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Investigation of hybrid photovoltaic-wind system with battery storage for high-rise buildings in Hong Kong

Jia liu
Building Services Engineering
The Hong Kong Polytechnic University
Kowloon, Hong Kong, China
jiajia.liu@connect.polyu.hk

Xi Chen
Building Services Engineering
The Hong Kong Polytechnic University
Kowloon, Hong Kong, China
climber027@gmail.com

Hongxing Yang *
Building Services Engineering
The Hong Kong Polytechnic University
Kowloon, Hong Kong, China
hong-xing.yang@polyu.edu.hk

Abstract—Renewable energy is attracting much attention due to limited traditional energy sources and severe environmental issues caused by the over-consumption of fossil fuels. It is promising to use renewable energy for the power supply to buildings, as the building sector accounts for a large portion of global energy consumption with a continuous increasing trend. This study aims to analyze the technical and economic feasibilities of applying hybrid photovoltaic-wind-battery systems for high-rise buildings in Hong Kong based on the TRNSYS platform. Detailed economic benefits of the hybrid renewable energy system are estimated considering the feed-in tariff, transmission line loss saving, network expand and infrastructure saving, and social benefit of carbon reduction. It is found that the hybrid photovoltaic-wind-battery system can cover 24.79% of the annual electrical load of a high-rise building. The average self-consumption and self-sufficiency ratio of the hybrid system is 100% and 46% respectively. Battery storage in the hybrid system can not only improve the self-consumption and self-sufficiency performance, but also benefit the utility grid relief. The levelized cost of energy of the hybrid photovoltaic-wind-battery system is about 0.431 US$/kWh. This study can provide references for the development of hybrid renewable energy systems in Hong Kong and guide the application of renewable energy and battery systems to high-rise buildings in urban regions.

Keywords—photovoltaic, wind, battery, high-rise building, technical-economic feasibility

I. Introduction

Aiming to alleviate the energy and environment crisis, the multilateral Paris agreement is proposed focusing on reducing greenhouse gas emissions and controlling global temperature. It is ambitiously projected to reach carbon neutrality before 2100 and control the global temperature rise below 2°C based on pre-industrial levels [1]. Comprehensive plans are set in China to limit carbon emissions for important sectors. The electricity generation by coal energy will be about 5% in 2050 in China, which is significantly reduced compared with that in 2017 for 67%. It is expected that the non-fossil electricity will reach 44% by 2025 and 77% by 2035 with renewable energy accounting for 67% in China to response to the Paris agreement [2]. And in Hong Kong, the coal resource for generating electricity continues to phase down in recent years. About 3%-4% of renewable energy potential from wind, solar and waste-to-energy can be exploited by 2030, with 1% equals to up to 440 million kWh electricity which can support 90000 households. Nearly 70% of carbon emissions are attributed to the electricity generation, and almost 90% of electricity is consumed by the building sector in Hong Kong [3]. Therefore, it is significant to use renewable energy for the power supply to buildings, which accounts for over 60% of carbon emissions in the high-density city. Since renewable energy such as solar photovoltaic (PV) and wind sources is usually unpredictable and unmatched with the building load, electrical energy storage technologies are introduced to couple with renewable energy to ensure a stable power supply to buildings. Although various energy storage technologies are developed in recent years, the battery remains the most commonly used technology for renewable energy storage [4] for its convenience.

The hybrid renewable energy and battery storage system has been studied by many researchers in recent years. The energy flexibility of using PV-wind system with electric vehicle technology for high-rise office buildings in Hong Kong is studied. Two energy management strategies including renewable-to-demand and off-peak grid supported strategies are proposed to optimize the system performance [5]. The life cycle assessment of a standalone hybrid PV-wind-battery system is studied based on the case study of an microgrid island in Hong Kong regarding the environmental impact and energy payback period. It is concluded that the hybrid microgrid renewable energy system has a superior environmental performance and the energy payback time is around 9 years [6]. The loss of power supply probability (LPSP) of off-grid PV-wind systems with battery storage applied in islands of Hong Kong is analyzed, showing that the local solar and wind sources have good complementary characteristics for power supply. The authors show that the hybrid renewable system with 5 days power storage battery is appropriate for ensuring 0% LPSP [7]. The technical feasibility of applying an off-grid PV-wind system with pumped hydro storage technology to an island in Hong Kong is studied, indicating that the renewable energy system can achieve 100% energy autonomy for the remote island [8]. Few studies focus on exploring the technical and economic feasibilities of using hybrid PV-wind-battery systems in high-rise residential buildings in Hong Kong, especially when attractive economic incentives on developing renewable systems are introduced in recent years.

This study mainly aims to investigate the technical and economic feasibilities of applying hybrid PV-wind systems with battery storage to high-rise residential buildings in Hong Kong. Comprehensive economic benefits of applying the renewable system including the feed-in tariff (FiT), transmission line loss saving, network expand and infrastructure saving, and social benefit of carbon reduction are developed for evaluation based on the local regulations. This study indicates the technical and economic feasibilities of using hybrid PV-wind-battery systems in high-rise buildings of Hong Kong. It provides references for applying renewable energy systems with battery energy storage in high-rise buildings to achieve a higher penetration of renewable applications into high-density urban regions.

II. METHODOLOGY

A typical public house block of the New Harmony One issued by the Hong Kong Housing Authority is adopted as the case study [9]. It is reported that more than 30% of the population in Hong Kong live in this kind of building as a standard design accepted by most newly established public housing sectors [10]. This high-rise building has 30 floors with 16 flats per floor (large room designed for 4 members and small room for 2 members) and the layout of each floor is shown in Fig. 1. The building is established in SketchUp and then imported into TRNSYS platform to generate the load profile. The detailed parameters of the building envelope are adopted from the reported data by the Hong Kong Building Environmental Assessment Method Society [10, 11].

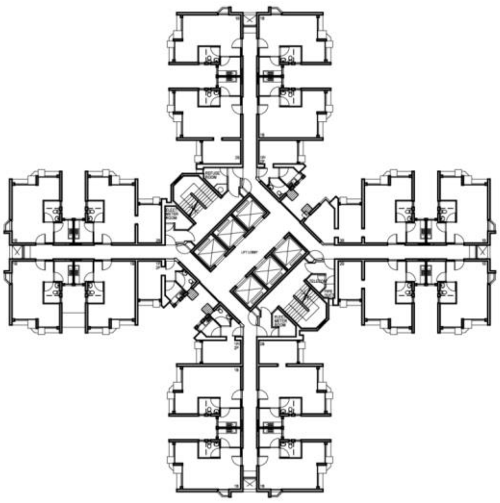

Fig. 1 Typical floor layout of the studied residential building

The detailed building load is generated considering the building ventilation, air conditioning, residents, equipment and indoor lighting according to the local design code issued by the Hong Kong Electrical and Mechanical Services Department (EMSD) [12]. The internal components in the TRNSYS platform including Type 56, Type 648, Type 667, Type 752, Type 655 and other auxiliary units are used to simulate the building load. Type 15 is used as the weather data supply with the external file of typical meteorological year. It is calculated that the average annual internal gain load of the high-rise building is 38.84 kWh/m^2 with 3.3 kWh/m^2 in July. The average annual air-conditioning load in the studied building is 43.99 kWh/m^2 and the average hot water load per unit area in the building is about 46.51 kWh/m^2, which is comparable to that of air conditioning. The calculated building results agree with the survey results reported by Wan et al. that the reliable range of the average annual air-conditioning and hot water electricity in standard public residential housing blocks in Hong Kong is 40-45 kWh/m^2 and 41-50 kWh/m^2 [13]. The average total building load per unit area is 129.33 kWh/m^2, and it is about 13.66 kWh/m^2 in July.

The hybrid PV-wind-battery system is established in the TRNSYS platform considering the energy supply (PV and wind), battery storage, building load, utility grid and energy management. Both rooftop and facade PV panels are installed in the building based on the empirical equivalent circuit model developed by Duffie et al. [14]. The building integrated PV model Type 567 is used to simulate façade PV panels integrated with the multi-zone building model Type 56 developed from Duffie and Beckman's thermal algorithm [15]. An adjacent shading factor of 40.69% is considered for the high-rise building compared with a standalone baseline building as Hong Kong is a high-density city [16]. And the wind turbine is modelled by Type 90 with external parameters from manufactures.

The battery storage unit is simulated considering the battery state of charge (SOC) and battery cycling aging as shown in (1).

$$SOC_i = SOC_0 + \frac{\int Pbat_{net}}{Bat_{rated} \cdot SOH} \tag{1}$$

where SOC_0 is the initial battery state of charge; $Pbat_{net}$ is the net power flow through the battery, kW; Bat_{rated} is the rated capacity of the battery, kWh; SOH is the battery state of health considering the battery cycling aging [17, 18].

The utility grid is connected to the hybrid PV-wind-battery system which cannot only offer power to the unsatisfied building load but also import surplus renewable energy. The energy management strategy of maximizing self-consumption is used in this study. When renewable energy from PV panels and wind turbines is not enough, the utility grid will supply power to meet the unsatisfied load. And whenever surplus renewable energy is available after meeting the building load and charging the batteries, it will be fed into the utility grid.

To evaluate the technical and economic feasibilities of the hybrid PV-wind-battery for the power supply to the high-rise building in Hong Kong, the load cover ratio (as in Eq. (2)) and system levelized cost of energy (LCOE as in Eq. (3)) are adopted as evaluation indicators.

$$load\ cover\ ratio = \frac{E_{RE\ to\ load} + E_{battery\ to\ load}}{E_{load}} \tag{2}$$

where $E_{RE\ to\ load}$ is energy from PV panels and wind turbines to the building load, kWh. $E_{battery\ to\ load}$ is energy from battery to the building load, kWh. E_{load} is total building demand, kWh.

$$LCOE = \frac{NPV_{inv} + NPV_{mai} + NPV_{fit} + NPV_{tra} + NPV_{exp} + NPV_{car}}{\sum_{n=1}^{n=N} \frac{E_{RE} \cdot (1-\delta_{RE})^{n-1}}{(1+i)^n}} \quad (3)$$

where NPV_{inv} is the net present value (NPV) of the system investment cost, \$; NPV_{mai} is NPV of the maintenance cost, \$; Investment and maintenance cost of the PV panel, wind turbine, battery and inverter are included. The discount rate of 4.5% and interest rate (i) of 5.8% [19] are calculated. NPV_{fit} is NPV of grid feed-in tariff, \$. Up to 5 HK\$/kWh (about 0.641 US\$/kWh) can be received with the installed capacity less than 10 kW until end 2033 and the renewable electricity after 2033 will belong to the system owner. The current electricity tariff is 0.145 US\$/kWh and the electricity price rising rate of 1.4%/year reported by Hong Kong EMSD is considered [20]. NPV_{tra} is NPV of the transmission line loss saving, \$. The major sources for current electricity supply in Hong Kong are coal, natural gas and nuclear energy, and power plants are usually far away from populated residential areas. The average transmission line loss during 2010 to 2014 is about 13.541% of the electricity output [21], which can be saved when generating energy from building integrated PV. NPV_{exp} is NPV of the network expand and infrastructure saving. China Light and Power Hong Kong Limited reported 38% of capital investment spent on maintaining the reliability of the electricity supply, 30% spent on projects related to emission reduction and carbon reduction, 24% spent on meeting the electricity demand of new development areas and infrastructure developments, and 8% spent on building smart cities and digital technologies [20]. The application of renewable energy can release part of the pressure in expanding the network and infrastructure. NPV_{car} is NPV of social benefit of carbon saving, \$. The carbon intensity of electricity in Hong Kong is about 0.66 kgCO_2/kWh [22] and the social cost of carbon is about 0.024 US\$/kg CO_2 [23] which can be positively saved using renewable energy. The lifetime of the PV-wind-battery system is 20 years in this study. E_{RE} is the electricity generation of the renewable energy from PV panels and wind turbines in the first year, kWh. δ_{RE} is the annual degradation rate of the system. n is a certain year in the lifetime and N is the total system service lifetime. i is the annual real discount rate.

III. RESULTS

A. *Technical performance analysis*

The annual power flow of applying hybrid PV-wind-battery system for the power supply to the high-rise building is simulated in the TRNSYS platform at a timestep of 0.125 h, and the results of typical weeks in June and December are discussed. Fig. 2 shows the power flow of the hybrid PV-wind-battery system in the third week of June. During this week, the total building load is about 44514.35 kWh and renewable sources can cover about 20.79% of total building load, while battery storage covers 3.36% of load. And the other 75.85% of building load is covered by the utility grid.

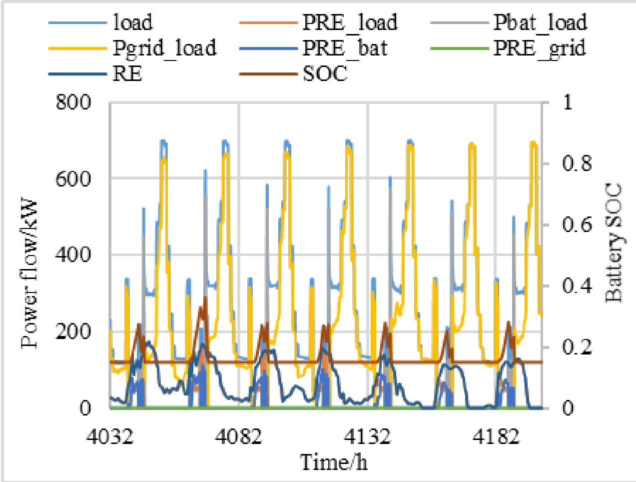

Fig. 2 Power flow in week 3 of June

The power flow of the third week in December is shown in Fig. 3 as below. During this week, the total building load is less than that in summer of about 26453.71 kWh since the air-conditioning load is significantly reduced in winter. Renewable sources can cover about 23.25% of total building load and more energy can be taken by battery storage for 9.99% of total load. And the other 66.76% of building load is covered by the utility grid.

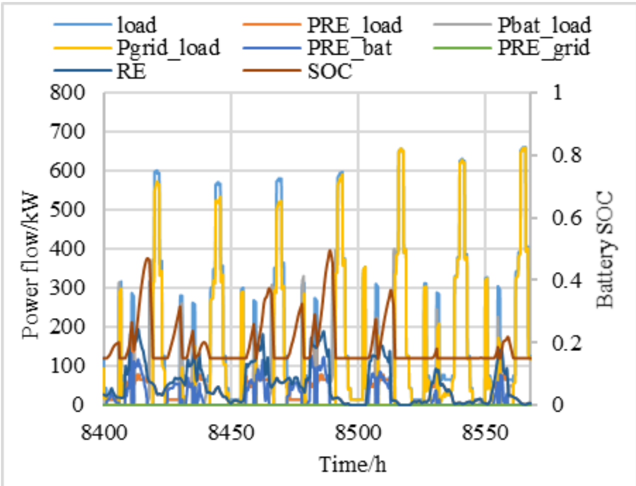

Fig. 3 Power flow in week 3 of December

For the annual performance of the hybrid PV-wind-battery system for the power supply to the high-rise building, it indicates that the battery storage can cover 4.75% of the annual electrical load, which equals to 88524 kWh. The PV-wind-battery system can cover 24.79% of total load demand in one-year period and the PV-wind system covers 20.04% of total building load without battery storage. For the PV-wind-battery system applied in the residential building in Hong Kong, the average self-consumption ratio and self-sufficiency ratio is 100% and 46% respectively, which is much higher than the case without battery for 88.31% and 41.94%. The grid feed-in renewable energy also differs greatly when the battery is not installed for the renewable system, which would bring much pressure to the utility grid for large-scale applications in the future. Fig. 4 shows the net grid power of the system with and without battery storage.

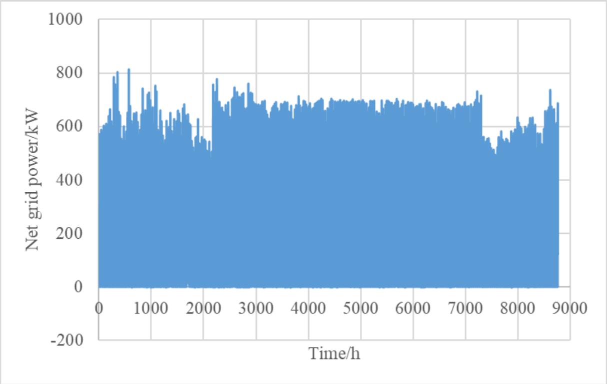

Fig. 4(a) Net grid power of the system with battery storage

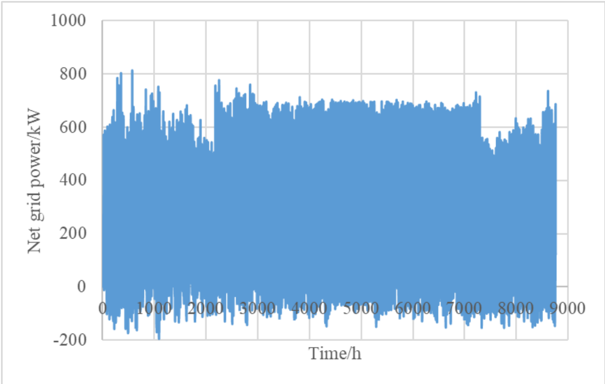

Fig. 4(b) Net grid power of the system without battery storage

B. Economic performance analysis

The investment cost includes the initial cost and maintenance cost of major components (i.e. rooftop and façade PV panels, wind turbines, battery units and inverters). About 70.76 kW of PV panels are installed in the rooftop of the high-rise building and 805.95 kW of PV panels are installed in the façade of the building with 3500 US$/kW including the installation cost. Five wind turbines are considered with a total capacity of 100 kW at a cost of 2500 US$/kW. And a small size battery storage unit of 3 kWh is matched to each home for 1440 kWh for the whole building costing 1000 US$/kWh. Inverters are installed to convert PV and wind power of 976.71 kW at a cost of 700 US$/kW. It is calculated that the annual output of the roof top PV is about 1.215 kWh/W and 218.019 kWh/m2. For the façade PV, the annual output is 0.247 kWh/W and 37.003 kWh/m2, which is much less than that of rooftop PV with the consideration of adjacent shading effects. The annual output of the wind turbine is 2.037 kWh/W. the lifetime of PV panels and wind turbines is 20 years, and the battery and inverter will serve 5 years and 10 years respectively.

The NPV of the initial cost and maintenance cost of the hybrid system is about 7627499 US$ in 20 years. And the NPV of total economic benefits of the hybrid renewable system is about -3320614 US$ in 20 years. So the LCOE of the PV-wind-battery system for 20 years is about 0.431 US$/kWh.

IV. CONCLUSION

This study investigates the technical and economic feasibilities of using hybrid PV-wind-battery system for the power supply to high-rise buildings in Hong Kong. Comprehensive economic benefits of applying the renewable system are evaluated based on the local regulations. Important findings are drawn as below:

(1) The PV-wind-battery system can cover 24.79% of the annual electrical load of a typical high-rise building in Hong Kong. The average self-consumption and self-sufficiency ratio of the hybrid renewable energy system is 100% and 46% respectively. Battery storage can not only improve self-consumption and self-sufficiency performance, but also benefit the utility grid relief.

(2) Economic benefits of the hybrid PV-wind-battery system for the power supply to the high-rise residential building including the FiT subsidy, transmission line loss saving, network expand and infrastructure saving, and social benefit of carbon reduction are considered for the LCOE evaluation. The LCOE of the hybrid PV-wind-battery system in 20 years is about 0.431 US$/kWh. This study clarifies the technical and economic feasibilities of applying the hybrid PV-wind-battery system to high-rise buildings in Hong Kong. It can provide references for the application design of PV-wind-battery systems in high-rise buildings to achieve higher penetration of renewable applications into high-density urban regions.

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