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Mitigating Building Carbon Emissions in High-density Cities: A Case Study of Hong Kong#

Xiaoyu Jin [1], Fu Xiao [2*]

1 Department of Building Environment and Energy Engineering, The Hong Kong Polytechnic University

2 Research Institute for Smart Energy, The Hong Kong Polytechnic University
(Corresponding Author: linda.xiao@polyu.edu.hk)

ABSTRACT

Countries worldwide are adopting carbon neutrality targets to address global warming challenges. High-density cities, viewed as a promising path toward a sustainable future, exhibit a unique emission pattern dominated by the building sector. Therefore, this study devised a lightweight and adaptable modeling framework to project long-term carbon emissions from building operations, outlining a decarbonization roadmap for the building sector in high-density cities, with Hong Kong as a case. Using multi-source data, the features of each district are considered, such as land planning, technology, and socioeconomic factors. The model was built and validated by data over ten years, with a mean percentage error of 5%. Results reveal that radical policies are necessary for carbon neutrality, necessitating simultaneous energy demand and supply decarbonization. Limited space for renewables in such cities makes demand-side technologies vital. Electrifying home appliances display significant carbon reduction potential. Among building types, public facilities, multi-functional commercial buildings, and private housing offer substantial reduction potential. The proposed carbon mitigation roadmap underscores the complex nature of achieving carbon neutrality in high-density cities, calling for comprehensive strategies from various sectors.

Keywords: high-density cities, carbon neutrality road-mapping, mitigation technologies, multi-source data fusion

1. INTRODUCTION

Achieving carbon neutrality by the mid-century has become a global priority, leading to decarbonization efforts in the building sector [1]. Country-level or city-level decarbonization roadmaps for the building sector under different future scenarios have been devised by researchers [2]. However, these roadmaps have either focused on only one type of building, such as residential buildings [3], or on the demand side of building energy consumption [2]. Achieving carbon neutrality requires collaborative stakeholder efforts on demand and supply sides, considering diverse aspects like power generation, appliances, and building properties [3].

High-density cities are sustainable due to compact urban forms, mitigating energy consumption and transportation-related carbon emissions [4]. However, limited space poses challenges for harnessing renewables. City-level carbon emission structures differ from rural areas, with buildings dominating emissions in cities like Taipei, Tokyo, and Hong Kong, as shown in Fig.1. As urbanization accelerates globally [5], governments of high-density cities must comprehensively understand the decarbonization potential of various carbon emitters within their building sectors [6]. Thus, a generalizable carbon-emission modeling framework is essential for decarbonization roadmaps and policies in high-density cities.

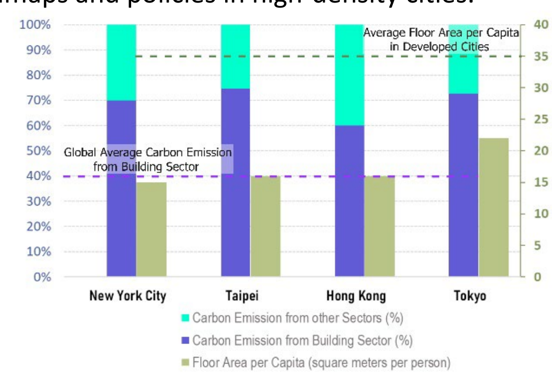

Fig. 1 The Building-dominated Carbon Emission Patterns in High-density Cities

Hong Kong is a typical high-density city. Despite its ambitious plan for carbon neutrality by 2050 [7], the potential for renewable energy sources remains limited, projected to contribute up to a maximum of 15% of

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electricity generation [7]. The government planned to have a fuel-centric decarbonization roadmap, where the supply side will account for 70% of the decarbonization contribution [8]. Given the building-dominant emission pattern on the demand side, the feasibility of this fuel-centric decarbonization plan is doubtful. As such, it becomes essential to quantify the decarbonization contributions from each sector and propose more targeted measures.

Therefore, this study establishes a modeling framework for long-term carbon emissions projection in high-density city building sectors, using Hong Kong as an example. The research endeavors to address the following key questions:

1. For the building sector in Hong Kong, how far is it between the carbon neutrality target and the reality?
2. For the decarbonization contributions from the demand and supply sides of the building sector, how can they be quantified and balanced properly?
3. What should be the focus of the policy roadmap towards carbon neutrality in Hong Kong?

2. METHODOLOGY

2.1 *A modeling framework for projecting building-sector*

This study develops a carbon-emission modeling framework for high-density city buildings, considering technological transformations on demand and supply sides, policy implementation, and public awareness. It quantifies carbon reduction potential on both sides to inform policymaking and transformation decisions. Analyzing power-generator operational strategies decouples and correlates demand and supply side contributions. As shown in Fig.2, the framework uses forward and backward modeling to compare government targets with reality, highlighting gaps for carbon neutrality. The bottom-up analysis identifies key contributors at the technological level (i.e., maximizing appliance efficiency) and the social level (i.e., optimizing education and government policies).

Fig. 2 illustrates the carbon emission modeling framework's architecture. Policies are categorized into demand-side and supply-side, quantified for input adjustments. Extensive policies and technical measures for demand-side carbon mitigation are examined, and potential energy reductions are quantified by comparing future technology-adopted estimated energy use with current baseline values, which are mainly derived from the Mandatory Energy Efficiency Labelling Scheme [9]. Policies on fuel-mix development guide the supply-side configuration.

The emission factor is determined by assessing demand and supply side statuses. The supply side follows local power companies' long-term plans for fuel mix, while the demand-side daily load profiles scale from government-provided electricity consumption profiles. Power plants operate based on the merit order principle, dispatching low marginal cost plants (e.g., solar, wind, and nuclear) first, followed by increasing marginal cost plants (e.g., coal, natural gas, and oil) until demand is met.

For end uses like cooking and hot water, emissions of gas and oil can be calculated directly by multiplying the constant emission factors with consumption estimates obtained from the Hong Kong Annual Digest of Statistics [10]. The model's output, total carbon emissions, results from summing electricity, gas, and oil emissions.

2.2 *Multi-source data fusion for modeling*

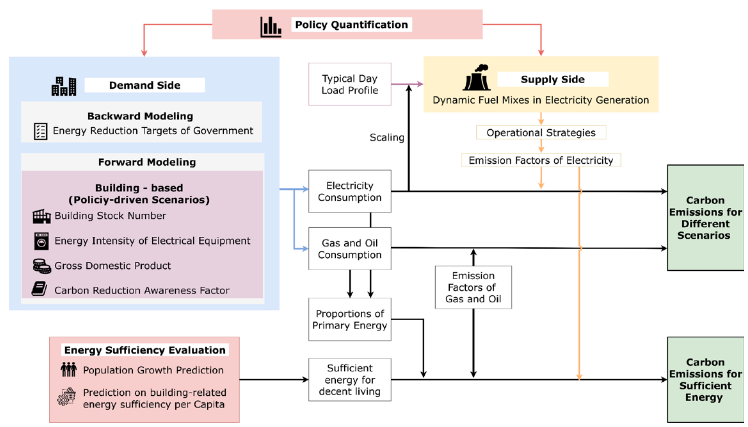

Fig. 2 Modeling framework

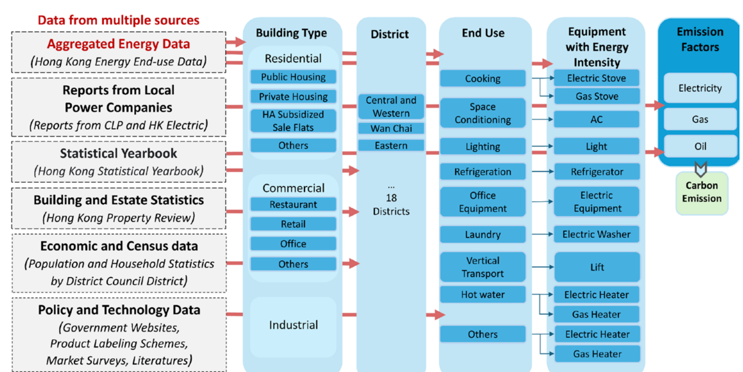

Fig. 3 Multi-source data fusion for modeling

Currently, Hong Kong only has aggregated level energy data at the city level. However, considering the building type distribution, land development plans, and economic development status can vary among districts, this study utilized data from multiple sources. As shown in Fig. 3, the energy usage and carbon emission can be decomposed into different districts, and be projected individually. This will improve the performance of the model, as well as provide policy insights by district. All the datasets used in this study are publicly available and were released by the Hong Kong government or the local power company CLP. The power generation data are obtained from CLP's Climate Vision 2050 [11]. The energy consumption information is from Hong Kong End-Use Data published by the EMSD [12]. The building stock numbers are obtained from the Hong Kong Property Review [13] and the Hong Kong Statistical Yearbook [10]. The population and economy data are obtained from the Population and Household Statistics by the District Council [14], and the population projection is from the Census and Statistics Department of Hong Kong [15], taking the baseline projection. The historical and projected GDP data are obtained from the International Monetary Fund [10].

2.3 Scenario settings

Four scenarios shown in Table 1 aim to transition Hong Kong's buildings to carbon neutrality: Government plan (GOV), business-as-usual (BAU), moderate policy (POL1), and radical policy (POL2). GOV aligns with China Light and Power Company's 2050 zero-carbon power generation plan and follows the government's targets for reduced electricity use in various building types by 2035 and 2050 [16]. BAU reflects current conditions, while POL2 projects the scenario with the most radical policies, and POL1 is a transitional scenario between BAU and POL2, which can be regarded as a feasible pathway with moderate policies.

2.4 Calculation methods

This study simulated energy consumption on the demand side using LEAP software [17], decomposing energy-use intensity and value from historical building energy end-use data. The power generation was simulated using electricity generation plans and assumptions, considering the electricity demand on typical days for each year.

The outputs, i.e., carbon emissions, under the BAU scenario from 2017 to 2019 were used for validation. The mean percentage of errors compared with real data was 5%.

The bottom-up carbon emission model has the following components. As shown in Equation (1), the total carbon emission of 1-year C_t is calculated as the sum of emissions from each fuel type, which is the product of energy consumption E_{it} and the corresponding emission factor F_{it}.

$$C_t = \sum F_{it} \times E_{it} \qquad (1)$$

Energy consumption E_{it} is calculated using Equation (2), where S_t is service level, representing the energy service development level in a city; in this study, this is defined by the local economic development status using GDP per capita. People's awareness of carbon reduction is represented by AW_t. The terms in the brackets of Equation (2) represents the energy consumption without social factors (the original energy-consumption term). As the statistics of building amount are recorded in floor area A_{jt} or building stock number B_{jt}, the original energy consumption terms of these buildings are calculated separately, and then multiplied by energy-use intensity EUI_{jt} and energy use per building stock EU_{jt}, respectively.

$$E_{it} = S_t \times AW_t \times \left(\sum A_{jt} \times EUI_{jt} + \sum B_{jt} \times EU_{jt}\right) \quad (2)$$

The energy-use intensity and energy use per building is calculated respectively by summing the corresponding end-use intensities or end-use values, as shown in Equation (3) and Equation (4).

$$EUI_{jt} = \sum I_k \qquad (3)$$

$$EU_{jt} = \sum D_k \qquad (4)$$

The social and economic hypothesis is shown by the service level defined in Equation (5). For each council district in Hong Kong, the service level S_t is defined as GDP per capita at year *t* divided by GDP per capita in 2007. It is assumed that the service level will develop according to the current trend. Therefore, S_t in the future will follow the extrapolation result.

$$S_t = \frac{GDPpc_t}{GDPpc_{2007}} \qquad (5)$$

A lower people's awareness indicator of carbon reduction indicates more carbon reduction. Therefore, it is assumed to decrease continuously following linear trends with different slopes under the three scenarios. Considering the education level in Hong Kong, the final carbon reduction amount is determined to range from 2% to 4% under the three scenarios.

The building number was predicted based on the historical data of building stock numbers or building floor areas, and the government's land-use plan is used as the boundary for prediction [18]. Specifically, the amount of each building type was predicted separately by applying the regression models of the *sklearn* package, using the building number by districts and types from 2007 to 2016 as input.

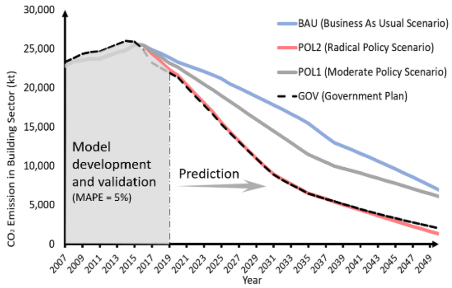

Fig. 4 Carbon emissions of Hong Kong's building sector till 2050 under various scenarios

3. RESULTS

As shown in Fig. 4, the carbon gap between reality (BAU) and the ideal (POL2) is large. From 2007 to 2050, BAU would emit over 200 million tons more CO2 than GOV. In 2050, BAU emissions surpass GOV's threefold (6930 kt vs. 2022 kt).

The POL2 scenario largely overlaps with the GOV scenario, indicating that the government's 2050 plan is feasible if the assumptions of the POL2 scenario hold.

Zero carbon emissions by 2050 are unattainable in all four scenarios. To reach net-zero emission, the carbon sink or storage will be required. The Hong Kong government reported that 456 kt of carbon sink from the forest [19], which means that the building sector will require approximately 1500 kt of carbon storage capacity or equivalent carbon credits purchased on the carbon market to achieve a net-zero energy target.

Fig. 5 quantifies the synergistic carbon reduction on the demand and supply sides and develops a feasible domain for decarbonization to guide policymaking.

The carbon emissions gap between reality (BAU scenario) and the simulated ideal situation (POL2 scenario) from 2020 to 2050 is 207 million tons of CO_2 (as mentioned earlier), resulting from joint contributions of the demand and supply sides. The trade-off between the demand and supply sides is depicted in Fig. 5 with inclined lines. The *x*- and *y*-axes represent accumulated carbon reduction on the demand and supply sides, respectively. Each yellow dashed line shows the accumulated carbon reduction until the target year. The orange line bounded by the red dots represents a feasible range of contributions from the demand and supply sides. A higher point on the orange line signifies greater supply-side contribution, while a lower point indicates greater demand-side contribution. For instance, in 2050, points "S" and "D" represent the maximum supply and demand-side contributions under the POL2 scenario, obtained by simulating the policy implementations of the supply and demand sides separately. All feasible lines create a triangular-like domain, offering insights into the required supply and demand-side contributions at each stage of carbon reduction.

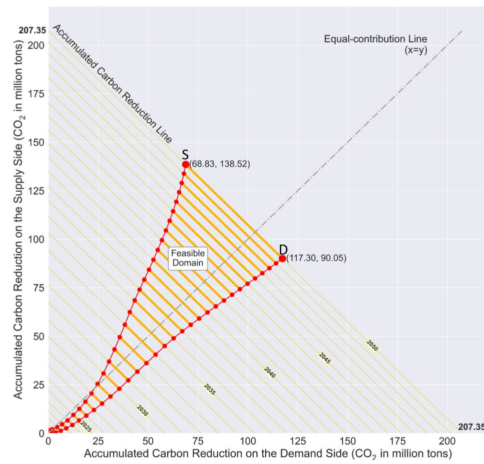

Fig.5 Paths for realizing carbon neutrality: carbon reduction on the demand and supply sides

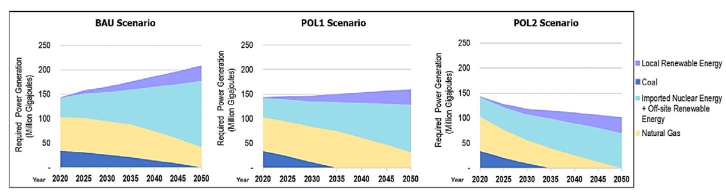

Fig. 6 Power generation capacity by scenarios

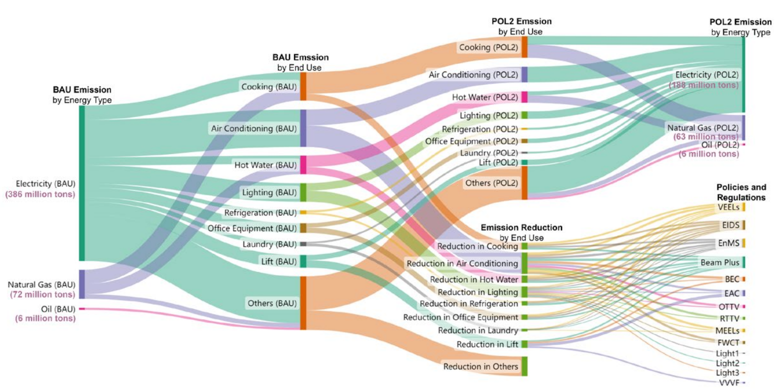

Fig. 7 Carbon emission flow by end use

Identifying the upper limits of decarbonization capacity on both sides can aid in the setting of realistic and achievable targets for carbon reduction and provide a basis for tracking progress toward these targets. Fig. 5 presents these upper limits and shows that neither the supply side nor the demand side can solely support the building sector to realize carbon neutrality by 2050. A comparison of the feasible line and the equal-contribution line reveals that the demand side will be dominant until 2030, after which the supply side will play an increasingly important role as fuel transformation progresses. Points "S" and "D" show that the supply side will reduce carbon emissions by 66% to 43% of the total by 2050, corresponding to a reduction amount of 90 to 138 million tons. This suggests that the Hong Kong government's estimation of the supply side's contribution (70%) [8] to carbon reduction is too high.

The power generation roadmap shown in Fig. 6 encompasses energy sources including coal (to phase out by 2035), stable and relatively clean natural gas, clean but limited renewables, and imported nuclear energy and off-site renewables. Among these energy sources, the developmental trends of coal and renewable energy are more certain than those of the other categories of fuels, while natural gas and nuclear power will be the intermediate source during transformation and the substitute for renewables. The Hong Kong government is committed to phasing out coal by 2035. Thus, no power

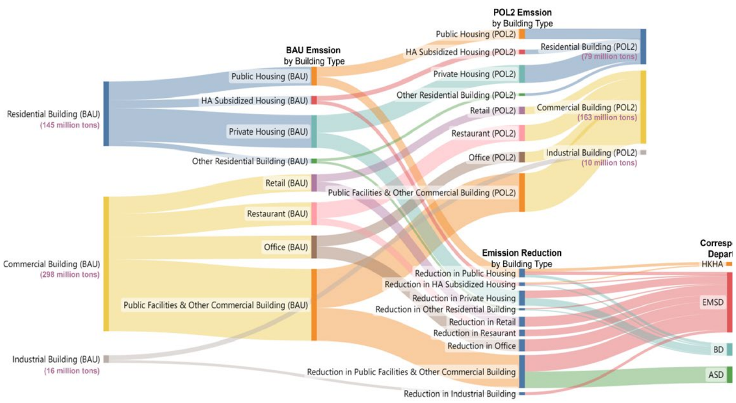

Fig. 7 Carbon emission flow by building type

from coal will be generated by 2050 under all the scenarios, although the BAU scenario involves the slowest transformation. In addition, the amount of renewable energy will continue growing, but will not exceed 15% of the current power capacity (26.8 million GJ) [7]. The insufficient local renewable generation is because of the limited space for installing renewables such as photovoltaic panels.

For the demand side, technology enhancement and policy implementation for each end-use can reduce carbon emission. Fig. 7 decomposes 2020-2050 carbon emissions into end-use types for BAU and POL2, and also breaks down local policies' carbon-cutting effect on each end-use, vital for future reduction.

In general, the end-use types that have large emission-reduction proportions (i.e., >45%), including air conditioning, lighting, office equipment and lifts, generally only use electricity. In terms of total emission reductions, air conditioning has the largest potential, followed by lighting. Fortunately, many technologies with great energy-saving potential are also feasible for air conditioning and lighting, such as predictive control, oil-free chillers, and novel refrigeration cycles for air conditioning, and efficient compact fluorescent lamps and optimized luminance-based control for lighting. Moreover, according to the policy and regulation column in Fig. 7, air conditioning and lighting are the focus of many policies and regulations, which illustrates the great opportunities for deploying energy-saving technologies.

The major challenge of decarbonization is in cooking and hot water, which often rely on non-electric energy sources. Notably, some countries are overly optimistic about electrifying cooking [20]. This study takes a more cautious stance due to Hong Kong's dining habits [21], which makes electrified cooking tough, especially for restaurants. Carbon emissions can still be generated from gas. This conservatism is valid in similar Asian high-density cities. Further, cooking and heating devices are already efficient [22], limiting energy-saving potentials. Additionally, most of their relevant policies like Smart Meter Monitoring and Energy Information Display System [23] and the Building Environmental Assessment Method Plus Assessment [24] mostly supervise total energy, not appliance-level improvements.

Similarly, Fig. 8 illustrates the decarbonization amount by building types. Commercial buildings, particularly public facilities, account for the largest proportion of carbon emissions in both scenarios, but they have a relatively lower proportions of decarbonization compared to retail and office buildings. Restaurants have limited carbon reduction potential due to the difficulty of fully replacing gas stoves with electric stoves. Residential buildings, with private housing being the highest contributor to carbon emissions, show similar emission-saving proportions among different building types. Except for private housing, multiple government departments supervise and regulate the energy usage of residential buildings.

4. CONCLUSIONS

This study presents a flexible framework for modeling carbon emissions in high-density cities, unlocking the path to carbon neutrality. The model considers economic and technological development levels, addressing both supply and demand sides. Applied to Hong Kong as a representative city, the framework utilizes open aggregated datasets and supplementary social statistics to trace decarbonization efforts in detail. The model's validation underscores its feasibility for cities with low data disclosure levels, suggesting potential applications in other high-density urban environments.

Addressing the key research questions outlined at the study's outset, it becomes evident that bridging the substantial gap between reality and the zero-carbon targets in 2050 necessitates embracing the most radical policy scenario in Hong Kong's building sector. This entails leveraging existing advanced technologies to meet the challenge effectively. Collaborative efforts between the supply and demand sides of electricity are identified as crucial for effective decarbonization.

On the demand side, electrification of home appliances presents a significant carbon reduction potential, though decarbonizing gas-based end-use types remains challenging. Effective energy-saving regulations and incentives should consider market acceptance. More retrofitting and behavioral efforts are required for private housing and commercial buildings.

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