIC Group and Tesla directly influence more than 1,100 parts and component suppliers. In the textile industry, Dongfang International plays a leading role, driving sustainability efforts across raw materials, intermediate processing and related stages. The company is strengthening the carbon footprint background database and advancing research and development for accounting models specific to basic raw materials. Additionally, it is developing regional electricity carbon footprint accounting models. Key measures include enabling carbon footprint self-declaration or third-party evaluation and certification, introducing carbon footprint labels on product packaging or manuals, and creating a centralized platform for product carbon footprint disclosure to enhance the transparency of carbon footprint information. Furthermore, Dongfang International is establishing a life cycle unit process database that aligns with both China's specific conditions and international standards. The Shanghai carbon market, officially launched in 2013, now includes 378 enterprises across 28 industries such as iron and steel, petrochemicals, chemicals, automobiles, aviation, and water transportation. As of June 2024, the Shanghai carbon market spot transactions (including auctions) had reached 249 million tons, with a total turnover of 4.609 billion yuan. In 2022, the total energy consumption of Shanghai’s transportation sector was approximately 19.02 million tons of standard coal, reflecting a year-on-year reduction of about 19%. To address pollution from ships, Shanghai has issued the “Regulations on Prevention and Control of Pollution from Ships in Shanghai”, achieving a 97.78% disposal rate for oil sewage, domestic garbage, and wastewater from inland waters in 2022. The operation of the Shanghai carbon market has demonstrated significant progress in emission reduction by actively engaging government entities, enterprises, industry organizations, and technical service institutions. It has supported the development and expansion of professional institutions and social organizations involved in carbon footprint monitoring, accounting, evaluation, verification, certification, information disclosure, and public welfare supervision. Additionally, it has enhanced the capacity and expertise of these professional and technical service institutions to conduct international business.

However, there are still many problems in promoting carbon footprinting in metropolitan cities, foremost among which is the lack of a unified and up-to-date product carbon footprint database[9]. In China, the majority of product carbon footprint accounting relies on international commercial software, such as Germany's GaBi and the Netherlands's SimaPro. However, these tools lack unified evaluation standards, comprehensive factor databases, and consistent calculation methods[10]. A critical issue is the significant gap in domestic measurement foundations for carbon emission factors, which are essential for accurate carbon footprint assessments. For instance, China's electricity emission factors are divided into five distinct categories, with data updates lagging behind the actual needs. As of 2017, the National Development and Reform Commission released the 2015 national grid average emission factor, which remained in use until the end of 2021. Similarly, the average emission factors for regional power grids have only been publicized for 2010 to 2012, while provincial power grid data are only available for the years 2010, 2012, and 2016. Given the increasing shift toward cleaner energy sources in China's power supply, the lag in updating these factors results in carbon emission accounting that deviates from reality. Consequently, the measured carbon emissions of domestic products tend to be overestimated, which undermines their international competitiveness. The lack of a unified database further exacerbates this issue. Discrepancies in data from different sources lead to inaccurate carbon footprint measurements, complicating the precise accounting of carbon emissions. Moreover, differing calculation methods and standards across regions and enterprises hinder the comparability and verification of results. At an international level, the absence of standardized carbon footprint data poses a barrier to international cooperation and carbon trading efforts. Second, product-level carbon management lags behind organizational-level carbon management. To promote carbon emission reduction, Shanghai launched a pilot carbon trading program in 2012 and established a national carbon trading platform in 2021. Procedures, standards, and management norms for carbon emission trading have been gradually constructed. However, the definition of product carbon footprint remains unclear, and no leading department has been designated to oversee this. Additionally, the carbon footprints of industrial products, construction products, and everyday consumption products span various industries and involve multiple enterprises across both upstream and downstream sectors. The complexity of data collection and accounting is further exacerbated by differences in industry, scale, and geographic location. As a result, the key market participants have limited willingness to actively engage in the accounting of product carbon footprints or disclose carbon emission information. Third, a unified product carbon labeling certification system has not yet been established. As China's carbon labeling system is still in its early stages, there are various domestic standards, some of which are of low quality. These labels can be divided into three categories: the first is those developed by government departments or public non-profit organizations; the second includes labels certified by third-party independent organizations; and the third consists of labels added by enterprises themselves. The constant influx of these different types of carbon labels into the market has led to consumer confusion and, in some countries, skepticism, which could undermine trust in carbon labels. Furthermore, the cost of carbon footprint certification is high. A simple certification process can cost between 30,000 and 50,000 yuan per product, while a complex process can approach 100,000 yuan. Companies also need to undergo multiple certifications to meet the requirements of different export markets and customers. Even companies that are committed to carbon reduction efforts often struggle to convey accurate and reliable low-carbon information about their products to the market through a uniform, credible, and easily understood label. These issues highlight that current carbon footprint assessments focus primarily on individual enterprises. The lack of industry-specific parameter factors affects the accuracy of carbon footprint measurements for key carbon-emitting industries. This gap could hinder the achievement of carbon neutrality goals.

Shanghai, a city with a highly export-oriented economy, serves as a major hub for foreign trade. Although it benefits from a strong talent pool in the green and low-carbon industry and a high degree of internationalization in its enterprises, Shanghai faces significant natural constraints. With a permanent population of 24 million and a limited land area, the city has very little space for photovoltaic power generation or offshore wind power. As a result, the low-carbonization of energy is subject to these geographic limitations. Additionally, due to its high population density, Shanghai also grapples with the transportation and building emissions challenges common to "consumption-oriented" cities in developed countries. In this regard, it plays a crucial as both a "pioneer" and "pathfinder" in China's transition to a low-carbon economy. Moreover, its economy is characterized by a strong focus on international trade, financial services, and other global businesses, alongside a diversified industrial and service sector. To accomplish the goals of carbon peaking and carbon neutrality, it is essential to carry out comprehensive carbon footprint assessments.

In response to the EU Carbon Border Mediation Mechanism (CBAM), the Battery Bill, and other carbon-related regulations being implemented, there is an urgent need to explore a comprehensive product carbon footprint management system. This system would offer additional pathways for cities across the country to follow. Specifically, the approach should include the following: First, aligning with international standards and establishing a product carbon footprint accounting framework tailored to the city's major industrial products. This includes developing technical standards for carbon footprint accounting in sectors such as iron and steel, automobiles, electronic information products, and chemicals. It is also important to enhance cooperation with internationally recognized carbon footprint testing and certification organizations and to actively participate in the development of international carbon footprint-related standards and regulations[11]. Second, leveraging existing industry platforms to build a comprehensive public service platform for product carbon footprints. This would involve utilizing data platforms from universities, research institutions, and other organizations, in conjunction with the manufacturing processes of products of related industries, to develop an industry-wide carbon footprint measurement model that covers the entire product life cycle. At the same time, efforts should be made to strengthen the capacity of carbon footprint testing and certification organizations. Third, the government can improve relevant low-carbon and green procurement policies, establish a dedicated fund for product carbon footprint management, and prioritize supporting key export enterprises in Shanghai to obtain carbon footprint labeling certification. This would further promote the green and low-carbon transformation of enterprises[12].

The calculation of the carbon footprint not only maps the relationship between economic efficiency and various economic factors, but also represents a crucial class of production functions within economics. In this context, carbon productivity, as a key indicator, serves as an important metric for assessing the efficiency of economic activities and their input-output ratios, making it a vital marker of both overall and resource-use efficiency. Looking ahead to the long-term development of carbon footprint in products and services in Shanghai, the goal is to align with the regional integration and internationalization of foreign trade in the Yangtze River Delta (YRD) region. This includes, first, promoting the sharing of carbon footprint data within the YRD region. The "Single Window" for international trade gathers extensive cargo declaration and logistics data, which can be used to provide reliable information for enterprises to access low-carbon supply chain financial services. This, in turn, facilitates carbon footprint tracking and carbon emission measurement for enterprises in the YRD region. Second, actively engaging in low-carbon development is a significant draw for foreign trade and investment. For enterprises, adopting low-carbon practices is essential for gaining recognition in the international market and boosting competitiveness. For Shanghai, it is a crucial requirement for attracting foreign investment and optimizing its trade structure. By measuring the carbon footprints of key products, we can further stimulate foreign-related enterprises to enhance their low-carbon transformation efforts, facilitate their integration into the global industrial, supply, and value chains, and support Chinese enterprises and brands in expanding globally. In the current study, through exploration and analysis of problems Shanghai faces as a megacity in terms of carbon footprinting, we have found that the carbon footprint of megacities has a substantial impact on both the structure and overall consumption of urban energy, potentially reversing the adjustment in urban and industrial structures. Our future research, taking Shanghai as an example, will focus on understanding the overarching concept of megacity carbon footprints and the challenges involved, aiming to provide further valuable insights for other cities undergoing green transformation.

DECLARATION

Authors' contributions

Design research, article structure and theme selection: Liu H
Participation in data collection and literature analysis: Niu Y

Availability of data and materials

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Both authors have declared that there are no conflicts of interest.

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Not applicable.

Consent for publication

Not applicable.

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