Development of urban building energy models in Hong Kong based on open-source datasets

Zhang Deng¹,², Xi Chen², Jingjing Yang¹, Yixing Chen*¹
¹ College of Civil Engineering, Hunan University, Changsha, China
² Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, Hong Kong, China

Abstract
The building sector accounts for 66% of total energy consumption and 93% of electricity consumption in Hong Kong, which is a challenge for decarbonization. Urban building energy modeling (UBEM) is an efficient way to simulate the energy use of building stocks and conduct retrofit option assessments, supporting the implementation of carbon reduction policies. This paper investigated Hong Kong’s building stock, developing urban building energy models for residential, office, and hotel buildings. Firstly, various open-source data was collected for data mapping and integration to create a GIS-based building dataset. Then, local building energy codes and standards were referenced to develop archetype buildings based on the year built. A downtown district of 257 buildings was selected as the case study. Urban building energy models were generated by the UBEM tool- AutoBPS, using a building-by-building approach. The rooftop photovoltaic (PV) power generation of 257 buildings was calculated, with an annual PV yield of 11,436 MWh, accounting for 5.4% of the total electricity use. The development workflow can be applied to create other building archetypes, and the models can support building energy efficiency programs in Hong Kong.

Highlights
- Developed urban building energy models in Hong Kong based on open data sources
- Big data mapping and integration for city building dataset
- Archetype development for residential, office, and hotel buildings
- Rooftop PV potential was assessed considering the shading effect

Introduction
With the rapid development of global urbanization, over 50% of the world’s population lives in cities, which is expected to grow to 68% by 2050 (United Nations Human Settlements Programme, 2022). Urbanization has accelerated social and economic development and significantly increased energy consumption and greenhouse gas (GHG) emissions. According to statistics, cities currently account for 75% of global energy consumption and 70% of annual global carbon emissions (International Energy Agency, 2021). To cope with environmental challenges, many cities have proposed ambitious long-term GHG emission reduction plans. For example, San Francisco and New York City in the United States committed to reducing GHG emissions by 40% below the 1990 level by 2025 and 2030, respectively (Y. Chen et al., 2017). Hong Kong issued the "Energy Saving Plan For Hong Kong’s Built Environment 2015–2025+", to reduce energy intensity by 40% by 2025 using 2005 as the base year (Environment Bureau, 2015).

In Hong Kong, residential and commercial buildings consumed 66% of total primary energy and 93% of total electricity in 2020 (Electrical and Mechanical Services Department, 2022). Therefore, building energy saving is crucial to achieving Hong Kong’s decarbonization targets. Building energy modeling (BEM) can be used to optimize the passive design and evaluate energy retrofit for an individual building. Urban building energy modeling (UBEM) is emerging to estimate building energy use in cities in recent years. Bottom-up physical UBEM is a large-scale BEM approach using EnergyPlus or IDA ICE as dynamic thermal simulation engines (Hong et al., 2020). It can support city managers and decision-makers to conduct energy planning for new districts and energy efficiency programs for existing districts.

UBEM requires much high-level information, including building geometric and non-geometric data. Geometric data mainly contains building footprints, number of floors, building height, building type, year built, and so on. Some big cities, such as New York, Boston, London and Berlin, have made this geographical information system (GIS) data public via the open data portal (Hong et al., 2020). Non-geometric data includes envelope, internal loads, equipment schedules, heating, ventilation, and air conditioning (HVAC) system parameters, etc. Unlike single BEM, where detailed data can be obtained through the on-site survey, it is often difficult to acquire for thousands of buildings at an urban scale. These parameters are usually assumed based on archetype or prototype buildings, where archetype buildings are representative buildings that reflect common typologies and properties in the building stock.

Currently, there are some studies about urban modeling in Hong Kong. Huang et al. (2020) proposed the Urban Building Energy and Climate (UrBEC) model, a coupled urban microclimate model and building energy model.
They used the model to assess the cooling demand of a residential neighbourhood of 41 buildings, and the combined heat gains to the external space from direct and reflected solar radiation, traffic and the exhaust from HVAC systems. Liu et al. (2021) developed six residential archetypes through the government's building codes survey and on-site measurement in Hong Kong, namely cruciform Concord public rental housing (PRH) buildings (after 2000s), the Y-shape Trident PRH buildings (after 1980s), old tenement house (before 1970s), old private housing (from 1970s to 2000s), new private housing (after 2000s), and village houses. Then, they assessed the impacts of urban heat on thermal performance (indoor temperature and relative humidity) of 1036 residential buildings by coupling a high-resolution urban climate simulation with UBEM (Liu et al., 2023).

As discussed previously, most available studies focus on investigating the thermal performance of residential archetypes or residential buildings, combined with urban climate simulation. There is a need for a comprehensive UBEM to include residential and commercial buildings, which can assess the energy performance of urban buildings. Therefore, this paper proposed a method to develop urban building energy models in Hong Kong. Open-source data and local codes were collected to develop the building dataset and archetype database. Urban building energy models of 257 buildings in a district were generated by the UBEM tool - Automated Building Performance Simulation (AutoBPS). Then, the building energy uses and rooftop PV potential were calculated by EnergyPlus.

**Methods**

Figure 1 shows the workflow for developing urban building energy models. Firstly, GIS-based urban building data in Hong Kong is collected via various sources. Secondly, data mapping and integration are conducted by GIS tool-QGIS to create the building dataset for the case study. Thirdly, residential and commercial archetypes are developed based on local building energy codes and literature. Then, the UBEM tool - AutoBPS is used to automatically generate urban building energy models. Urban building energy consumption and rooftop PV potential are calculated by the simulation engine EnergyPlus. The details of each step are introduced in the following section.

**Study area**

Hong Kong is a densely populated city located on the eastern Pearl River Delta in South China, as shown in Figure 2, with a total population of 7.5 million in a 1104 km² territory. It lies between 22°08′ to 22°35′ north latitude and 113°49′ to 114°31′ east longitude. Hong Kong has a humid subtropical climate. Summers are long, hot and humid from May to September. The hottest month of the year is July, with an average high of 32°C and low of 27°C. The coldest month of the year is January, with an average low of 14°C and high of 19°C. The city receives 1829 h of bright sunshine annually.

![Figure 2: The location and map of Hong Kong.](image-url)
GIS data mapping and integration

The GIS-based building footprints were collected from a public platform—Hong Kong GeoData Store (Lands Department, 2022), with 413,961 original records. They contained completed, demolished, and some duplicate footprints. After data cleaning, there were 339,511 records with the information of unique building structure id, building name, and the number of floors above ground. These footprints not only included common buildings, but also substations, toilets, etc., which had a small site area. Digital Topographic Map iB1000 included building footprints, and the elevation information of baselevel and rooflevel for each building. Building height could be obtained by subtracting the rooflevel from the baselevel, then added to building footprints through the function of “join attributes by location” in QGIS, with 231,302 valid records.

The year built information was obtained from the occupation permit (OP), which was stored in a table with the building structure id. Since the OP did not cover village houses, the year built was merged with building footprint data to constitute 61,424 records. From the data, 34% of the buildings were built before 1980, 44% of the buildings were built between 1980 and 2000, and 22% of the buildings were built after 2000.

However, there was no available building type information from the open data portal. Another data source OpenStreetMap could be used but had some limited information about building use and land use (only residential and commercial categories). Therefore, 362 buildings in a high-density district of Wan Chai were selected as the UEBM case study, as shown in Figure 3. Their building types were determined by OpenStreetMap and validated by online investigation. There were 128 residential buildings, 113 office buildings, and 16 hotel buildings for modeling, also considering the shading effect from 105 other surrounding buildings. Figure 4 shows the summary information of the selected buildings, indicating many high-rise buildings in this old district. Most of the buildings are built before 1970. The building height ranges from 12.8m to 175.7m, with a median of 55.1m.

---

**Figure 3:** (a) The distribution of selected buildings (in blue) and surrounding buildings (in gray) in the district; (b) the satellite image of the buildings.

---

**Figure 4:** (a) The distribution of the year built; (b) the distribution of building height.

---

**Archetypes development**

Archetypes development is generally divided into classification and characterization (Deng et al., 2022). Archetype classification refers to that buildings are grouped based on building size, type, and year built. The selection of HVAC system is related to the building size. Large commercial buildings commonly adopt a centralized air-conditioning system, whereas smaller buildings will adopt split air conditioners. The building type is useful in determining internal loads and equipment schedules. Additionally, the thermal properties of the envelope and the system efficiency show the discrepancy in different construction periods due to the technology development. In this study, buildings were divided into 6 classes: mid-rise residential (4–7 floors), high-rise residential (above 7 floors), small office (below 6 floors), large office, small hotel (below 6 floors), and large hotel.
Archetype characterization means that non-geometric parameters are assigned to each archetype. For residential buildings, since there are no PRH buildings in this area, they were further classified based on three time periods: before 1970, 1971-2000, and after 2001, following the literature (Liu et al., 2021). Their parameters of envelope, internal loads, air conditioners, schedules, etc., referring to (Liu et al., 2021). For commercial buildings, the Buildings Department published the first building energy code on the overall thermal transfer value (OTTV) of buildings in 1995 (Buildings Department, 1995). The code aimed to improve the average insulation performance of building envelopes. Apart from OTTV legislations, building energy efficiency regulations on the building service installation were considered. The Electrical and Mechanical Services Department (EMSD) firstly launched the Building Energy Code (BEC) in 2005, then updated in 2007, 2012, 2015, 2018, 2021. The BEC provided the design standards about air-conditioning installation, lighting installation, electrical installation as well as lift installation. So, eight time periods were defined respectively based on the issue time of the code: before 1995, 1996-2005, 2006-2007, 2008-2012, 2013-2015, 2016-2018, 2019-2021, and after 2022. The non-geometric parameters were obtained from the BEC (Electrical and Mechanical Services Department, 2021) and (Yu & Pan, 2023)(Yang et al., 2008). HVAC system was mainly used for space cooling from April to October. Cooling was available from 08:00 pm to 07:00 am for residential buildings. For office buildings, HVAC’s daily operation schedule is from 06:00 am to 07:00 pm on weekdays, from 06:00 am to 03:00 pm on Saturdays, unavailable on Sundays. For hotel buildings, HVAC’s operation schedule is all day. Figure 5 shows the daily schedules of lighting, equipment, and occupancy in different building types.

Urban building energy models
After archetypes development, all those non-geometric parameters were added to AutoBPS and stored in JavaScript Object Notation (JSON) format to create an archetype library. AutoBPS was a UBEM tool developed in the previous study (Deng et al., 2023), which applied a building-by-building approach to automatically generate multi-zone (one zone per floor) models based on the city building dataset, considering the shading effect by surrounding buildings. AutoBPS calculated urban building energy use, and analyzed energy retrofit and rooftop PV potential via EnergyPlus. The required input data for AutoBPS was obtained by mapping and integration, then saved in the GeoJSON format, including attributes of building id, building height, number of floors above ground, building type, and year built. Figure 6 shows an example EnergyPlus model of the target building surrounded by shading buildings. When the distance between the target building and a surrounding building is less than 2.5 times the surrounding building’s
height, then the surrounding building is considered a shading building (Deng et al., 2023).

![Figure 6: EnergyPlus model of the target building with shading buildings.](image)

AutoBPS estimated the potential for rooftop PV production in buildings via EnergyPlus PV module, using the Equivalent One-Diode model (known as by TRNSYS PV model). Table 1 shows the key parameters of a common PV module. The optimum tilted angle for rooftop PV installation is close to the latitude of the local position. It was set 23° in Hong Kong (Peng & Lu, 2013). Considering the occupied area for some building services components, the available roof area for PV installation was chosen as 60% of the roof area (Peng & Lu, 2013). Additionally, solar panels are installed at the south-facing orientation to have a higher annual average insolation (Wong et al., 2016).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar cell type</td>
<td>/</td>
<td>Crystalline Silicon</td>
</tr>
<tr>
<td>Number of cells in series</td>
<td>/</td>
<td>60</td>
</tr>
<tr>
<td>Module current at maximum power</td>
<td>A</td>
<td>7.5</td>
</tr>
<tr>
<td>Module voltage at maximum power</td>
<td>V</td>
<td>30</td>
</tr>
<tr>
<td>Short circuit current</td>
<td>A</td>
<td>8.3</td>
</tr>
<tr>
<td>Open circuit voltage</td>
<td>V</td>
<td>36.4</td>
</tr>
<tr>
<td>PV module area</td>
<td>m²</td>
<td>1.7</td>
</tr>
</tbody>
</table>

**Results**

The annual building energy uses of 257 buildings were simulated by AutoBPS. Typical meteorological year (TMY) data was selected as the weather data, which was based on the recent 15 years (2004-2018) and obtained from ClimateOneBuilding (Lawrie & Crawley, 2019). TMY file of Hong Kong in EnergyPlus Weather File (EPW) format was downloaded for energy simulation. Figure 7 shows the annual energy use intensity (EUI) distribution of different buildings. The yearly EUIs of residential buildings ranged from 121 kWh/m² to 276 kWh/m², with a median of 176 kWh/m². For office buildings, the median EUI was slightly higher, with 196 kWh/m². Hotel buildings showed the highest median EUI among these buildings, which was 390 kWh/m². Since there is no metered energy data for each building, energy use statistics or reference studies were used for validation. The Energy Efficiency Office (EEO) of EMSD listed energy utilization indexes for selected energy-consuming groups by field surveys, covering residential, commercial and transport sectors. EEO divided residential buildings into principal groups: PRH, private housing, and individual houses. In this case study, selected residential buildings belonged to private housing. The annual EUI of private housing and hotel is 174 kWh/m² and 498 kWh/m², respectively. Some existing research also investigated the annual EUI of office buildings (Jing et al., 2017), from 74 kWh/m² to 529 kWh/m² and a median value of 220 kWh/m². Comparing these data showed that the simulated results were within a reasonable range.

Figure 8 shows the spatial distribution of annual rooftop PV power generation. High-rise buildings with larger roof areas had higher PV yield, while PV yield was lower for those mid-rise buildings due to the shading effect. The annual PV yield ranged from 0.6 to 281 MWh, and the total generation of 257 buildings was 11,436 MWh, which accounted for 5.4% of the total electricity use.
The energy accounting potential reference studies are conducted by AutoBPS to calculate the rooftop PV potential of buildings and urban areas. Diverse occupant behavior and pattern could impact energy use, which was not considered. These factors will introduce more uncertainties on urban building energy models, which needs further exploration.

Conclusion
This paper developed urban building energy models in Hong Kong via various open data sources. Data mapping and integration were conducted to establish the GIS-based building dataset for UBEM. The energy use of 257 buildings (residential, office, hotel) in a district was calculated by AutoBPS. The simulated results showed a reasonable range compared with statistical data and reference studies. AutoBPS simulated the rooftop PV potential to get an annual PV yield of 11,436 MWh, accounting for 5.4% of the total electricity use. The models developed here can provide support for the city manager and policymaker to make decisions about building energy efficiency. In the future, we will consider the impacts of urban microclimate on building energy consumption and update UBEM models.

Acknowledgment
The work described in this paper was supported by the CUHK Direct Grant for Research No. 4055168, and the Hong Kong SAR RGC Faculty Development Scheme (Project No. UGC/FDS16/E04/21).

References
Electrical and Mechanical Services Department. (2022). Hong Kong Energy End-use Data 2022.


