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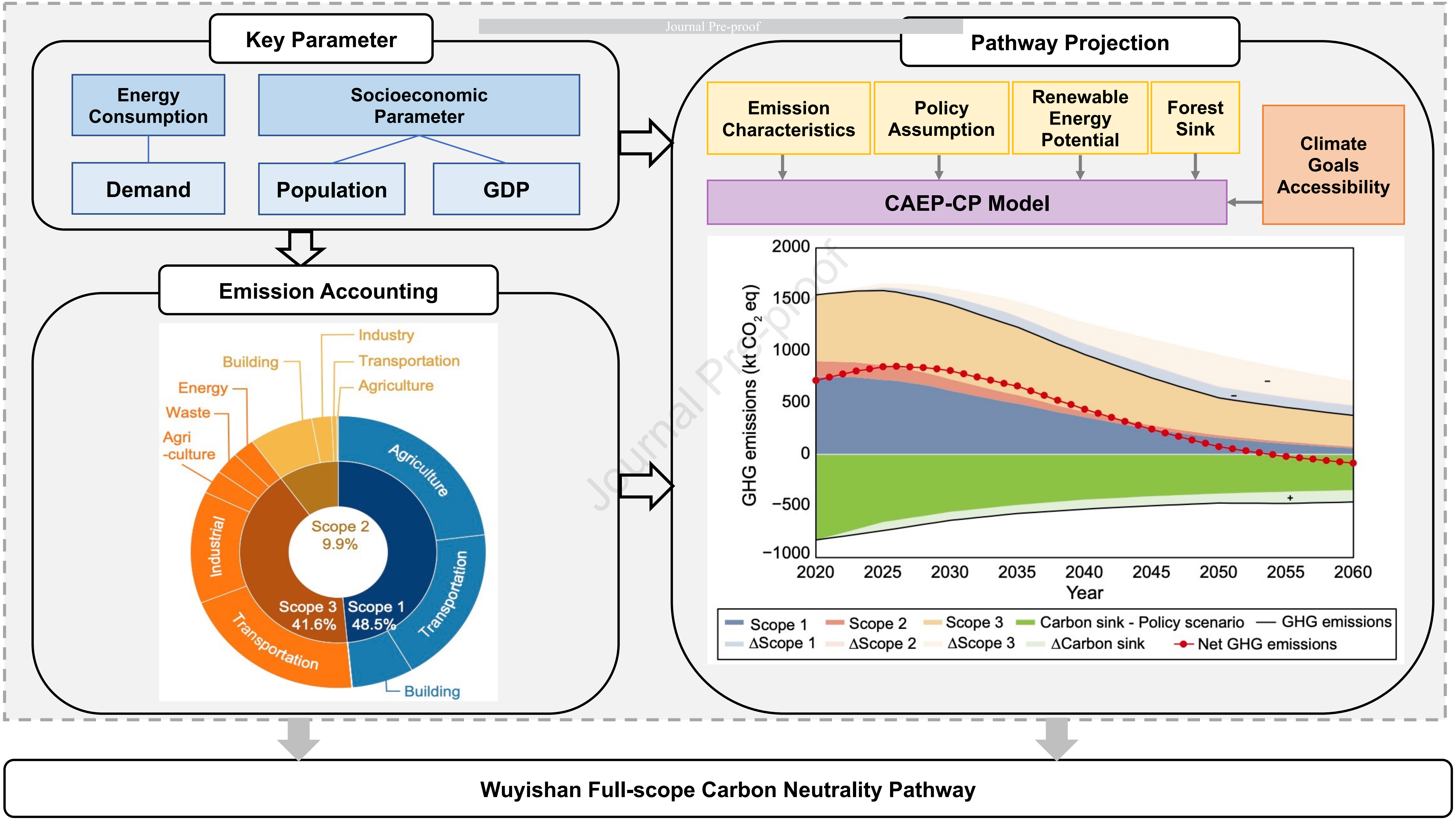
Key Parameter
Energy Consumption
Socioeconomic Parameter
Demand
Population
GDP
Emission Accounting
Industry
Building
Transportation
Energy
Agriculture
Waste
Agri -culture
Industrial
Agriculture
Scope 2 9.9%
Transportation
Scope 3 41.6%
Scope 1 48.5%
Transportation
Building
Pathway Projection
Emission Characteristics
Policy Assumption
Renewable Energy Potential
Forest Sink
Climate Goals Accessibility
CAEP-CP Model
GHG emissions (kt CO_2 eq)
Year
Scope 1
Scope 2
Scope 3
Carbon sink - Policy scenario
GHG emissions
ΔScope 1
ΔScope 2
ΔScope 3
ΔCarbon sink
Net GHG emissions
Wuyishan Full-scope Carbon Neutrality Pathway

Expanding Carbon Neutrality Strategies: Incorporating Out-of-Boundary Emissions in City-Level Frameworks

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ABSTRACT: Cities are increasingly vital in global carbon mitigation efforts, yet few have specifically tailored carbon neutrality pathways. Furthermore, out-of-boundary indirect greenhouse gas (GHG) emissions, aside from those related to electricity and heat imports, are often overlooked in existing pathways, despite their significance in comprehensive carbon mitigation strategies. Addressing this gap, here we introduce an integrated analysis framework focusing on both production and consumption-related GHG emissions. Applied to Wuyishan, a service-oriented city in Southern China, this framework provides a holistic view of a city's carbon neutrality pathway, from a full-scope GHG emission perspective. The findings reveal the equal importance of carbon reduction within and outside the city's boundaries, with out-of-boundary emissions accounting for 42% of Wuyishan's present total GHG emissions. This insight highlights the necessity of including these external factors in GHG accounting and mitigation strategy development. This framework serves as a practical tool for cities, particularly in developing countries, to craft effective carbon neutrality roadmaps that encompass the full spectrum of GHG emissions.

KEYWORDS: greenhouse gas emissions, full-scope emission accounting, carbon neutrality pathway, city-level

1. INTRODUCTION

The rapid acceleration of global climate warming, which has pushed temperatures 1.2 °C above 1850–1900 levels [1] exacerbated the urgency [2] of achieving the Paris Agreement targets, which is to keep warming to well below 2 °C and strive for a target of 1.5 °C [3]. As the world's largest energy consumer and carbon emitter [4], China announced ambitious targets to reach a carbon peak by 2030 and carbon neutrality by 2060 [5]. This commitment is expected to lower global warming projections by around 0.2–0.3 °C [6]. To implement national strategies, China established a "1+N" policy framework to decompose industrial and sub-national participation [7]. As sub-national actors, cities are the primary units in China's administrative system that formulate and implement measures [8], creating a promising opportunity to assist mitigation efforts [9]. On the other hand, pursuing carbon neutrality will help cities upgrade low-carbon technologies and cultivate a sustainably developed industrial chain. As China's urbanization advances, the net-zero emission transition of cities becomes a key to achieving carbon neutrality in the country.

Promoting and implementing cities' carbon neutrality commitments require a concrete and feasible roadmap to guide governments [10]. Over 10,000 cities worldwide have committed to climate mitigation, adaptation, and financing actions [11]. Furthermore, 235 cities have proposed carbon neutrality [12]. To regulate and monitor these commitments, several voluntary transnational climate initiatives have been established [13-15]. However, many of those initiatives only require reports on commitments [16], resulting in cities facing a dearth of technical support for devising localized strategies for emissions reduction and detailed abatement measures [17]. The heterogeneity of national, industrial, and urban responses to the environmental systems, for instance, the differentiated accessibility of offsetting carbon emissions [18], results in the inability to directly replicate global or national carbon abatement roadmaps on cities [16]. Therefore, city-specific carbon-neutral pathways need to be developed based on local characteristics of the economic structure, technological potential, and resource endowment (including renewable energy resources and carbon removal potentials) [19].

For policymakers, achieving a comprehensive understanding of emission inventory [20-24] and designing the city-level carbon emission pathway and control strategies [25] hold equal importance. Yet, full-scope carbon emissions still lack concerns when pursuing carbon-neutral cities [26]. According to the greenhouse gas (GHG) protocol, the sources and boundaries for city-level GHG emission inventory include scope 1, scope 2, and scope 3 emissions [27, 28] (Fig. 1) (detailed definitions in Supplementary Information). Scope 1 and scope 2 emissions are referred to as territorial or production-based GHG emissions and are usually reported and supervised by municipal authorities. Full-scope emissions cover territorial and out-of-boundary supply chain (scope 3) emissions, providing a more comprehensive picture of urban emissions for deep decarbonization. While cities' territorial emissions are well understood, the out-of-boundary emissions embodied in consumption are not comprehensively reported in the accounting inventories [16]. A few city-level studies [29-32] explored scope 3 emissions, yet they generally focused on the status quo, lacking a systematic approach for policy design to comprehensively and objectively assess future emission pathways. In addition, few international climate initiatives require municipalities to make commitments to address out-of-boundary emissions [16].

In the realm of urban environmental commitments, there is a conspicuous absence of explicit reduction pledges related to consumption or supply chain factors at the city level. Consequently, it has become increasingly important to establish comprehensive emission neutrality pathways tailored specifically to cities. Most cities import electricity, fuels, water, food, and construction materials for their basic supply systems [33]. Consequently, consumption-based emissions account for a considerable carbon footprint, especially for service-oriented cities. Policies that ignore consumption-based emissions may have the opposite effect from the original intentions [34]; affluent service-oriented cities may outsource emission-intensive industries to less developed regions, resulting in potential carbon leakage by cross-border product transfers. In contrast, policies that deal with full-scope emissions allow wealthier cities to subsidize emission reductions in nearby energy-producing towns and ensure a leading demonstration [35]. Therefore, including out-of-boundary emissions when evaluating a city's emissions and planning its reduction pathways is necessary.

To fill the gaps, we focus on the city-level full-scope emissions and establish an integrated methodology of GHG emission accounting and reduction pathway design. To be more detailed, we calculate a city's full-scope emissions based on sub-sectoral modules and life cycle assessments and propose future carbon neutrality pathways using the Chinese Academy of Environmental Planning Carbon Pathways (CAEP-CP) model [36]. We chose

Wuyishan city as our case study, which is located in Fujian province, China (see Fig. S1). Wuyishan city pledges to be a pilot city for carbon peak and carbon neutrality in China. It is also a typically service-orientated city. With the continuous industry structure transition, the proportion of the tertiary industry will further increase, suggesting the increasing importance of analyzing carbon mitigation strategy in service-orientated cities. This study's methodology provides a portable precedent for other cities, especially in developing countries, in planning a carbon neutrality roadmap.

2. MATERIAL AND METHODS

This study framework that projected the full-scope carbon neutrality pathway in Wuyishan city included three parts: emission accounting, pathway projection, and uncertainty analysis (see Supplementary Fig. S2).

2.1. Emission accounting

In this paper, the hybrid analysis [37-39] method was used to calculate full-scope GHG emissions for Wuyishan city. The hybrid analysis integrated the advantages of the top-down model (emission inventory method) and the bottom-up model (process analysis method), thereby unifying these two methods in the same analytical framework [40]. According to the Kyoto Protocol, GHGs mainly encompass six types, i.e., carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. The contribution of varying GHGs to global warming was reflected by global warming potential (GWP), which was finally expressed as carbon dioxide equivalent (CO_2eq).

Scope 1 emissions were determined following the Intergovernmental Panel on Climate Change (IPCC) guidelines (2006) [41], including fossil fuel combustion, industrial processes and product use, waste, agriculture, forestry, and other land uses (AFOLU). Several city departments were involved in fossil fuel combustion, including energy, industry, transportation, and building sectors, as classified according to the 2019 Refinement to the 2006 IPCC Guidelines for National GHG Inventory [42]. In this work, industrial process emissions were not included in scope 1 emission estimation as all industrial enterprises in Wuyishan city did not involve such processes. In addition, the treatment of solid waste, domestic sewage, and industrial wastewater in Wuyishan city, which was conducted outside the city, was incorporated into our scope 3 emission calculations. Agriculture emissions comprised the various facets of agricultural activities, including manure management, enteric fermentation, rice cultivation, and planting soils. The specific emission factors of agricultural activities were modified to fit Wuyishan's local situation. AFOLU represented changes in GHG emissions associated with agriculture, forestry, and other land use practices. Scope 2 emissions covered indirect GHG emissions from imported electricity. Owing to regional variations in technical levels and energy compositions, the grid emission factor (EF_{Grid}) preferentially relied on the local grid emission factor（Fujian provincial grid emission factor) [43]. Scope 3 emissions included GHG emissions from the consumption of products purchased from outside the jurisdiction, cross-border traffic, and waste disposal. Product consumption refers to the carbon emissions from upstream production, processing, and transportation of products outside the city boundaries (such as water, food, construction materials, fuel, and other consumer goods). As the main sources of food-related emissions were water, grains, and meat [44], the production far exceeded the consumption in Wuyishan city [45], and there were no food-related emissions in scope 3. Cross-border transportation refers to emissions from urban cross-border transportation, including long-distance vehicles (passenger and freight), railway, marine, and aviation. It was generally calculated using the miles traveled method [46], with GHG emissions equally divided between the departure and destination cities. Lastly, waste emissions encompassed GHG emissions stemming from the landfill and incineration treatment of municipal solid waste, domestic sewage treatment, and industrial wastewater treatment.

GHG emissions of Wuyishan city were calculated as follows：

$$GHG_{\mathrm{Total}} = GHG_{\mathrm{Scope1}} + GHG_{\mathrm{Scope2}} + GHG_{\mathrm{Scope3}} = \sum AD_{i,j} \times EF_{i,j} \qquad (1)$$

where $AD_{i,j}$ represented the activity level (product or energy) of consumption j in scope i; $EF_{i,j}$ represented the GHG emission factor for j; i represented scope 1, scope 2, or scope 3.

2.2. Emission pathway projection

In the analysis of the carbon neutral pathway in Wuyishan, the future development characteristics of Wuyishan city were considered to set basic socio-economic parameters. The basic parameters, including population, economy, urbanization, and electricity consumption, were projected according to government planning and existing literature (see Table 1).

This study, employing the CAEP-CP model, took a comprehensive approach by considering the socio-economic development and industrial development characteristics of Wuyishan city. Furthermore, it aligned with the ambitious target of reaching a carbon emission peak by 2030 in Fujian province, with Wuyishan city pioneering the province in achieving the peak and neutralization (Fig. S2). This study investigated future emission pathways of Wuyishan city under two scenarios with different levels of energy efficiency, activity, energy structure, and resource endowment of future industries or sectors (transportation, building, agriculture, industry, carbon sink, etc.). We first designed the policy scenario that considered measures including accelerating the development of renewable power, increasing the proportion of electric vehicles, and improving energy efficiency and electrification of buildings. Additionally, more aggressive measures were introduced under the low-carbon scenario, in which a faster development of renewable power, a higher proportion of electric vehicles, and more prominent energy-saving renovation and electrification of buildings were implemented. For scope 3 emissions, the policy scenario only focused on measures on the demand side, while the low-carbon scenario focused more on the consumption choices of residents, such as the government and residents prioritizing the purchase and use of low-carbon products. In terms of forest carbon sink, the policy scenario only considered the improvement of forest management. However, the low-carbon scenario also considered the optimal restructuring of forest structure.

To be detailed, the carbon emissions of each sector were determined by both the activity level and the emission factor. Through the assumptions of emission reduction measures, the activity level or emission factor of each sector could be predicted, thereby allowing for the calculation of future carbon emissions in each sector.

For the energy sector, according to the requirements of the National Energy Administration for the promotion of rooftop distributed photovoltaic projects in counties and districts [49], the promotion of rooftop photovoltaics would be the main emission reduction measure in Wuyishan city in the future. According to the potential calculation based on the rooftop photovoltaic area, the total photovoltaic capacity of Wuyishan city would be 337,600 kilowatts (Fig. S3b in the Supplemental Information). Correspondingly, in the low-carbon scenario, we assumed that by 2025, 2035, and 2060, the installed capacity of rooftop photovoltaics would reach 67,500 kilowatts, 242,000 kilowatts, and 337,600 kilowatts, respectively.

For the industry sector, since the tea industry was dominant in scope 1 and scope 2 emissions, we referred to the 14th Five-Year Plan for the tea industry in Wuyishan city [50]. We assumed that the tea yield would reach 24,000 tons, 27,000 tons, and 33,000 tons in 2025, 2035, and 2060, respectively, and we derived scope 1 and scope 2 energy consumption to calculate GHG emissions. For scope 3 emissions, it was assumed that the carbon emission factor per product unit would drop by 5% every five years by purchasing low-carbon products, and the demand for products was predicted based on population forecast.

For the transportation sector, fuel consumption, mileage, and emissions were projected by forecasting the proportion of local vehicles (including private cars, buses, and light-duty trucks) that were electric vehicles and the substitution rate of sustainable aviation fuel [51, 52]. In the low-carbon scenario, the proportion of electric vehicles in Wuyishan city would reach 20%, 60%, and 100% in 2025, 2035, and 2060, respectively. For scope 3 emissions, according to the tourism industry development plan [47], the number of tourists was predicted to reach 20 million, 33 million, and 65 million in 2025, 2035, and 2060, respectively. Sources of tourists and travel methods adopted the ratio of 2020, that was, the proportion of tourists in the province and tourists from outside the province was 6:4. For tourists from outside the province, 54%, 42%, and 4% of trips used high-speed rail, road, and air travel, respectively. For tourists in the province, 33%, 67%, and 0% of trips used high-speed rail, road, and air travel, respectively. The mileage was the average distance from Wuyishan city to the corresponding city or provincial capital city. The carbon emission factors per unit distance for high-speed rail, road, and air travel were referenced from the report of the Chinese Academy of Engineering [53]. By 2025, 2035, and 2060, these factors were projected to decrease by 25%, 50%, and 80%, respectively, compared to 2020. These reductions were used to calculate the cross-border transportation GHG emissions.

For the agriculture sector, based on the "Implementation Plan for Agricultural and Rural Emission Reduction and Carbon Sequestration" [54], which mentioned "optimizing paddy field irrigation management to reduce methane emissions from paddy fields", we assumed a decrease in methane emissions per unit of rice field yield of 25%, 70%, and 92% in 2025, 2035, and 2060, respectively, compared to 2020. The future changes in rice production and fertilizer usage were determined based on the forecast of the first industry gross domestic product (GDP) to project GHG emissions.

For the building sector, we referenced the requirements in the "Fujian Province's Special Plan for Urban and Rural Infrastructure Construction in the 14th Five-Year Plan" [55] and "Fujian Province Construction Industry 14th Five-Year Development Plan" [56]. It was assumed that the electrification rate of new buildings would be 100% in 2025 and the electrification rate of existing buildings would reach 95% in 2035 and 100% in 2045. In this way, we obtained energy consumption per unit building area. Together with future building area data according to population forecast, emissions of the construction sector can be calculated.

For the waste sector, we referenced the requirements in the "Accelerating the Establishment and Improvement of the Implementation Plan for a Green, Low-Carbon, and Circular Development Economic System in Fujian Province" [57] and the "Fujian Province's Long-term Special Plan for Waste-to-Energy Incineration (2019–2030)" [58]. We assumed that the carbon emission factor of a unit waste disposal would be reduced by 5% every five years, and the future waste generation was predicted by the population (per capita waste generation remains unchanged), to obtain the GHG emission of waste disposal.

2.3. Data Sources

Data used in this study were collected from three sources: yearbooks of statistics, literature and documents, and government departmental survey data. Details could refer to Supplementary Information Text. The emission factor of fossil energy combustion was collected from the IPCC Guidelines for National Greenhouse Gas Inventories (2006) [41], product emission factor data were from the China Products Carbon Footprint Factors Database [59], and grid emission factors were derived from the Ministry of Ecology and Environment [60]. The GWP values came from the IPCC Sixth Assessment Report [9].

2.4. Uncertainty analysis

The uncertainty of GHG emission accounting mainly came from applied activity data and emission factors. By referring to the IPCC guidelines [41], we adopted the methods of quantifying the uncertainty for activity level and emission factor to determine the probability distributions using the Monte Carlo simulation method. Equation (1) was used in the simulation process, and each parameter was simulated for 10,000 trials. The detailed process could be referred to in our previous study [61].

3. RESULTS

3.1. Full-scope GHG emissions in Wuyishan city

The full-scope GHG emissions in Wuyishan city were estimated as 1545.6 kt CO_2eq (90% confidence interval: 1386.6–1704.0 kt) in 2020, in which the non-CO_2 emissions of 300.1 kt CO_2eq (19.4%). Our results reveal that out-of-boundary (scope 3) emissions had nearly equal weight to territorial emissions (scopes 1 and 2). Specifically, scope 1, scope 2, and scope 3 emissions contributed 48.5% (749.1 kt CO_2eq), 9.9% (152.9 kt CO_2eq), and 41.6% (642.6 kt CO_2eq) of total GHG emissions, respectively; the carbon sink in Wuyishan city was estimated as high as 830.9 kt CO_2eq, which offset 54% of full-scope emissions. Figure 2 shows the detailed breakdown of emissions for each scope with the sectoral contribution.

The sectoral emission contribution showed significant differences between territorial and out-of-boundary emissions (detailed data refer to Table S1). For territorial emissions, agriculture (39.5%) and transportation (33.1%) sectors were the primary sources, followed by building (23.6%) and industry (3.8%) sectors. Notably, the emissions in the agricultural sector (357.0 kt CO_2eq) were generally contributed by non-CO_2 GHG (84.1%). With a high share of primary industries (5.7% higher than the national average), rice cultivation and livestock breeding were well developed, resulting in high CH_4 (172.3 kt CO_2eq) and N_2O emissions (116.0 kt CO_2eq). High emissions in the transportation sector (289.6 kt CO_2eq) were mainly due to private vehicle ownership and freight transportation, among which passenger vehicles, light freight, and motorcycles together contributed 84.7%. The building sector was the third largest source (212.8 kt CO_2eq), in which scope 1 emissions (104.7 kt CO_2eq) were about the same as scope 2 emissions (108.1 kt CO_2eq). The building sector consumed 76.5% of the city's total electricity consumption in 2020, making it the leading contributor to total scope 2 emissions.

The pattern of scope 3 emissions was related to the urban economy and industry structure [62], mainly from the use of upstream raw materials and downstream waste disposal. Among the 642.6 kt CO_2eq out-of-boundary emissions, transportation (49.0%) and industry (32.0%) stood out as the two major contributors. In 2020, Wuyishan city, owning one of the five national parks in the territory, welcomed a substantial influx of tourists, totaling 10.79 million visitors. This surge in tourism put more requirements on cross-border transportation, leading to 315.2 kt CO_2eq emissions. For the industry sector, Wuyishan city was featured in tea-making and bamboo (accounting for 55.5% of the industrial profit [45]). Due to the relatively homogeneous industrial enterprises within the city, most enterprises purchased raw materials from outside the city, such as packaging materials for tea-making, resulting in 114.3kt CO_2eq scope 3 emissions. Besides, construction materials, such as cement and steel, used in the building under construction contributed to 91.3 kt CO_2eq. Other sectors, including energy, agriculture, and waste, together account for 19.0% of scope 3 emissions due to urban energy and fuel import, agricultural fertilizer use, and municipal solid waste disposal.

In terms of carbon removal, the substantial increase in forest coverage to 80.5% in Wuyishan city in 2020 [45] yielded a carbon sink of 830.9 kt CO_2eq. This carbon sink was mainly brought by the forest biomass stock, accounting for 77.5% of the total carbon sink, followed by the soil organic matter stock (15.7%) and the forest dead organic matter stock (6.8%) (Fig. S3a).

3.2. Pathway toward carbon neutrality in Wuyishan city

To facilitate the comparison with existing studies, future GHG emission pathways constructed based on territorial (scopes 1 and 2) and full-scope (scopes 1, 2, and 3) perspectives in Wuyishan city are discussed separately. Generally, both net territorial and full-scope GHG emission (considering carbon removal) pathways show similar trends for policy and low-carbon scenarios, which gradually increase and peak before 2030, followed by a continuous decrease (Fig. 3).

Major mitigation measures under the policy scenario drive Wuyishan to achieve net zero territorial emissions around 2045, 15 years ahead of China's national target (2060). Specifically, net territorial GHG emissions are projected to peak around 2028 (259.7 kt CO_2eq) and then decrease markedly in the following decades, declining to −7.3 and −172.0 kt CO_2eq in 2045 and 2060, respectively (Fig. 3a, Table S2a). Such reductions underscore the effectiveness of GHG controls, particularly in the building and agriculture sectors. In the building sector, measures including promoting electrification and enhancing energy efficiency are projected to yield remarkable results, with sectoral GHG emission reductions of 85.0% in 2045 and a staggering 93.7% by 2060 (Table S2a). Similarly, in the agriculture sector, due to effective controls on rice cultivation and fertilizer use, non-CO_2 GHG emissions (i.e., CH_4 and N_2O) will fall to 143.2 kt CO_2eq in 2045 (52.3% lower relative to 2020 levels). As to carbon removal, given the relatively high forest coverage and mainly mature tree species, the carbon sink will inevitably decline to 406.2 kt CO_2eq in 2045, compared with 830.9 kt CO_2eq in 2020 (Table S2a). Despite the substantial reductions, forest carbon sinks would still play a critical role in offsetting territorial GHG emissions and achieving carbon neutrality.

When out-of-boundary emissions are considered, our results suggest that Wuyishan city cannot achieve full scope neutrality under the policy scenario before 2060 (Fig. 3b). Our estimates suggest that scope 3 emissions in Wuyishan will increase by 156.7 kt CO_2eq (24.4%) from 2020 to 2030, stabilize after 2030, and peak in 2035 (800.7 kt CO_2eq), then gradually decrease to 532.9 kt CO_2eq in 2060 (Table S2a). Particularly, due to the expected substantial increase in future tourism, the transportation sector would contribute to a 140.4 kt CO_2eq increase in GHG emissions in 2035 compared to 2020. However, we anticipate a downward trend after 2035, primarily due to nationwide initiatives, such as new vehicles and the promotion of sustainable aviation fuel acceleration, which will reduce emissions from residents traveling to Wuyishan from other regions. In contrast, with the development of the tea industry, emissions from the industrial sector would continue to increase (by 44.9 kt CO_2eq in 2060). This is largely attributed to the consumption of packaging materials. Considering all these factors, net full-scope emissions in Wuyishan would peak around 2029, but still, 46.8% (333.3 kt CO_2eq) of the 2020 emissions would be emitted in 2060, miles away from the net zero target (Fig. 3b).

Fortunately, additional consumption-based measures, enhanced forestry management, and renewable energy generation would help Wuyishan city achieve full-scope GHG neutrality before 2060. Under the low-carbon scenario, net full-scope emissions in Wuyishan will peak in 2026 at 851.5 kt CO_2eq (three years earlier than in the policy scenario with an 18.9% lower peak level) and reduce to −86.3 kt CO_2eq in 2060 (Figs. 3d and 4a, Table S2b).

For territorial emissions, our model shows that Wuyishan city is one of the highest resource origins in Fujian Province for annual solar radiation, which is conducive to promoting the development and construction of distributed photovoltaic (PV) power plants (Fig. S3b). With 163.9 megawatts of installed PV capacity in Wuyishan city expected by 2030, 52.5 kt CO_2eq is expected to be reduced per year, particularly in the building sector (Fig. 4b). Besides, enhanced stringency on measures, including vehicle electrification promotion (to 50% in the year 2030) and rice cultivation and fertilizer use controls, under low-carbon scenario are expected to achieve additional 38.4 and 34.1 kt CO_2eq GHG mitigation benefits in the transportation and agriculture sectors, respectively, in 2030 compared to the policy scenario (Fig. 4b).

Furthermore, altering the tree species structure can effectively decelerate the decline of carbon sink, ultimately resulting in increased carbon offsetting over the medium and long term. This strategy emphasizes optimizing the tree species structure, involving replacing mature trees with young saplings. The above measure will result in a short-term decrease in carbon sinks brought by forest biomass stock, with no significant downward advantage until 2030, which will be 6.0% lower than the policy scenario (−23.3 kt CO_2eq). However, in the long term, the carbon sink will stabilize after 2045 and reach 462.2 kt CO_2eq in 2060, 32.7% higher than the policy scenario (Fig. 4). Considering the mitigation measures for territorial emissions and carbon sink in the low-carbon scenario, net territorial emissions will neutralize around 2035 (about ten years earlier than in the policy scenario) and fall to −389.0 CO_2eq in 2060 (Fig. 3b).

For the considerable out-of-boundary emissions, a range of consumption-based measures is available, which could be supported by the government of Wuyishan city to achieve the full-scope neutrality goals (Fig. 4a). As Wuyishan city is still in continuous economic growth, the urbanization process will continue to advance; tourism is on the rise, and cross-border travel and transportation activities are becoming more frequent, leading to the growing demand for passenger and freight transport. Passenger growth is the main factor leading to the transportation scope 3 emission rise in a short period. But nationwide full electrification penetration would accomplish an emission reduction of 145.7 kt CO_2eq in 2060 (Table S2). On the other side, due to the increasing consumption of building and packaging materials from new construction, the industrial sector is the only sector increasing scope 3 emissions after 2030 and will become the largest emitter (62.0%) in scope 3 emissions by 2060. The low-carbon scenario encourages the use of lower-carbon upstream raw materials for enterprises (including construction materials, such as cement and steel, and other primary supplies) and the control of the entire industrial chain (such as logistics transportation and product packaging brought by tea companies). As a result of low-carbon upstream and downstream products and processes, the industrial sector would reduce an additional 62.7 kt CO_2eq emissions in 2060 compared to the policy scenario (Fig. 4b). Compared to the policy scenario, the stronger measures under the low-carbon scenario are expected to achieve the full-scope neutrality goal before 2060 in Wuyishan (Figs. 3d and 4).

4. CONCLUSIONS and DISCUSSIONS

Cities are fundamental administrative units in China to implement low-carbon policies. This paper establishes an integrated methodology to account for city-level full-scope emissions and assess the city's carbon peak and neutrality pathways with scope 3 emissions incorporated. The efficacy of this methodology is demonstrated through a case study of Wuyishan city, a typical service-orientated city in China. Notably, scope 3 emissions constitute a significant portion (42%) of the city's overall emissions, highlighting the importance of addressing both internal and external sources for carbon reduction. When it comes to full-scope GHG emissions, Wuyishan city is poised to achieve substantial mitigation by 2025, primarily through strategies such as PV installation, 100% industrial electrification, transitioning to electric vehicles, and waste incineration (Fig. 5). By 2035, the city is set to witness a rapid expansion of PV installed capacity to 242,000 kW, along with a 60% electric vehicle adoption rate. Additionally, an electrification rate of 95% is targeted for buildings. In the agriculture sector, efforts will focus on reducing chemical fertilizers and improving rice water irrigation management. All sectors must undergo further low-carbon transition to achieve full-scope carbon neutrality before 2060. The PV installed capacity needs to reach the maximum potential of 337,600 kW. Furthermore, the electric vehicle and electrification rates of new buildings should reach 100%. The industry sector should actively engage in mitigation efforts by purchasing low-carbon products, while the transportation sector should focus on reducing emissions by incorporating sustainable aviation fuels. Additionally, the waste sector needs a 35% reduction in waste proposal GHG intensity.

Our study attempts to investigate full-scope GHG accounting and carbon pathway planning for a city, which aligns with the current policy needs. The Chinese government is vigorously promoting the establishment of a unified and standardized carbon emission statistics and accounting system, which includes the extended measurement of implicit and consumption-based emissions [63]. Scope 3 emissions are traditionally neglected in the city’s GHG accounting, thereby underestimating urban emissions. It is insufficient to paint a complete picture of urban GHG emissions or support the development of a sustainable and low-carbon society. Our study finds that Wuyishan's scope 3 emissions are about the same as scope 1 and scope 2 emissions. For other cities, scope 3 emissions far exceed their territorial emissions [30]. As the carbon neutrality target advances, many cities are gradually transitioning towards tertiary industries and becoming service-oriented, which in turn increases the scope 3 emissions significantly [64]. Accounting scope 3 emissions makes it possible to fair compare the carbon neutrality targets of net producer cities and net consumer cities.

Noticeable territory emission reductions are brought about by measures in various fields, including vigorous electrification processes, energy efficiency improvement, and the development of renewable energy generation [25]. Common paths to becoming a carbon-neutral city include energy-efficient buildings, zero-carbon transportation, striving for 100% renewable energy, and reducing waste and water [65]. In our study, Wuyishan city attributes more than half of the emission reductions to electrification and renewable energy development. Offsetting residual emissions is also a significant way [66, 67]. Cities often have limited coverage and geological resources, which curtail their capacity to extract carbon from the atmosphere and safely sequester it on a land base. The role of other forms of carbon sequestration and offsetting becomes even more critical. Using nature-based solutions, such as restoration and management of native ecosystems, emerges as a viable avenue for creating a stable carbon sink while simultaneously promoting enhanced biodiversity — an imperative for sustainable development [68]. Consequently, this approach stands as a priority for offsetting choice. Additionally, in most cities, sectors like coal power, waste incineration, and cement industries play pivotal roles in adopting carbon capture technologies, although not applicable to Wuyishan city with the limited scales of these industries. By partnering with carbon sequestration sites, cities could invest in establishing carbon capture and sequestration chains to facilitate the deployment of large-scale removals, achieving win-win results.

However, those traditional reduction measures have little effect on scope 3 emissions. Emission reduction measures on the consumption side differ from those on the production side, focusing more on low-carbon consumption by public participation and emission control covering the industry chain. Mitigation measures, such as using upstream and downstream low-carbon products, raising public awareness, changing lifestyles, and enhancing low-carbon consumption, can bring considerable scope 3 emission reduction benefits. These benefits, often underestimated, should be actively promoted for the future. Carbon neutrality cannot be realized through the sole efforts of the management department in implementing regulatory policies; rather, it necessitates the active participation of all stakeholders, including the public sector, private sector, and citizens [69, 70]. New industrial and economic development opportunities are essential drivers of those stakeholders. Since scope 3 emissions occur outside the administrative boundaries of cities, broader coordination among higher levels of governance (e.g., regional, national, international) is required for net-zero consumption emissions, especially for systems that operate on a larger scale, such as the power grid [71]. Collaborative initiatives like the Covenant of Mayors can provide a valuable platform for small-sized cities to engage in collaboration across different levels of government [72, 73]. Consequently, a city's net-zero goal for full-scope GHG emission helps to extend its influence and drive the entire region or other cities nearby to improve reduction ambitions.

With Wuyishan city being one of the first pilot cities to reach the emission peak, the results of this study hold immense value, offering operational, replicable, and extensible experiences and practices, especially for service-orientated cities. This research strongly supports future research on implicit carbon emission accounting on the consumption side. However, there are still some limitations in this study. Data uncertainty and sensitivity significantly impact the carbon footprint estimation, especially for scope 3 emissions. Consequently, there is a compelling need for further reduction of such uncertainties. Moreover, the uncertainty inherent in the emission accounting process arises from factors like activity levels and emission factors, which cannot be overlooked [41]. To tackle this issue, we measure and control the uncertainty range by considering the vital parameters' probability distribution through a Monte Carlo approach. In the pathway projection, the policy scenario assumptions strongly depend on the city's future development plans, thus generating substantial uncertainty. In this study, local and provincial governments' macro plans are investigated in detail to keep the scenario construction firmly grounded in reality. Future research can continue to reduce the uncertainty in emissions accounting and future scenario construction and seek more robust transition pathways in the highly uncertain future. Although future scenarios are constructed and simulated based on macro policies rather than cost-based optimization analyses, the cost is a critical factor to be considered when developing mitigation strategies, which should be incorporated when implementing the measures. Even with these limitations, our results are expected to shed light on full-scope emission accounting and future pathway planning for cities in China and other countries.

Supporting Information

The following Supporting Information is available free of charge. Data for GHG emissions and emission pathways under different scenarios by scope and sector, and the geographical location figure of Wuyishan city.

CRediT authorship contribution statement

Zhe Zhang: Conceptualization, Methodology, Investigation, Data Curation, Visualization, Writing - Original Draft. **Mingyu Li:** Investigation, Data Curation, Writing - Original Draft. **Li Zhang:** Conceptualization, Investigation, Data Curation, Visualization, Writing - Original Draft, Supervision. **Yunfeng Zhou:** Data Curation. **Shuying Zhu:** Visualization. **Chen Lv:** Investigation. **Yixuan Zheng:** Investigation, Writing - Review & Editing, Supervision. **Bofeng Cai:** Conceptualization, Investigation, Supervision. **Jinnan Wang:** Conceptualization.

Declaration of competing interest

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

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Figure 1. The system boundary of GHG emission accounts for scopes 1, 2, and 3.

Figure 2. Breakdown of GHG emissions by scope and sector. **a**, Relative contribution by scopes and sectors. **b**, Estimated GHG emissions and sinks from different sources.

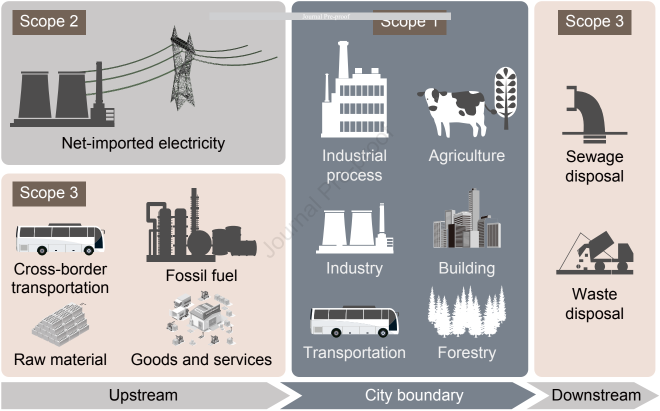
Figure 3. **a**, **c**, Net territorial GHG emissions covering scope 1, scope 2 emissions, and carbon sink of emission project under the policy (**a**) and low-carbon (**c**) scenarios. **b**, **d,** Net full-scope GHG emissions covering scope 1, scope 2, scope 3 emissions, and carbon sink of emission project under the policy (**b**) and low-carbon (**b**) scenarios. The black and grey full lines indicate the mean, and the shading shows the intervals of percentiles.

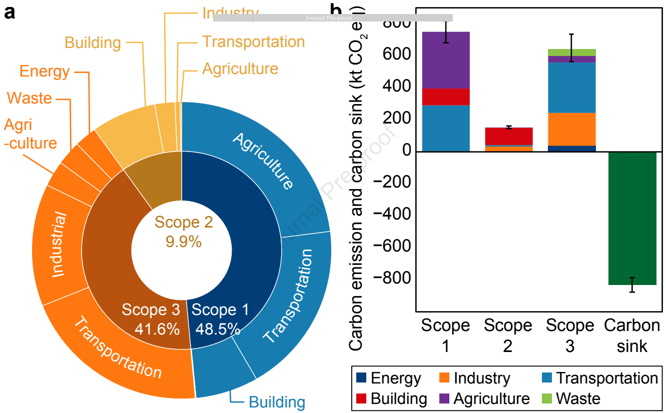
Figure 4. GHG emission pathway under low-carbon scenario and the difference between the policy and low-carbon scenarios by scope (**a**) and sector (**b**). The minus sign (−) represents the GHG emission reduction, and the plus sign (+) represents carbon sink enhancement under the low-carbon scenario compared to the policy scenario.

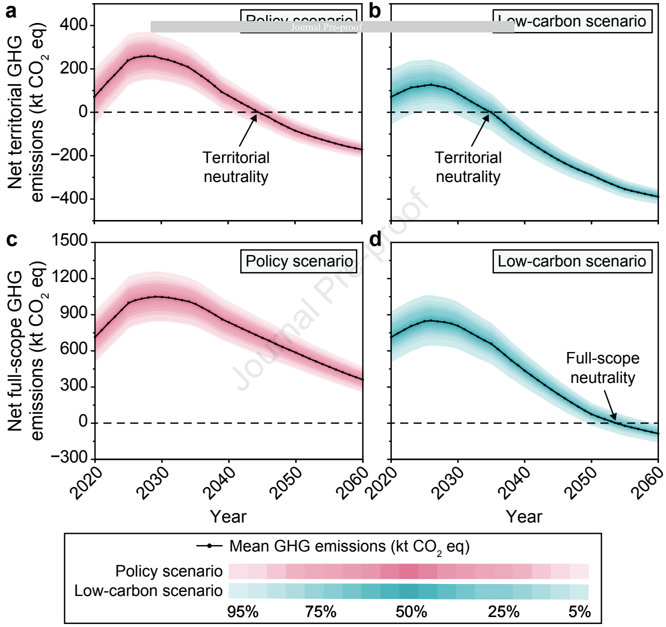
Figure 5. Carbon neutrality roadmap for Wuyishan city in the short, medium, and long term.

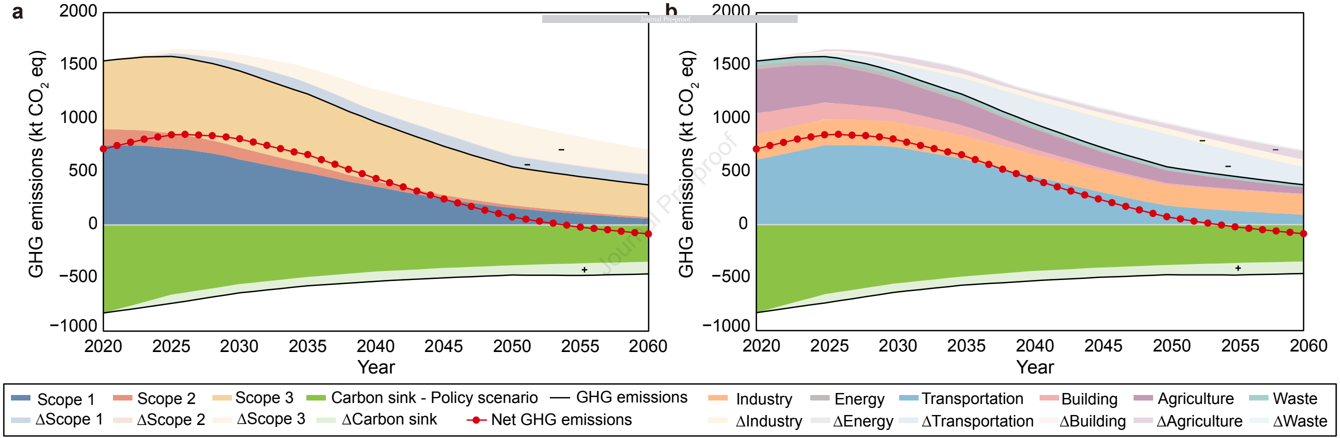
Table 1. Socio-economic key parameters for future scenario projection

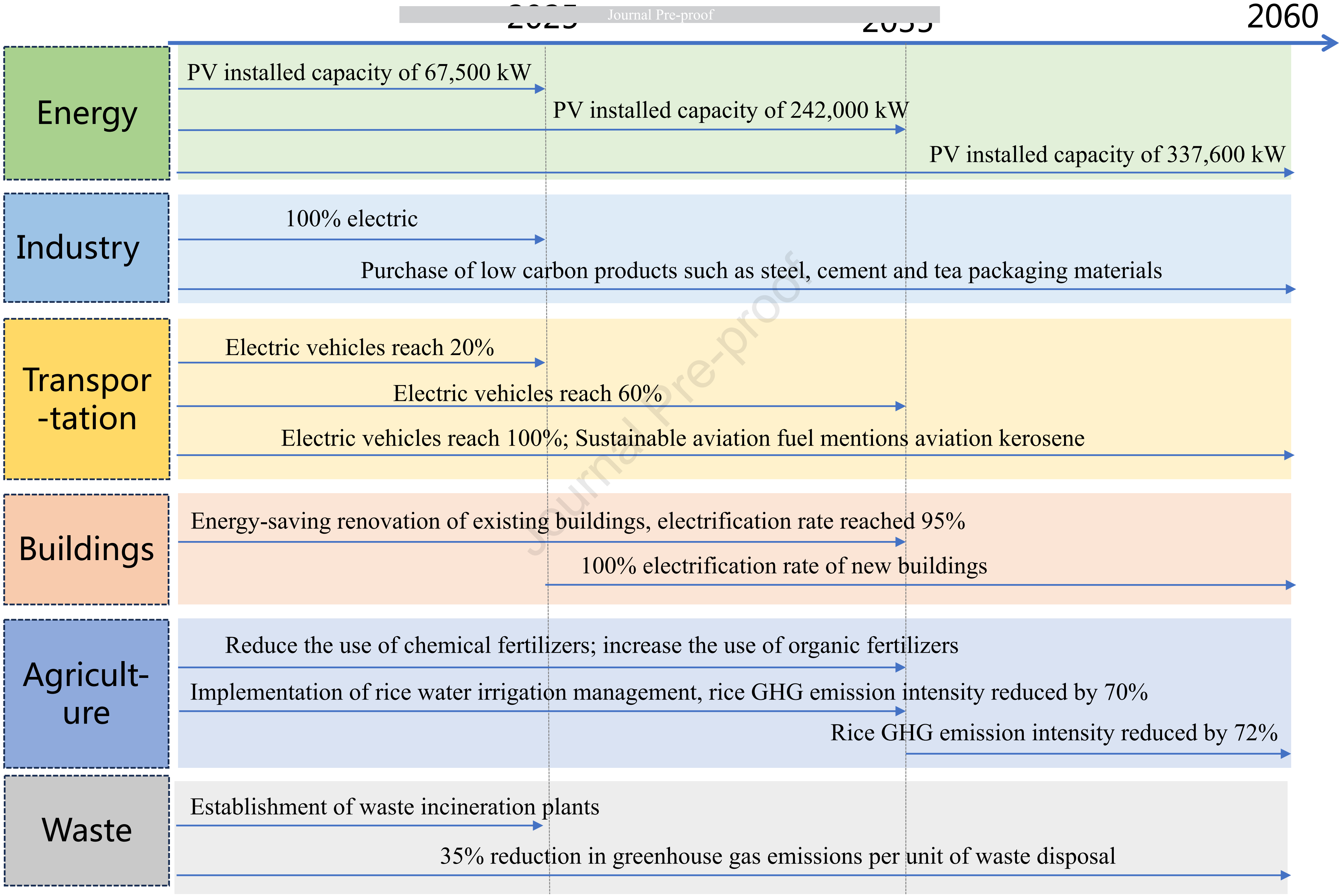
Parameters	Year							Reference
	2020	**2025**	**2030**	**2035**	**2040**	**2050**	**2060**	
Population (thousand)	256.7	258.6	259.6	258.7	256.7	249.0	239.5	[47]
GDP growth rate (%)	0.1	7	6.3	6.0	5.5	3.0	2.5	[47]
Urbanization rate (%)	60	65	70	74	77	80	82	[47]
Total social electricity consumption (GWh)	615	733	837	936	1033	1141	1200	[48]
Per capita electricity consumption (kWh)	2395	2836	3226	3618	4024	4582	5009	[48]


Scope 2
Net-imported electricity
Scope 1
Industrial process
Agriculture
Industry
Building
Transportation
Forestry
Scope 3
Sewage disposal
Waste disposal
Scope 3
Cross-border transportation
Fossil fuel
Raw material
Goods and services
Upstream
City boundary
Downstream


a
Scope 2
9.9%
Scope 3
41.6%
Scope 1
48.5%
Agriculture
Transportation
Building
Transportation
Industrial
Agri
-culture
Waste
Energy
Building
Industry
Transportation
Agriculture
b
Carbon emission and carbon sink (kt CO_2 eq)
800
600
400
200
0
-200
-400
-600
-800
Scope
1
Scope
2
Scope
3
Carbon
sink
Energy
Industry
Transportation
Building
Agriculture
Waste


a
b
Policy scenario
Low-carbon scenario
400
200
0
−200
−400
Net territorial GHG emissions (kt CO2 eq)
Territorial neutrality
Territorial neutrality
c
d
Policy scenario
Low-carbon scenario
1500
1200
900
600
300
0
−300
Net full-scope GHG emissions (kt CO2 eq)
Full-scope neutrality
2020
2030
2040
2050
2060
Year
Year
Mean GHG emissions (kt CO2 eq)
Policy scenario
Low-carbon scenario
95%
75%
50%
25%
5%


a
b
GHG emissions (kt CO_2 eq)
2000
1500
1000
500
0
−500
−1000
2020
2025
2030
2035
2040
2045
2050
2055
2060
Year
Scope 1
Scope 2
Scope 3
Carbon sink - Policy scenario
GHG emissions
ΔScope 1
ΔScope 2
ΔScope 3
ΔCarbon sink
Net GHG emissions
Industry
Energy
Transportation
Building
Agriculture
Waste
ΔIndustry
ΔEnergy
ΔTransportation
ΔBuilding
ΔAgriculture
ΔWaste


2060
Energy
PV installed capacity of 67,500 kW
PV installed capacity of 242,000 kW
PV installed capacity of 337,600 kW
Industry
100% electric
Purchase of low carbon products such as steel, cement and tea packaging materials
Transpor
-tation
Electric vehicles reach 20%
Electric vehicles reach 60%
Electric vehicles reach 100%; Sustainable aviation fuel mentions aviation kerosene
Buildings
Energy-saving renovation of existing buildings, electrification rate reached 95%
100% electrification rate of new buildings
Agricult-
ure
Reduce the use of chemical fertilizers; increase the use of organic fertilizers
Implementation of rice water irrigation management, rice GHG emission intensity reduced by 70%
Rice GHG emission intensity reduced by 72%
Waste
Establishment of waste incineration plants
35% reduction in greenhouse gas emissions per unit of waste disposal

Highlights：

- We propose a framework to investigate the city-level carbon neutrality pathway.
- A full-scope GHG emission perspective is considered.
- Carbon reductions within and outside city's boundaries are equally important.
- We suggest including out-of-boundary emissions in GHG accounting.

Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: