Energy for Sustainable Development 68 (2022) 182–191

Contents lists available at ScienceDirect

Energy for Sustainable Development

Photovoltaic rooftop's contribution to improve building-level energy resilience during COVID-19 work-from-home arrangement

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ARTICLE INFO

Article history:
Received 13 January 2022
Revised 23 February 2022
Accepted 19 March 2022
Available online 6 April 2022

Keywords:
Photovoltaic rooftop
Energy resilience
COVID-19
Work-from-home

ABSTRACT

The COVID-19 pandemic has introduced opportunities for more research in resilience as globally cities experienced lock-down, causing change to conventional energy consumption pattern especially in the residential sector. This study aims to quantify the increased energy demand during work-from-home arrangement, using high-rise public residential buildings in Hong Kong, where its government announced work-from-home arrangement four times in 2020. Building energy modellings were conducted to compare the total energy demand of residential units during normal and work-from-home arrangements, followed by validation against peer models and empirical data. A 9% residential energy demand increase was demonstrated, hence additional energy supply became desirable for the sake of resilience. This study assesses the possibility to leverage photovoltaic rooftop to supplement the increased energy demand. The photovoltaics' potential contribution was estimated by solar energy simulation and evaluated in terms of the capability to utilize its generation output to supplement the additional energy demand. During the four work-from-home periods, it was shown that a photovoltaic system could have supplemented 6.8% - 11% of the increased energy demand, mainly subject to the air-conditioning operation and solar generation. These findings are valuable to safeguard energy resilience in upcoming grid planning and operation.

Introduction

The COVID-19 pandemic has opened opportunities for more research in resilient cities. With cities experiencing lock-down, city planners and designers are challenged by the ability to rapidly adapt to the more unpredictable future (Lai et al., 2020). COVID-19 imposes disruption in energy access and distribution, and livelihoods globally (Samuels et al., 2021). Since understanding energy demand is vital for efficient electricity grid planning and operation, it is a common lesson-learnt that work-from-home arrangement during the COVID-19 crisis has imposed severe challenges on grid operators to maintain reliable energy supply (Abdeen et al., 2021; Jiang et al., 2021). Therefore, it is essential to understand the impact of work-from-home on residential flat's energy demand. It is envisaged the residential sector energy demand will increase as building occupants spend more time at home, leading to heavier use of household electrical equipment, including air-conditioning, lighting, and household electrical equipment. During the COVID-19 crisis in 2020, the Hong Kong Government announced special work-from-home arrangement four times, in January, March, July, and December respectively. In total, the work-from-home arrangement lasted for 124 working days in the year of 2020, and the normal working arrangement only accounted for 85 working days. Buildings are responsible for more than 90% of total electricity consumption in Hong Kong. In particular, residential buildings are the major source, accountable for one third of the total consumption (Du et al., 2020). This implies that residential buildings could have notable impact on the city-scale energy demand. Moving forward, it is even predicted that work-from-home can become a common practice in Hong Kong as the labour force has generally adopted to the arrangement (Vyas & Butakhieo, 2021). It is inevitable that energy consumption in residential buildings during work-from-home arrangement is different compared to normal work arrangement.

High-rise public residential buildings were specifically targeted for energy modelling in this study as they accommodated about half of the Hong Kong population. Land acquisition in Hong Kong has been physically limited by its hilly geography. Shortage of land supply has been a legacy challenge to provide sufficient housing in this highly populated city. To overcome this challenge, the development of high-rise public housing was proposed in the 1980s as a solution to improve land-use efficiency and increase affordable housing supply (Deng et al., 2016). Over the past half-decade, Hong Kong experienced a

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https://doi.org/10.1016/j.esd.2022.03.009
0973-0826/

dramatic increase in housing demand, leading to an immense production of residential buildings (Jaillon & Poon, 2009). Nowadays public housing accommodates about half of the population in Hong Kong, serving over 1.3 million domestic units (Hui & Wong, 2004). Various domestic block designs of public residential buildings were rolled out in the 1990s. One of the leading designs was known as the "Concord" series. Concord-series building can comprise up to 40 storeys with 8 flats per floor, providing 320 flats per block (Chan & Chan, 2011). As it was envisaged that there would be an increase in energy demand when occupants spent more time at home, it would be desirable to consider additional energy supply retrofitting for the sake of resilience and sustainability (Luo & Oyedele, 2021). While currently it has not yet been a common practice to equip on-site rooftop photovoltaic system on public residential buildings, this study also aims to assess the possibility of leverage photovoltaic system as a solution to supplement the increased energy demand. The potential contribution of the photovoltaic system is evaluated in terms of the capability to utilize its generation output to supplement the additional energy demand.

The study focuses on the context of high-rise public residential buildings with respect to the fact that public residential buildings accommodate about half of the Hong Kong population. This study has two major objectives. Firstly, building energy modelling is conducted to quantify the increased residential energy demand, followed by validation by comparing with peer models and empirical data. Secondly, while currently it is not a common practice to install photovoltaic system on public residential building rooftops, this study aims to testify the possibility to deploy solar rooftop in these buildings. The potential contribution of the photovoltaic system is estimated by solar energy simulation, and evaluated in terms of the capability to utilize its generation output to supplement the additional energy demand. The findings of this study are believed to be significant in understanding the impact of work-from-home arrangement on residential energy consumption. The contributions are prolonged as work-from-home arrangement is expected to become more common in the long term as the general work force has adopted to this practice during the pandemic. This study's outcomes are valuable to safeguard energy resilience in upcoming grid planning and operation.

Literature review

Energy resilience during the COVID-19 crisis

COVID-19 imposes disruption in energy access and distribution, and livelihoods globally. It is reported that in some developing countries, COVID-19 even caused energy poverty to an extent that 220 billion US dollars were lost (Zaman et al., 2021). Besides, in developed counties, there has been a thorough change in work practices from attending offices to work-from-home. For example, a survey suggested almost all employees had changed to work-from-home during lock-down in the UK (Chung et al., 2020). This has caused a redistribution among electricity consumer groups, essentially from commercial to residential due to work-from-home arrangement. In addition, electricity consumption profile on grid level has changed as peak demands and their corresponding instants shifted according to work-from-home occupant behaviors (Bielecki et al., 2021).

Despite work-from-home has become a trending office practice, its implication on social building energy use is still under-researched in the past few years (Hampton, 2017). The influence of work-from-home on energy use has attracted further attention during the COVID-19 pandemic period (Cheshmehzangi, 2020). In the US, it was reported the energy consumption of residential sector increased by 30% during lock down, but the overall electricity demand was lower due to the reduced demand in commercial and manufacturing sectors (Krarti & Aldubyan, 2021). In South Korea, the total energy consumption in most facilities decreased compared to pre-COVID-19 year. In contrast, energy consumption in residential buildings increased during COVID-19 (Kang et al., 2021). The electricity consumption in Spain faced an overall decline of 13%, but some households used 6% more energy compared to pre-lock-down period (Santiago et al., 2021). Overall, it is evident that electricity demand has become more unpredictable compared to normal social situation prior to the COVID-19 pandemic and has caused technical challenges to the power sector globally (Madurai Elavarasan et al., 2020).

Solar energy's contribution to energy resilience

Literatures are plentifully available to substantiate that solar energy, as an alternative to fossil fuel, has contributed to enhanced energy efficiency (Al-Shahri et al., 2021; Li et al., 2020). With respect to local climate conditions, renewable energy is considered as one of the elements in the Energy Triangle, alongside with energy conservation and increasing efficiency (Jamaludin et al., 2017). On the other hand, solar energy is closely associated with energy security and resilience. Energy resilience covers a wide range of factors, including reliability, economy, environment (Adefarati & Bansal, 2019). Communities around the globe have been facing different level of energy security issue. The growing population has led to the pressing to the limit of the planet's carrying capacity with a finite amount of resources. However, energy resilience remains an unpopular topic on the municipal level (Mola et al., 2018).

On-site decentralized renewable energy generation is believed to be advantageous to a city's energy resilience as reliance on external factors such as unreliability in outer supply are reduced (Gómez-Navarro et al., 2021). With the aid of optimal weather conditions, for instance solar irradiance, photovoltaic renewable energy system is capable of delivering reliable performance by maintaining steady output (Acuña et al., 2017). The solar energy generation can be further supported by battery energy storage system to supplement electricity supply during severe events (Galvan et al., 2020). In particular, solar rooftop has a crucial role to play in promoting general adoption of photovoltaic system on a community scale. Various studies are carried out to assess rooftop solar energy potential (Abdullah et al., 2019; Nelson & Grubesic, 2020) to better understand the possibility to produce solar energy in existing infrastructure. In addition, energy management algorithms have been developed to improve energy resilience by controlling roof solar panel output (Prince et al., 2019).

Solar energy application in Hong Kong

Owing to Hong Kong's Climate Action Plan 2030+ and 2050 carbon neutral ambition, the government and the building industry are spending huge efforts in examining technologies in energy efficiency enhancement and building decarbonization (HKSAR Government, 2020). In general, building decarbonization can be achieved via passive design, energy efficient system, on-site renewable energy and user behavioral changes (Qin & Pan, 2020).

The solar potential in Hong Kong is significant. It is estimated that Hong Kong could offer 54 km^2 suitable rooftop area for potential solar system, making up to 5.97 GWp capacity and capable of potentially producing 5981 GWh annually (Peng & Lu, 2013). Solar renewable energy is mostly popular in low rise buildings as the energy performance is more promising given the lower energy requirement (Morakinyo et al., 2019). Although building-integrated photovoltaic has earned interest recently, rooftop solar remains to be the mainstream deployment. Despite building-integrated photovoltaic offers additional surface area for energy generation, this technology has not been widely adopted due to its technological limitation and uncertain economic return (Baljit et al., 2016). For example, shading on the building façade could significantly hinder the efficiency of building-integrated photovoltaic (Zomer et al., 2020).

The government also offers financial incentives via feed-in tariff scheme. The scheme's objective is to enable renewable energy system owners to recover the installation costs. The feed-in tariff rates are $5 for ≤10 kW; $4 for >10 kW to ≤200 kW; and $3 for >200 kW to ≤1 MW (HKSAR Government, 2017). The effectiveness of the feed-in-tariff is widely discussed in terms of its effectiveness in fostering photovoltaic development in Hong Kong (Dato et al., 2021). Overall, the rate of photovoltaic deployment in Hong Kong is expected to increase owing to its high solar potential (Wong et al., 2016).

Methodology

Whole building energy modelling

Overview of whole building energy modelling

Building energy consumption analysis is a complex task as it considers interactions between the building physical features, HVAC systems, and dynamic outdoor conditions, such as weather. The interactions are modelled using mathematical algorithm and physical principles based on the user's input data (Fumo et al., 2010). The major objective of building energy simulation is to assist decision-making in building designs, assessing energy consumptions in alternative scenarios, such as different architectural features, HVAC system specifications and occupancy (Gao et al., 2019; Zhu et al., 2013). EnergyPlus is building energy simulation programme developed by the US Department of Energy. EnergyPlus is capable of estimating a building's energy use based on user-configurable modular systems, supported by a head and mass balance-based zone simulation (Crawley et al., 2001). A complete energy modelling requires the outdoor weather condition, building geometry, construction materials properties, household electrical equipment specifications, and the building's operation schedule.

Outdoor weather condition

Outdoor weather condition is a crucial input in building energy modelling as it facilitates the dynamic thermal analysis of the building HVAC system. A typical weather year in Hong Kong was developed as a precise representation of the periodic change in the local weather conditions, based on statistical analysis of 25 years of weather data in Hong Kong (Chan et al., 2006). The weather file was converted into an open-source EnergyPlus weather format for the building simulation community, including major weather indices covering dry bulb temperature, dew point temperature, wind speed and solar radiation.

Building geometry

Standard typical floor plans of public housing buildings are available on the official Hong Kong Housing Authority website (Hong Kong Housing Authority and Housing Department, 2019). One of the leading typical public housing layouts is named as “concord”. The building geometry includes a core structure, and four wings extended in 4 directions. Located on these wings are the residential units. Each floor comprises of 8 residential units, each unit including a master bedroom, 2 bedrooms, 2 toilets, a kitchen, and a living room. The unit floor area is about 60 m^2, and the entire floor size is about 650 m^2. The core structure is mainly the common area, consisting of the lobby and building services functions such as lift shaft and ducts. The energy consumption in the common area not considered in this study as it was believed that the energy consumption in common area would not be affected by work-from-home arrangement.

These public housing residential buildings come in high-rise form and usually comprises of 40 storeys (Du et al., 2020; Ting Kwok et al., 2018). According to previous studies, the building orientation of concord-type public residential buildings in Hong Kong would not significantly influence the building energy consumption due to its self-shading building form (Yu et al., 2020). Therefore, this study adopted a general building orientation for the sake of minimal complication. Design Builder was used to construct the geometry to further facilitate the energy modelling (Fig. 1).

Construction materials properties

Construction material selection of the building envelope is closely associated with building energy use subject to its insulation performance (Valančius et al., 2015). Suitable envelope material can reduce thermal loss and temperature variation during the day, and hence reduce internal cooling demand (Jeanjean et al., 2013). Typical building material properties were made referenced from the Building Environmental Assessment Method (BEAM Plus) (HKGBC, 2010), which is a green building certification scheme administrated by the Hong Kong Green Building Council and the BEAM Society, covering a wide range of building sustainability aspects, including site, energy, water, waste and materials, and indoor environmental quality (Wong & Kuan, 2014). The physical properties of construction materials are summarized in Tables 1–3. Symbolic abbreviations are used as follow: Thermal conductivity (k), density (ρ), specific heat (Cp), and solar absorptivity of exposed surface (α). The window-to-wall ratio is assumed to be 0.4 (Ting Kwok et al., 2018).

Energy consumption sources

Examples of the major energy consumption sources in residential buildings include air-conditioning, lighting, and household electric equipment (Jia & Lee, 2016; Wan & Yik, 2004). Hong Kong's public residential buildings are ventilated both naturally and by air-conditioning.

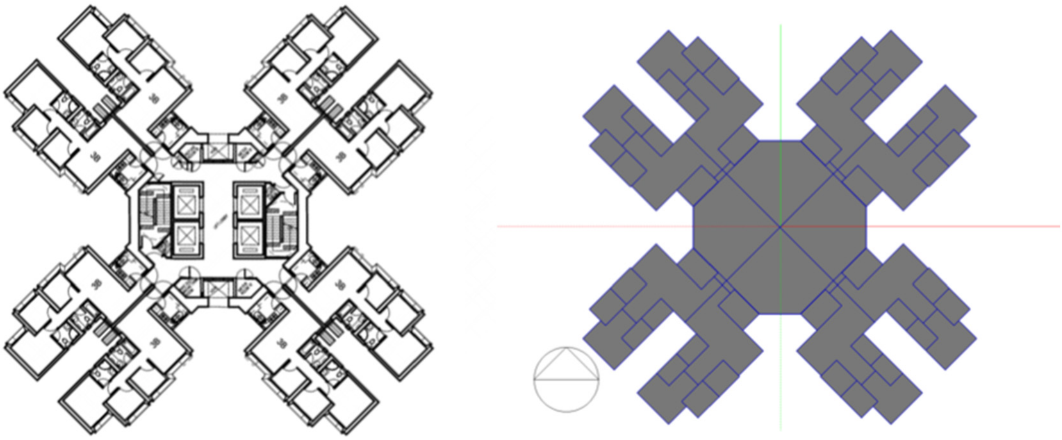

Fig. 1. Standard typical floor plans of concord-type public residential building provided by the Hong Kong Housing Authority (left), and the geometry built in Design Builder to facilitate the whole building energy simulation (right).

Table 1
Physical properties of building envelope construction materials (HKGBC, 2010).

External walls	Thickness/m	Material	k/W/mK	ρ/kg/m^3	Cp/J/kgK	α
Layer 1	0.005	Mosaic tiles	1.5	2500	840	0.58
Layer 2	0.01	Cement / Sand plastering	0.72	1860	840	–
Layer 3	0.1	Heavy concrete	2.16	2400	840	–
Layer 4	0.01	Gypsum plastering	0.38	1120	840	0.65

Table 2
Physical properties of roof construction materials (HKGBC, 2010).

External walls	Thickness/m	Material	k/W/mK	ρ/kg/m^3	Cp/J/kgK	α
Layer 1	0.025	Concrete tiles	1.1	2100	920	0.65
Layer 2	0.02	Asphalt	1.15	2350	1200	–
Layer 3	0.05	Cement / Sand screed	0.72	1860	840	–
Layer 4	0.05	Expanded polystyrene	0.034	25	1380	–
Layer 5	0.15	Heavy concrete	2.16	2400	840	–
Layer 6	0.01	Gypsum plaster	0.38	1120	840	0.65

Local exhaust by windows and mechanical extract are provided for specific rooms, such as kitchens and bathrooms, to remove pollutants. In regularly occupied spaces, windows and air-conditioning (window units or split-units) are typically used as general practice (Burnett, 2004). According to the floor plan, it was believed that each residential unit in the modelled building could house 4 people, with the master bedroom accommodating 2 people, and each bedroom accommodating 1 person. Riding on technology development and improving coefficient of performance (COP) of air-conditioners in newer models (Jia & Lee, 2016), this study's model assumed a Hong Kong Energy Label Grade 1 air-conditioner with COP 3.4 to be used in the living room, master bedroom and bedroom. The air-conditioner was also set to operate only from April to October, while the rooms were ventilated naturally in the remaining months.

Other than air-conditioning, the remaining major energy consumption sources, including lighting and household electric equipment, were modelled. The lighting power density was supposed to be 8 W/m^2, referencing the dormitory design criteria as stipulated in the Hong Kong Code of Practice for Energy Efficiency of Building Services Installation (EMSD HK, 2018). Furthermore, the equipment load was referred from BEAM Plus guidebook. The equipment load was thought to be 142 W per living room, and 45 W per master bedroom and bedroom (HKGBC, 2010). These model input parameters are summarized in Table 4.

Table 3
Physical properties of window glazing material (HKGBC, 2010).

External walls	Thickness/m	Material	k/W/mK	ρ/kg/m^3	Cp/J/kgK	α
Layer 1	0.006	Tinted glass	1.05	2500	840	0.65

Table 4
Modelling input parameters: Occupancy, lighting power density and equipment load of regularly occupied spaces.

Space	Maximum occupancy/ No. of people	Lighting power density/W/m^2	Equipment load/W per room
Living room	4	8	142
Master bedroom	2	8	45
Bedroom	1	8	45

Table 5
Modelling input parameters: Lighting power density and equipment load of non-regularly occupied spaces.

Space	Lighting power density/W/m^2	Equipment load/W per room	Ventilation/ACH
Kitchen	13	3100	20
Toilet	11	–	20

In addition to regularly occupied spaces, lighting was also provided in non-regularly spaces (13 W/m^2 in kitchen, and 11 W/m^2 in toilet). The equipment load, mainly made up of refrigerator and wash machine, was assumed to be 3100 W in kitchen referring to estimated typical electrical appliances input power (HK Electric, 2015). 20 air-change per hour (ACH) was assumed to remove pollutants in these spaces. These model input parameters are summarized in Table 5.

Normal routine and work-from-home occupancy and operation schedules

To facilitate energy modelling in the building design industry, BEAM Plus stipulates a set of universal occupancy schedule and building operation schedule, including air-conditioning, lighting, and household equipment (HKGBC, 2010). These schedules are considered to reflect the building occupants' normal routine and behavior. By coupling the energy consumption sources and their operation schedule, a model was built to represent building energy consumption under normal social circumstances and served as a baseline for further comparison.

In the year of 2020, Hong Kong Government announced special work arrangement 4 times to combat local epidemic situation by reducing the flow of people and social contact. Special work arrangements required government employees to work from home, and private institutions were recommended to follow suit. These announcements were made in January, March, May, and December respectively (Table 6). When condition permitted, the Government resumed normal work arrangement. Overall, the work-from-home arrangement accounted for 124 working days, and the normal working arrangement only accounted for 85 working days. Under the influence of the local epidemic, the general public were asked to stay at home, it was envisaged that the energy consumption of residential buildings was severely altered.

In order to compute the difference in building energy consumption between normal social circumstances and work-from-home arrangement, an alternative energy model was additionally developed. Despite universal schedules are provided in general guidelines, human reactions in real world situation may be overlooked in these pre-determined schedules inputted in the simulation (Du & Pan, 2021). Since occupancy is directly correlated to building energy use, it is essential to calibrate traditional modelling assumptions to reflect the non-typical occupant routine under work-from-home arrangement. Occupancy schedules and building operation schedules were modified from normal work arrangement to work-from-home arrangement, including the below adjustments:

- Occupants stayed in their bedrooms to perform office duties during working hours.

Table 6
Time records of government special work arrangement announcement.

Date	Government announcement
29 January 2020	Commence special work arrangement
2 March 2020	Resume normal work arrangement
23 March 2020	Commence special work arrangement
4 May 2020	Resume normal work arrangement
20 Jul 2020	Commence special work arrangement
24 Aug 2020	Resume normal work arrangement
2 December 2020	Commence special work arrangement
6 January 2021	Resume normal work arrangement

- Air-conditioning was turned on when occupants stayed in the bedrooms during working hours.
- Lightings in the bedrooms were kept at a 50% capacity in the morning and were fully turned on in the afternoon.
- Electrical equipment load in the bedrooms was at 100% during working hours.
- Occupants spent more time in the living room during lunch and after working hours.
- Lightings in the living room were kept at 100% capacity after working hours and before bedtime.
- Electrical equipment load in the living room was slightly higher than normal work arrangement.

The occupancy schedules and building operation schedules, under both normal work arrangement and work-from-home arrangement, are shown in Table 7 and Table 8.

Photovoltaic energy generation simulation

Currently it is not a usual practice to install rooftop solar panel on public residential buildings in Hong Kong. Therefore, a photovoltaic simulation was carried out to simulate the annual energy yield of a hypothetical rooftop energy system, and subsequently assess the opportunity for generating on-site solar electricity to supplement the increased energy demand during the work-from-home period. The modelled residential building rooftop had an area of 650 m^2. It was understood that not 100% of this 650 m^2 rooftop area would be suitable for photovoltaic installation. To estimate the suitable rooftop area for photovoltaic installation, an architectural suitability factor of 0.7 and a solar suitability factor of 0.55 were applied to the building's rooftop area with reference to a previous solar potential analysis (Peng & Lu, 2013). As a result, 250 m^2 roof area was approximated to be suitable for photovoltaic, equivalent to a 38.5 kWp system made up of 250 W polycrystalline photovoltaic panels, with 16% efficiency. The panels were set to be south facing, with 22° tilt as optimum condition (Jacobson & Jadhav, 2018). The photovoltaic simulation was carried out by deploying PVsyst, an effective simulation program used by engineers and researchers to conduct solar energy performance analysis during design (Irwan et al., 2015; Manikandan et al., 2020). PVsyst was capable to output a profile of monthly solar energy generation, which could be used to compare with the building energy demand during the work-from-home period. The shading effect in dense built environment in Hong Kong, which could cause around 10% photovoltaic generation loss (Peng et al., 2013), was taken into account in the simulation.

Table 7
Occupancy schedules and operation schedules of master bedroom and bedroom.

Hour	Occupant (Fraction)		Air Conditioning		Lighting (Fraction)		Equipment (Fraction)	
	Normal	WFH	Normal	WFH	Normal	WFH	Normal	WFH
0	1	1	On	On	0.3	0.3	0.8	0.8
1	1	1	On	On	0	0	0	0
2	1	1	On	On	0	0	0	0
3	1	1	On	On	0	0	0	0
4	1	1	On	On	0	0	0	0
5	1	1	On	On	0	0	0	0
6	1	1	On	On	0.5	0.5	0	0
7	0.25	1	Off	On	0.2	0.2	0	0
8	0	1	Off	On	0.3	0.5	0	1
9	0	1	Off	On	0	0.5	0	1
10	0	1	Off	On	0	0.5	0	1
11	0	0.5	Off	On	0	0.5	0	1
12	0	0.5	Off	On	0	0.5	0	1
13	0.25	1	On	On	1	1	0	1
14	0.25	1	On	On	1	1	0.3	1
15	0.25	1	On	On	1	1	0.3	1
16	0.25	1	On	On	1	1	0.3	1
17	0.25	1	On	On	0	1	0.3	1
18	0.25	0.25	On	On	1	1	0.3	0.5
19	0.25	0.25	On	On	1	1	0.8	0.8
20	0.5	0.5	On	On	1	1	0.8	0.8
21	0.5	0.5	On	On	1	1	0.8	0.8
22	0.5	0.5	On	On	1	1	0.8	1
23	1	1	On	On	0.6	0.6	1	1

Table 8
Occupancy schedules and operation schedules of living rooms.

Hour	Occupant (fraction)		Air conditioning		Lighting (fraction)		Equipment (fraction)	
	Normal	WFH	Normal	WFH	Normal	WFH	Normal	WFH
0	0	0	Off	Off	0	0	0.2	0.2
1	0	0	Off	Off	0	0	0.2	0.2
2	0	0	Off	Off	0	0	0.2	0.2
3	0	0	Off	Off	0	0	0.2	0.2
4	0	0	Off	Off	0	0	0.2	0.2
5	0	0	Off	Off	0	0	0.2	0.2
6	0	0	Off	Off	0.3	0.3	0.4	0.4
7	0.25	0.25	Off	Off	0.5	0.5	0.5	0.6
8	0.5	0.5	Off	Off	0	0	0.5	0.6
9	0.5	0.5	Off	Off	0	0	0.5	0.6
10	0.5	0.5	Off	Off	0	0	0.5	0.6
11	0.5	0.75	Off	Off	0	0	0.5	0.6
12	0.45	0.75	Off	Off	0	0	0.5	0.6
13	0.5	0.5	On	On	0.5	0.5	0.6	0.7
14	0.5	0.5	On	On	0	0	0.4	0.5
15	0.5	0.5	On	On	0	0	0.4	0.5
16	0.5	0.5	On	On	0	0	0.4	0.5
17	0.5	0.5	On	On	0	0	0.4	0.5
18	0.5	1	On	On	0.5	1	0.4	0.5
19	0.75	1	On	On	1	1	1	1
20	1	1	On	On	1	1	1	1
21	1	1	On	On	1	1	1	1
22	1	1	Off	Off	1	1	1	1
23	0	0	Off	Off	0.5	0.5	1	1

Results and discussion

Building energy modelling

Building energy consumption under normal work arrangement

The energy model resulted in an annual profile of hourly electricity demand of all residential units. The model suggested the total yearly energy use to be 1,740,000 kWh, made up by air conditioning and ventilation, lighting, and household eletrical equipment. The minimum base load was 10 kW in non-air-conditioned months (January – March, and November – December), and increased to 31 kW in air-conditioned months (April to October). On the other hand, the maximum peak load was 200 kW in non-air-conditioned months, and rose to 1200 kW in air-conditioned months. These variations across the 8760 h within a year are shown in Fig. 2. The major energy consumption sources were modelled, contributed by air-conditioning and ventilation (60%), lighting (20%), and household electrical equipment (20%) (Fig. 3).

Validation modelling results under normal work arrangement

It is critical to validate building energy model results to ensure accurate reflection of reality. Validation of computation model can be carried out by comparing the modelling results with empirical data and peer models (Ryan & Sanquist, 2012). To overcome this difficulty, empirical data in relevant literature and public information are collected to provide evidence to validate the model. Firstly, according to the Energy Saving Plan For Hong Kong's Built Environment 2015–2025+ (Environment Bureau, 2015), the average household electricity consumption in Hong Kong is about 400 kWh per month. The high-rise residential building simulated in this study consisted of 320 residential units, each residential unit was modelled to consume 450 kWh per month, which is in range with the suggested empirical result. Secondly, a previous study (Wan & Yik, 2004) conducted surveys about actual

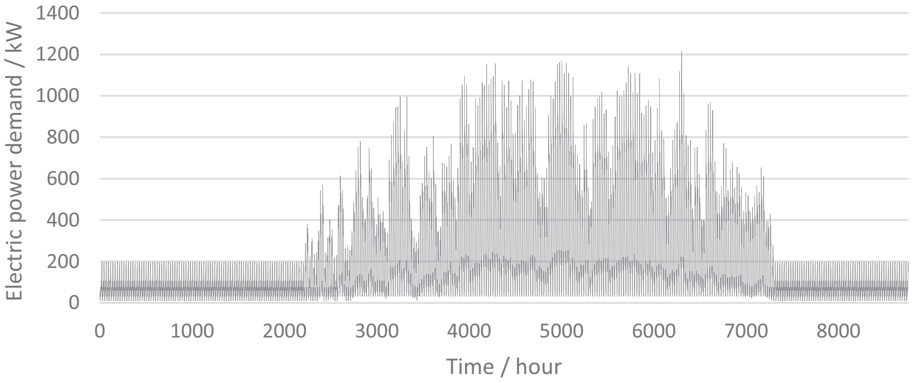

Fig. 2. Total electric power demand of all residential flats, results from building energy model.

household energy use, and suggested that residential flats equipped with air-conditioners had an energy intensity of 100 kWh/m^2. Referring to this study's modelling result, an energy intensity of 91 kWh/m^2 was estimated, which is also believed to be in range with the suggested surveyed result. Overall, by comparing the energy model results with empirical results provided by literature, it is thought that the model reflecting normal work arrangement provides reliable energy consumption data for further analysis.

Building energy consumption under work-from-home arrangement

As mentioned in the Methodology section, the occupancy and operation schedules under work-from-home arrangement were adjusted to reflect the difference from normal work arrangement. According to the energy modelling results, the energy consumption during work-from-home arrangement of air conditioning increased by 7%, lighting by 7%, and electrical equipment by 16%. The total consumption was 1,890,000 kWh, the energy intensity was 98 kWh/m^2, and the energy use per residential unit was 490 kWh/month. The total consumption under work-from-home arrangement increased by 9% as compared to the normal arrangement.

Validation of modelling results under work-from-home arrangement

To verify the credibility of the modelling results, actual electricity consumption data was referenced. Referring to the Hong Kong electricity provider's annual report (Holdings, 2020), the year-on-year change in electricity sales in the residential sector was 9%, comparing 2020 (COVID-19 impact year) and 2019 (pre-COVID-19 year). This figure echoes with the percentage difference in modelling results between normal and work-from-home arrangements, hence it is believed that the occupancy and operation schedules were calibrated appropriately, and the modelling results are close to reality.

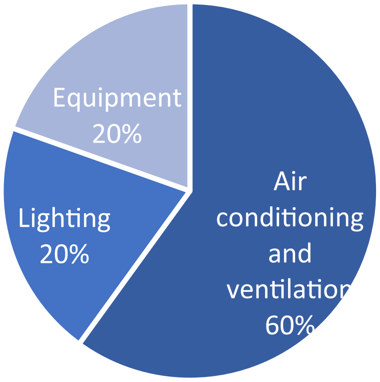

Fig. 3. Pie chart showing major energy consumption sources and their respective percentage contribution.

Rooftop photovoltaic system's contribution to increased energy demand

Photovoltaic system generation modelling results

A simulation was conducted to estimate the hourly generation of a 38.5 kWp, 250 m^2 rooftop photovoltaic system. The generation data are summarized in Table 9. Generally, the output was mainly during daytime between the 7th to the 18th hour. Across months, the generation was higher in the summer when solar irradiance was more abundant. July had the highest monthly generation of 3865 kWh and a daily average of 125 kWh, in contrast December had the lowest generation of 1765 kWh and a daily average of 57 kWh. Aggregating the monthly hourly generation, the annual generation was estimated to be 32,000 kWh.

Overview of energy demand and photovoltaic contribution during the four work-from-home periods

This study covered four work-from-home periods, including 29 January to 1 March, 23 March to 3 May, 20 July to 23 August, and 2 December to 31 December. The total building energy consumption under normal and work-from-home arrangements are presented in the above section. In this section and the upcoming sections, the energy demands during these four periods are specifically assessed and discussed.

During work-from-home arrangement, building occupants were expected to stay home which led to increased energy demand consumption. Since it was assumed that air-conditioning was functional from April to October, work-from-home arrangement during these months implied additional use of air-conditioning, lighting, and electrical equipment. For the remaining non-air-conditioned months, the increased energy demand was solely due to the increased use of lighting and electrical equipment.

Echoing with the objective of this study, the potential contribution of the rooftop photovoltaic system is presented in terms of the capability to utilize its generation output to supplement the additional energy demand. As an overview, the results are presented in Fig. 4. It is shown that the photovoltaic system could contribute 7% to 11% of the additional energy demand in the four periods. The results are critically discussed in-depth in the upcoming sections.

First work-from-home period

The first work-from-home arrangement was announced on 29 January and lasted until 1 March. Within this period, it was modelled that the total residential units' energy consumption was 79,800 kWh, in which the majority (79,100 kWh) was contribution by non-air-conditioning consumption, and the remaining owing to air-conditioning and ventilation consumption (700 kWh). By comparing

Table 9
Simulated monthly hourly generation of the rooftop photovoltaic system.

Month	Monthly hourly generation / kWh														Monthly total/kWh	Daily average/kWh
	0–6	7	8	9	10	11	12	13	14	15	16	17	18	19–23		
Jan	0	6	71	136	250	292	301	282	237	129	65	7	0	0	1776	57
Feb	0	11	59	132	194	244	252	313	266	193	88	30	0	0	1782	64
Mar	0	43	119	207	269	338	366	336	297	225	120	44	0	0	2364	76
Apr	0	67	171	264	321	329	342	343	323	256	140	56	1	0	2617	87
May	0	94	242	316	377	388	403	393	366	297	184	90	6	0	3194	103
Jun	0	89	256	329	361	381	410	386	347	294	200	77	21	0	3185	106
Jul	0	88	287	379	449	486	487	463	428	387	278	80	26	0	3865	125
Aug	0	85	221	347	416	457	469	431	397	318	194	70	7	0	3422	110
Sep	0	73	179	308	365	381	391	389	346	270	124	45	0	0	2874	96
Oct	0	54	136	287	376	420	407	380	315	189	74	11	0	0	2649	85
Nov	0	40	98	210	294	322	336	331	266	118	54	1	0	0	2070	69
Dec	0	20	81	150	264	306	317	272	210	98	46	1	0	0	1765	57

with normal work arrangement within the same period, the energy demand was estimated to be 29% higher during work-from-home condition. The percentage difference was mainly due to the higher consumption of lighting and electrical equipment when occupants stayed at home, but was not associated with air-conditioning which was assumed to be turned on during April to October. Simulation suggested that during the first work-from-home period, the rooftop photovoltaic system would have generated 1970 kWh. This accounted for 2.5% of the total residential units' energy consumption under work-from-home situation, and 11% of the difference between the two work arrangements.

Second work-from-home period

The second work-from-home period started on 23 March and finished on 3 May. This period spanned across natural ventilation and air-conditioned periods. From 23 March to 31 March, it was modelled that the residential units consumed 22,400 kWh, 29% higher than normal work situation. Similar to the first work-from-home period, the difference was mainly contributed by non-air-conditioning consumption.

From 1 April to 3 May, the work-from-home energy consumption was simulated to be 166,600 kWh which was 24% higher than normal work condition. Since air-conditioning was functional starting from April, and occupants were assumed to work in their air-conditioned bedroom, the air-conditioning and ventilation energy demand was modelled to be 19% higher than normal work arrangement, reaching 85,100 kWh. Besides the increased usage of lighting and electrical equipment led to a 30% increment in non-air-conditioning energy demand compared to normal work arrangement, accounting for 81,600 kWh. For the entire period of the second work-from-home situation, the total energy demand was 189,100 kWh, including 103,800 kWh of non-air-conditioning and 85,300 kWh of air-conditioning and ventilation. This was 24% higher in contrast to the energy demand of 152,000 kWh under normal work arrangement. During this period, the rooftop photovoltaic system would have produced 3500 kWh. In particular, the photovoltaic system could supplement 2.7% of energy demand from 23 March to 31 March (non-air-conditioned period), and 1.8% of energy demand from 1 April to 3 May (air-conditioned period). In total, the photovoltaic system could contribute to 1.9% of the total residential units' demand. Given the 37,100 kWh difference in total energy demand between the two work arrangements, the on-site photovoltaic system could potentially contribute to 9.5% of the additional energy demand.

Third work-from-home period

The third work-from-home period was from 20 July to 23 August. It was simulated that the residential units used 349,500 kWh. This

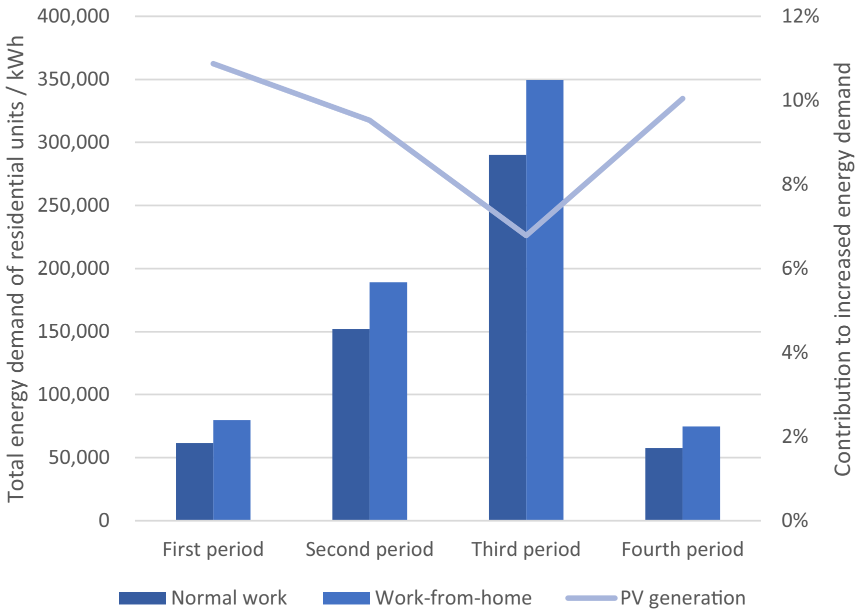

Fig. 4. Energy demand during normal work and work-from-home arrangements, and the PV generation contribution to the increased energy demand.

represented a 21% increment compared to the energy consumption during normal work arrangement (290,100 kWh). The increment was made up of 18% increase (40,000 kWh) in air-conditioning energy demand and 29% increase (19,500 kWh) in non-air-conditioning energy demand.

It was simulated that the rooftop photovoltaic system could have generated 4000 kWh during the third work-from-home period. The amount of output was equivalent to 1.2% of the total residential units' energy demand. The percentage contribution was relatively smaller compared to the first and second work-from-home periods because the flats were air-conditioned during third work-from-home period, despite the higher solar energy generation compared to other months. This was implied that the fact that the building consumed more energy when air-conditioning was used instead of natural ventilation. Nevertheless, the 4000 kWh photovoltaic output could provide 6.8% of the additional energy demand (59,500 kWh).

Fourth work-from-home period

The fourth work-from-home arrangement was announced on 2 December, as normal work was resume in January the next year. The fourth period concerned covered 2 December to 31 December within 2020. Within this period, the flats were not air-conditioned. Since the ventilation operation schedules in toilets and kitchen were the same in both work arrangements, there was no difference in air-conditioning and ventilation consumption. The increased energy demand was modelled to be 17,000 kWh, equivalent to 29% increment from 57,800 kWh (normal work) to 74,800 kWh (work-from-home). This percentage increments in the first and fourth work-from-home periods were the same as the operation schedules were identical. The photovoltaic system was modelled to be capable of producing 1700 kWh during this period. This amount was adequate to supplement 2.3% of total residential units' energy demand. As of the 17,000 kWh increase in energy demand, the photovoltaic generation could be contributable to 10% additional consumption.

Normal work arrangement periods

In addition to the above work-from-home periods, the possible contribution during normal work situation by the photovoltaic system is assessed. The normal work periods include 1 January to 28 January, 2 March – 22 March, 4 May to 19 July, and 24 Aug to 1 December. For these periods which lie within the non-air-conditioned months, the photovoltaic system was modelled to supplement 3% to 4% of the energy demand of all residential flats. In contrast, when normal work arrangement was applied during air-conditioned months, the photovoltaic system could contribute around 1.5% of the total energy demand.

Limitations and uncertainties

This study made a few critical assumptions which imposed certain limitations on the results. Firstly, the study assumed that all households had a uniform family size of 4 people based on the one master bedroom and two bedrooms floor plan. Referring to the Hong Kong government official population by-census results (Census and Statistics Department, 2016), the average household size was 3.0 in 2006 and 2.8 in 2016. The modelling input may have discrepancy compared to the average household size.

Secondly, the equipment performance specification, although was appropriately justified, was to certain level up to the authors' discretion. Performance indicators in residential flats are usually not mandated by government regulations because they are subject to the occupants' own wills. For instance, the lighting power density assumed in the model was based on the reference of mandatory lighting provision in dormitory, which was believed to be a close reference to residential unit. It was almost unavoidable to have some households installing excessive lighting and electrical equipment, or on the other extent using minimal lighting and equipment. The model has not captured such variations which could have been understood by surveying occupants but would have brought another level of complexity to the study. Within the scope of this study, it has not been possible to collect a whole year electricity data of a residential unit due to time constraints. In addition, the lack of suitable data in high rise buildings has been a common challenge faced by many fellow energy model developers (Yu et al., 2015). Nevertheless, the modelling results were validated by comparing with peer models and empirical results. It was believed that the modelling results were accurate reflections of reality.

Thirdly, with regards to the photovoltaic system generation, due to the high-rise nature of public residential flats (40-storeys), it was believed that surround shading would only have a limited impact on the output. Nonetheless, a 10% shading loss was taken into account in the simulation. On the other hand, the availability of roof space was another critical factor determining the generation output. Two factors, including architectural factor and solar suitability factor, were applied to the roof area to deduce the suitable area for photovoltaic installation. These factors could be further subject to the actual architectural roof layout, which could be affected by space irregularity or alternative use of space such as for placing HVAC equipment.

Conclusions

A building energy model was developed to estimate the annual energy demand of a 40-storey high-rise public residential building which comprises of 320 units. The modelling inputs were appropriately justified based on local and industrial references, and included major energy consumptions including air-conditioning, ventilation, lighting and household electrical equipment. Energy modelling results suggested an energy intensity of 91 kWh/m^2 and consumption 450 kWh per month per residential unit under normal work arrangement. These results were validated by comparing against peer models and empirical data, hence the model was believed to be an accurate reflection of the reality.

An alternative building energy model was developed to simulate the energy demand under work-from-home situation by adjusting the occupancy schedule and building operation schedules according to the Government's four announcements of special work arrangement in January, March, July and December 2020 respectively. Modelling results showed that the energy intensity rose to 98 kWh/m^2, and the energy use per residential unit increased to 490 kWh/month. This quantified a 9% energy demand increment under work-from-home arrangement as compared to normal work arrangement, which was validated to be consistent with the residential electricity sales report according to utility provider's official data. While it has not been a general practice to deploy solar rooftops on public residential buildings, this study testified the possibility to install solar rooftop and generate energy to supplement the increased energy demand. A solar energy simulation was carried out to estimate the annual output of a 250 m^2, 38.5 kWp rooftop photovoltaic system. The suitable roof area for installation was estimated based on the roof area, adjusted by an architectural factor and a solar suitability factor. The annual generation was estimated to be 32,000 kWh.

The potential contribution was evaluated in terms of the relative capability to utilize its generation output to supplement the additional energy demand. During the first work-from-home period (29 January to 1 March), the photovoltaic system could potentially contribute to 11% of additional energy demand. Moving on the second work-from-home period (23 March to 3 May), the photovoltaic system was modelled to supplement 9.5% of the increased energy consumption. The contribution slightly dropped because air-conditioning started operation in April, leading to an increase in energy consumption. In the third work-from-home period (20 July to 23 August), the solar generation could provide 6.8% of the additional energy demand. The relative percentage contribution dropped further because the flats were air-conditioned for the entire period, despite the higher solar energy generation compared to other months. For the fourth work-from-home period (2 December to 31 December), the generation was contributable to 10% additional consumption which was similar to the first work-from-home period. In the remaining times of normal work arrangement, the photovoltaic system could contribute to around 1.5% of total residential units' energy demand when air-conditioning was on, and 3–4% when air conditioning was off. The limitations and uncertainties of this study were critically discussed, including the assumed household size, equipment performance specification modelling input, and rooftop spatial availability for photovoltaic installation.

Overall, it is believed that rooftop photovoltaic system could contribute effectively to the increased energy demand during work-from-home arrangement, and it is feasible to improve the buildings' autonomy. In light of future possible crisis, it is recommended to enhance energy resilience on a building level by reviewing the feasibility of on-site generations in existing buildings, and consider to deploy renewable energy microgrids in new buildings under design. The findings are believed to be significant to provide understanding in the impact of work-from-home arrangement on residential energy consumption. The contributions are long-term as work-from-home arrangement may become more common in the future. This study's outcomes are valuable to safeguard energy resilience in upcoming grid planning and operation. Suggested future works are extending the scope to analyze electricity consumptions in other sectors including commercial and industrial to understand the change in total electricity consumption on a city scale. Although the work-from-home arrangement has led to an increase in residential energy demand, the consumption in other sectors is expected to decrease due to restricted business activities. A city-scale analysis can provide an overall insight in COVID-19's impacts on energy resilience.

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.

References

Abdeen, A., Kharvari, F., O'Brien, W., & Gunay, B. (2021). The impact of the COVID-19 on households' hourly electricity consumption in Canada. *Energy and Buildings*, *250*, Article 111280. https://doi.org/10.1016/J.ENBUILD.2021.111280.

Abdullah, W. S. W., Osman, M., Kadir, M. Z. A. A., & Verayiah, R. (2019). The potential and status of renewable energy development in Malaysia. *Energies*, *12*, 2437. https://doi.org/10.3390/EN12122437.

Acuña, L. G., Padilla, R. V., & Mercado, A. S. (2017). Measuring reliability of hybrid photovoltaic-wind energy systems: A new indicator. *Renewable Energy*, *106*, 68–77. https://doi.org/10.1016/J.RENENE.2016.12.089.

Adefarati, T., & Bansal, R. C. (2019). Reliability, economic and environmental analysis of a microgrid system in the presence of renewable energy resources. *Applied Energy*, *236*, 1089–1114. https://doi.org/10.1016/J.APENERGY.2018.12.050.

Al-Shahri, O. A., Ismail, F. B., Hannan, M. A., Lipu, M. S. H., Al-Shetwi, A. Q., Begum, R. A., ... Soujeri, E. (2021). Solar photovoltaic energy optimization methods, challenges and issues: A comprehensive review. *Journal of Cleaner Production*, *284*, Article 125465. https://doi.org/10.1016/J.JCLEPRO.2020.125465.

Baljit, S. S. S., Chan, H. Y., & Sopian, K. (2016). Review of building integrated applications of photovoltaic and solar thermal systems. *Journal of Cleaner Production*, *137*, 677–689. https://doi.org/10.1016/J.JCLEPRO.2016.07.150.

Bielecki, S., Dukat, P., Skoczkowski, T., Sobczak, L., Buchoski, J., & Maciag, Ł. (2021). Impact of the lockdown during the covid-19 pandemic on electricity use by residential users. *Energies.*, *14*. https://doi.org/10.3390/EN14040980.

Burnett, J. (2004). Indoor environments in Hong Kong's high-rise residential buildings. *Int. Hous. Conf. Hong Kong 2004 - Hous. 21st century challenges commitments, Hong Kong, 2–4 Febr. 2004*. http://ira.lib.polyu.edu.hk/handle/10397/42045 (accessed July11, 2021).

Census and Statistics Department (2016). Snapshot of Hong Kong Population | 2016 Population By-census. https://www.bycensus2016.gov.hk/en/Snapshot-04.html (accessed August15, 2021).

Chan, A. L. S., Chow, T. T., Fong, S. K. F., & Lin, J. Z. (2006). Generation of a typical meteorological year for Hong Kong. *Energy Conversion and Management*, *47*, 87–96. https://doi.org/10.1016/J.ENCONMAN.2005.02.010.

Chan, D. W. M., & Chan, A. P. C. (2011). Architectural science review public housing construction in Hong Kong: A review of its design and construction innovations public housing construction in Hong Kong: A review of its design and construction innovations. *Architectural Science Review*, *45*, 349–359. https://doi.org/10.1080/00038628.2002.9696950.

Cheshmehzangi, A. (2020). COVID-19 and household energy implications: what are the main impacts on energy use? *Heliyon.*, *6*, Article e05202. https://doi.org/10.1016/J.HELIYON.2020.E05202.

Chung, H., Seo, H., Forbes, S., & Birkett, H. (2020). *Working from home during the COVID-19 lockdown: Changing preferences and the future of work.*

Crawley, D. B., Lawrie, L. K., Winkelmann, F. C., Buhl, W. F., Huang, Y. J., Pedersen, C. O., ... Glazer, J. (2001). EnergyPlus: creating a new-generation building energy simulation program. *Energy and Buildings*, *33*, 319–331. https://doi.org/10.1016/S0378-7788(00)00114-6.

Dato, P., Durmaz, T., & Pommeret, A. (2021). Feed-in tariff policy in Hong Kong: Is it efficient? *City and Environment Interactions*, *10*, Article 100056. https://doi.org/10.1016/J.CACINT.2021.100056.

Deng, Y., Chan, E. H. W., & Poon, S. W. (2016). Challenge-driven design for public housing: The case of Hong Kong. *Frontiers of Architectural Research*, *5*, 213–224. https://doi.org/10.1016/J.FOAR.2016.05.001.

Du, J., & Pan, W. (2021). Diverse occupant behaviors and energy conservation opportunities for university student residences in Hong Kong. *Building and Environment*, *195*, Article 107730. https://doi.org/10.1016/J.BUILDENV.2021.107730.

Du, J., Yu, C., & Pan, W. (2020). Multiple influencing factors analysis of household energy consumption in high-rise residential buildings: Evidence from Hong Kong. *Building Simulation*, *13*, 753–769. https://doi.org/10.1007/s12273-020-0630-5.

EMSD HK (2018). *Code of practice for energy efficiency of building services installation 2018.*

Environment Bureau (2015). *Energy saving plan for Hong Kong's built environment 2015~2025+.*

Fumo, N., Mago, P., & Luck, R. (2010). Methodology to estimate building energy consumption using EnergyPlus Benchmark Models. *Energy and Buildings*, *42*, 2331–2337. https://doi.org/10.1016/J.ENBUILD.2010.07.027.

Galvan, E., Mandal, P., & Sang, Y. (2020). Networked microgrids with roof-top solar PV and battery energy storage to improve distribution grids resilience to natural disasters. *International Journal of Electrical Power & Energy Systems*, *123*, Article 106239. https://doi.org/10.1016/J.IJEPES.2020.106239.

Gao, H., Koch, C., & Wu, Y. (2019). Building information modelling based building energy modelling: A review. *Applied Energy*, *238*, 320–343. https://doi.org/10.1016/J.APENERGY.2019.01.032.

Gómez-Navarro, T., Brazzini, T., Alfonso-Solar, D., & Vargas-Salgado, C. (2021). Analysis of the potential for PV rooftop prosumer production: Technical, economic and environmental assessment for the city of Valencia (Spain). *Renewable Energy*, *174*, 372–381. https://doi.org/10.1016/J.RENENE.2021.04.049.

Hampton, S. (2017). An ethnography of energy demand and working from home: Exploring the affective dimensions of social practice in the United Kingdom, Energy Res. *Social Science*, *28*, 1–10. https://doi.org/10.1016/J.ERSS.2017.03.012.

HK Electric (2015). Estimated electricity cost of common appliances. https://www.hkelectric.com/en/customer-services/billing-payment-electricity-tariffs/know-more-about-electricity-consumption/estimated-electricity-cost-of-common-appliances (accessed August7, 2021).

HKGBC (2010). *BEAM Plus New Buildings.*

HKSAR Government (2017). GovHK: Feed-in Tariff. https://www.gov.hk/en/residents/environment/renewable/feedintariff.htm (accessed July11, 2021).

HKSAR Government (2020). The chief executive's 2020 policy address - Policy address. https://www.policyaddress.gov.hk/2020/eng/p125.html.

Holdings, C. L. P. (2020). *CLP Holdings 2020 Annual Report.*

Hong Kong Housing Authority and Housing Department (2019). Standard block typical floor plans | Hong Kong Housing Authority and Housing Department. https://www.housingauthority.gov.hk/en/global-elements/estate-locator/standard-block-typical-floor-plans/ (accessed July11, 2021).

Hui, E. C. M., & Wong, F. K. W. (2004). The Hong Kong housing authority and its financial arrangement over the past 50 years. *Int. Hous. Conf. Hong Kong 2004 - Hous. 21st century challenges commitments, Hong Kong, 2–4 Febr. 2004*. https://www.housingauthority.gov.hk/hdw/ihc/pdf/thkhafa.pdf (accessed July11, 2021).

Irwan, Y. M., Amelia, A. R., Irwanto, M., Fareq, M., Leow, W. Z., Gomesh, N., & Safwati, I. (2015). Stand-Alone Photovoltaic (SAPV) System Assessment using PVSYST Software. *Energy Procedia* (pp. 596–603). https://doi.org/10.1016/j.egypro.2015.11.539.

Jacobson, M. Z., & Jadhav, V. (2018). World estimates of PV optimal tilt angles and ratios of sunlight incident upon tilted and tracked PV panels relative to horizontal panels. *Solar Energy*, *169*, 55–66. https://doi.org/10.1016/J.SOLENER.2018.04.030.

Jaillon, L., & Poon, C. S. (2009). The evolution of prefabricated residential building systems in Hong Kong: A review of the public and the private sector. *Automation in Construction*, *18*, 239–248. https://doi.org/10.1016/J.AUTCON.2008.09.002.

Jamaludin, A. A., Mahmood, N. Z., & Ilham, Z. (2017). Performance of electricity usage at residential college buildings in the University of Malaya campus. *Energy for Sustainable Development*, *40*, 85–102. https://doi.org/10.1016/J.ESD.2017.07.005.

Jeanjean, A., Olives, R., & Py, X. (2013). Selection criteria of thermal mass materials for low-energy building construction applied to conventional and alternative materials. *Energy and Buildings*, *63*, 36–48. https://doi.org/10.1016/J.ENBUILD.2013.03.047.

Jia, J., & Lee, W. L. (2016). Drivers of moderate increase in cooling energy use in residential buildings in Hong Kong. *Energy and Buildings*, *125*, 19–26. https://doi.org/10.1016/J.ENBUILD.2016.04.064.

Jiang, P., VanFan, Y., & Klemeš, J. J. (2021). Impacts of COVID-19 on energy demand and consumption: Challenges, lessons and emerging opportunities. *Applied Energy*, *285*, Article 116441. https://doi.org/10.1016/J.APENERGY.2021.116441.

Kang, H., An, J., Kim, H., Ji, C., Hong, T., & Lee, S. (2021). Changes in energy consumption according to building use type under COVID-19 pandemic in South Korea.

Renewable and Sustainable Energy Reviews, *148*, Article 111294. https://doi.org/10.1016/J.RSER.2021.111294.

Krarti, M., & Aldubyan, M. (2021). Review analysis of COVID-19 impact on electricity demand for residential buildings. *Renewable and Sustainable Energy Reviews*, *143*, Article 110888. https://doi.org/10.1016/J.RSER.2021.110888.

Lai, K. Y., Webster, C., Kumari, S., & Sarkar, C. (2020). The nature of cities and the Covid-19 pandemic. *Current Opinion in Environment Sustainability*, *46*, 27–31. https://doi.org/10.1016/J.COSUST.2020.08.008.

Li, L., Lin, J., Wu, N., Xie, S., Meng, C., Zheng, Y., Wang, X., & Zhao, Y. (2020). Review and outlook on the international renewable energy development. *Energy and Built Environment*. https://doi.org/10.1016/J.ENBENV.2020.12.002.

Luo, X. J., & Oyedele, L. O. (2021). Assessment and optimisation of life cycle environment, economy and energy for building retrofitting. *Energy for Sustainable Development*, *65*, 77–100. https://doi.org/10.1016/J.ESD.2021.10.002.

Madurai Elavarasan, R., Shafiullah, G. M., Raju, K., Mudgal, V., Arif, M. T., Jamal, T., ... Subramaniam, U. (2020). COVID-19: Impact analysis and recommendations for power sector operation. *Applied Energy*, *279*. https://doi.org/10.1016/J.APENERGY.2020.115739.

Manikandan, S., Varun, M., & Manikandan, S. (2020). Performance Evaluation of Bifacial and Monofacial modules in vertical and latitude mounting at South India using PVsyst. *IOP Conf. Ser. Mater. Sci. Eng*. IOP Publishing Ltd. https://doi.org/10.1088/1757-899X/912/4/042066.

Mola, M., Feofilovs, M., & Romagnoli, F. (2018). Energy resilience: research trends at urban, municipal and country levels. *Energy Procedia*, *147*, 104–113. https://doi.org/10.1016/J.EGYPRO.2018.07.039.

Morakinyo, T. E., Ren, C., Shi, Y., Lau, K. K. L., Tong, H. W., Choy, C. W., & Ng, E. (2019). Estimates of the impact of extreme heat events on cooling energy demand in Hong Kong. *Renewable Energy*, *142*, 73–84. https://doi.org/10.1016/j.renene.2019.04.077.

Nelson, J. R., & Grubesic, T. H. (2020). The use of LiDAR versus unmanned aerial systems (UAS) to assess rooftop solar energy potential. *Sustainable Cities and Society*, *61*, Article 102353. https://doi.org/10.1016/J.SCS.2020.102353.

Peng, J., & Lu, L. (2013). Investigation on the development potential of rooftop PV system in Hong Kong and its environmental benefits. *Renewable and Sustainable Energy Reviews*, *27*, 149–162. https://doi.org/10.1016/J.RSER.2013.06.030.

Peng, J., Lu, L., Yang, H., Ho, K. M., & Law, P. (2013). *Experimentally diagnosing the shading impact on the power performance of a PV system in Hong Kong, 2013 World Congr. Sustain. Technol. WCST2013. (pp. 18–22), 18–22. https://doi.org/10.1109/WCST.2013.6750397.*

Prince, J. J. A., Haessig, P., Bourdais, R., & Gueguen, H. (2019). Resilience in energy management system: A study case. *IFAC-PapersOnLine.*, *52*, 395–400. https://doi.org/10.1016/J.IFACOL.2019.08.242.

Qin, H., & Pan, W. (2020). Energy use of subtropical high-rise public residential buildings and impacts of energy saving measures. *Journal of Cleaner Production*, *254*. https://doi.org/10.1016/J.JCLEPRO.2020.120041.

Ryan, E. M., & Sanquist, T. F. (2012). Validation of building energy modeling tools under idealized and realistic conditions. *Energy and Buildings*, *47*, 375–382. https://doi.org/10.1016/J.ENBUILD.2011.12.020.

Samuels, J. A., Grobbelaar, S. S., & Booysen, M. J. (2021). Pandemic and bills: The impact of COVID-19 on energy usage of schools in South Africa, Energy. *Sustainable Development*, *65*, 101–106. https://doi.org/10.1016/J.ESD.2021.10.001.

Santiago, I., Moreno-Munoz, A., Quintero-Jiménez, P., Garcia-Torres, F., & Gonzalez-Redondo, M. J. (2021). Electricity demand during pandemic times: The case of the COVID-19 in Spain. *Energy Policy*, *148*. https://doi.org/10.1016/J.ENPOL.2020.111964.

Ting Kwok, Y., Ka-Lun Lau, K., Yan, E., & Ng, Yung (2018). The influence of building envelope design on the thermal comfort of high-rise residential buildings in Hong Kong. *Wind. Conf. Rethink. Comf.*

Valančius, K., Motuziene, V., & Paulauskaite, S. (2015). Redeveloping industrial buildings for residential use: Energy and thermal comfort aspects, Energy. *Sustainable Development*, *29*, 38–46. https://doi.org/10.1016/J.ESD.2015.09.004.

Vyas, L., & Butakhieo, N. (2021). The impact of working from home during COVID-19 on work and life domains: an exploratory study on Hong Kong. *Policy Design and Practice*, *4*, 59–76. https://doi.org/10.1080/25741292.2020.1863560.

Wan, K. S. Y., & Yik, F. H. W. (2004). Representative building design and internal load patterns for modelling energy use in residential buildings in Hong Kong. *Applied Energy*, *77*, 69–85. https://doi.org/10.1016/S0306-2619(03)00104-1.

Wong, J. K. W., & Kuan, K. L. (2014). Implementing "BEAM Plus" for BIM-based sustainability analysis. *Automation in Construction*, *44*, 163–175. https://doi.org/10.1016/j.autcon.2014.04.003.

Wong, M. S., Zhu, R., Liu, Z., Lu, L., Peng, J., Tang, Z., ... Chan, W. K. (2016). Estimation of Hong Kong's solar energy potential using GIS and remote sensing technologies. *Renewable Energy*, *99*, 325–335. https://doi.org/10.1016/J.RENENE.2016.07.003.

Yu, C., Pan, W., Zhao, Y., & Li, Y. (2015). Challenges for modeling energy use in high-rise office buildings in Hong Kong. *Procedia Engineering*, *121*, 513–520. https://doi.org/10.1016/J.PROENG.2015.08.1100.

Yu, C. -R., Guo, H. -S., Wang, Q. -C., & Chang, R. -D. (2020). Revealing the impacts of passive cooling techniques on building energy performance: A residential case in Hong Kong. *Applied Sciences*, *10*, 4188. https://doi.org/10.3390/APP10124188.

Zaman, R., van Vliet, O., & Posch, A. (2021). Energy access and pandemic-resilient livelihoods: The role of solar energy safety nets. *Energy Research and Social Science*, *71*, Article 101805. https://doi.org/10.1016/J.ERSS.2020.101805.

D.Zhu, T.Hong, D.Yan, C.Wang, A detailed loads comparison of three building energy modeling programs: EnergyPlus, DeST and DOE-2.1E, Building Simulation 2013 63. 6 (2013) 323–335. doi:https://doi.org/10.1007/S12273-013-0126-7.

Zomer, C., Custódio, I., Antoniolli, A., & Rüther, R. (2020). Performance assessment of partially shaded building-integrated photovoltaic (BIPV) systems in a positive-energy solar energy laboratory building: Architecture perspectives. *Solar Energy*, *211*, 879–896. https://doi.org/10.1016/J.SOLENER.2020.10.026.