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Study on hybrid renewable energy systems for a net-zero energy commercial building sector in Hong Kong integrated with energy storage of pumped hydro and hydrogen taxis

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ABSTRACT

This study develops simulation models and novel energy management strategies of hybrid renewable energy systems integrated with energy storage of pumped hydro and hydrogen taxis for a net-zero energy commercial building sector in Hong Kong. A new time-of-use system management strategy considering the future high penetration of renewable energy installations is proposed based on the estimated local solar photovoltaic and offshore wind power potentials. The research results indicate that it is feasible to develop local hybrid renewable energy systems integrated with pumped hydro and hydrogen vehicle storages for achieving net-zero energy commercial building sectors in high-density regions. The time-of-use operations on the hybrid renewable energy and storage systems significantly reduce the annual electricity bill and equivalent carbon emissions of the net-zero energy commercial building sector. And the future time-of-use management considering renewable energy generations in determining on-peak and off-peak periods improves the renewable energy self-consumption, on-site load coverage and annual electricity bill of the net-zero energy commercial building sector compared with the current time-of-use operation. This study exploring the technical, economic and environmental feasibilities of developing hybrid renewable energy and storage systems for a net-zero energy commercial building sector provides significant guidance for policy makers to develop renewable energy for achieving carbon neutrality in commercial building sectors in urban regions.

Keywords: Solar photovoltaics, Wind turbine, Net-zero energy commercial building sector, Pumped hydro storage, Hydrogen vehicle storage

1. INTRODUCTION

Hong Kong is developing concrete plans to achieve net-zero carbon emissions by 2050, where an annual carbon emission reduction of 6.6% is needed from now on. It is reported that the estimated reduction in greenhouse gas emissions would increase the life expectancy to the equivalent of about 26000 lives and economic benefits of about HK$ 460B by 2050. And the greatest potential for reducing emissions comes from decarbonising electricity generation, developing energy efficient buildings and improving mobility [1].

Therefore, this study develops simulation models and novel energy management strategies of hybrid renewable energy systems for achieving the net-zero energy commercial building sector integrated with energy storage of pumped hydro and hydrogen taxis. The pumped hydro storage is the most mature energy storage technology applicable to large-scale energy systems, accounting for up to 90.3% of global energy storage installation capacity in 2020, accumulating to 160 GW [2]. The pumped hydro storage has long contributed to the grid stability with a high energy efficiency (75% - 85%), flexible and prompt response, and robust grid frequency support [3]. The renewable hydrogen enjoys development momentum in 2020 due to the reduced cost of electrolyzers and increasing penetration of renewable energy. The global operating capacity of hydrogen electrolyzers is about 82 MW, and over 130 GW of renewable hydrogen projects were planned at the end of 2020 [4]. Ambitious plans are also observed in many regions to develop hydrogen taxis given its long cruise distance (500 km), spacious space, quiet comfort and short refueling time (3 - 5 minutes). For example, Madrid reported to replace 1000 cabs with hydrogen fuel cell taxis [5]. Paris targets for 10000 hydrogen taxis by 2024, where the world's first hydrogen taxi company (Hype) was launched [6].

2. METHODOLOGY

This section introduces the detailed methodology of developing hybrid renewable energy systems for the net-zero energy commercial building sector integrated with energy storage of pumped hydro and hydrogen vehicles in a typical high-density city, Hong Kong. It introduces the load profile, renewable energy supply, hybrid energy storage, energy management strategy and system evaluation criteria, with the system schematic shown in Fig. 1.

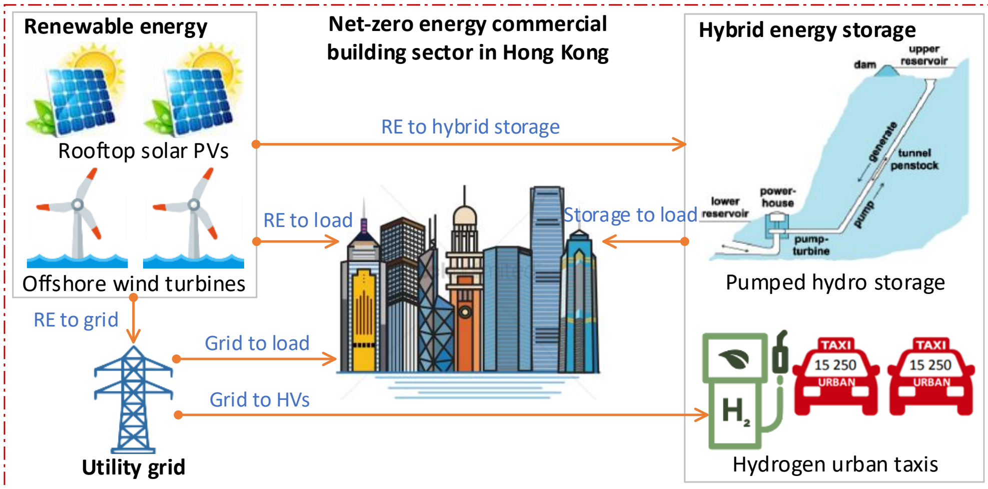

Fig. 1 Schematic of the net-zero energy commercial building sector with hybrid renewable energy systems integrated with energy storage of pumped hydro and hydrogen taxis

Load profile: The commercial sector accounts for majority of electricity consumption in high-density urban areas, for example, over 67% in Hong Kong as the largest contributor. Therefore, developing a reliable renewable energy and storage system for the commercial building sector is significant for achieving carbon neutrality in Hong Kong and similar urban areas. This study develops novel simulation models and energy management strategies of hybrid renewable energy systems integrated with energy storage of pumped hydro and hydrogen taxis for achieving a net-zero energy operation on the commercial building sector in Hong Kong based on the local estimated solar photovoltaic (PV) and offshore wind power potentials. The on-site annual energy use data of the tallest commercial building in Hong Kong (International Commerce Centre) are firstly collected and then a random variability of 10% on the dynamic electrical load is considered to obtain the estimated dynamic load profile of the commercial building sector in Hong Kong.

Renewable energy supply: The estimated development potentials of solar PV and wind turbine power in Hong Kong are adopted as the renewable energy supply for the commercial building sector. It was reported that about 5.97 GWp of rooftop PV systems can be installed in Hong Kong, and the annual potential energy output is predicted to be 5981 GWh, accounting for about 14.2% of the local annual electricity consumption in 2011 [7]. And it was studied that the potential offshore wind energy production in Hong Kong is about 112.81 × 10^8 kWh with an optimal installation layout, accounting for about 25.06% of the local annual energy consumption in 2011 [8]. Therefore, it is assumed that a total of around 40% of annual electricity consumption can be covered by the local available renewable energy, to supply power for the commercial building sector in Hong Kong for an annual balance between the energy consumption and energy generation.

Hybrid energy storage: The hybrid energy storage technologies, pumped hydro storage and hydrogen vehicle storage, are integrated with the large-scale renewable energy system for a reliable and flexible power supply to the net-zero energy commercial building sector. The pumped hydro storage is utilized given its stable and bulk power back up, high energy efficiency and prompt response. During the pumping mode, surplus renewable energy is charged to drive the water pumps to lift water from lower reservoirs to upper reservoirs (80 million m^3). And during the generating mode for meeting electrical load of commercial buildings, the water turbines are operated to release water from upper reservoirs to lower reservoirs to generate electricity. The variable speed pumps and turbines, both with 15 at a capacity of 100 MW each, are adopted in the system to flexibly and promptly response to the energy charging and discharging operations. The vertical water height between the upper and lower reservoirs is set to be 400 m.

Additionally, the hydrogen vehicle storage technology is also integrated considering the necessity of developing zero-emission vehicles in Hong Kong, especially urban taxis with a long daily cruise distance in urban areas. Currently, about 15250 urban taxis are operating in the urban streets in Hong Kong, most of which are used for over 20 years and need to be replaced [1]. The 15250 urban taxis are divided into three groups in different cruise schedules and distances including 40% (6100) in double shifts operating day and night with a cruise distance of 402 km [9], 30% (4575) in the day shift operating during 5:00 - 17:00 with a cruise distance of 201 km, and 30% (4575) in the night shift operating during 17:00 - 5:00 with a cruise distance of 201 km. The simulation model of hydrogen taxis is developed based on the commercialized product 2019 Toyota Maria with a full cruise distance of 502 km with a 5 kg hydrogen storage at 700 bars [10]. The hydrogen vehicle systems include electrolyzers (generating hydrogen driven by electric power), primary compressors (transporting hydrogen from electrolyzers to be stored in stationary hydrogen storage tanks), stationary hydrogen storage tanks, secondary compressors (transporting hydrogen from stationary storage tanks to hydrogen taxis), and hydrogen taxis (including fuel cells and mobile hydrogen storage tanks) [11].

Energy management strategy: Three energy management strategies of the hybrid renewable energy systems are developed integrated with energy storage of pumped hydro and hydrogen taxis. In Case 1 as the baseline case, renewable energy is firstly supplied to meet electrical load of the commercial buildings, and then surplus renewable energy is used to charge electrolyzers to produce hydrogen as the urban taxis require large amount of power supply to ensure daily cruises. Finally, residual renewable energy is used to drive the pumps of the pumped hydro storage technology before being fed into the utility grid. As for the load matching, the load shortage after being satisfied by renewable energy is firstly covered by the pumped storage considering the turbine capacity and discharging availability. And then the parked hydrogen taxis with available hydrogen storage are used to be discharged for meeting the electrical load considering the fuel cell capacity and storage level of mobile hydrogen tanks. The pumped hydro storage is prior to the hydrogen vehicle storage for energy discharging as the pumped hydro storage technology has a higher utilization efficiency and higher energy discharging power. The utility grid is connected to provide the power back up for electrical load and hydrogen taxis to ensure daily cruises. While Case 2 and Case 3 consider time-of-use (TOU) operation of the hybrid renewable energy and storage systems, where the current TOU schedule is concerned in Case 2 and the future TOU schedule is concerned in Case 3 (considering future large renewable energy installations in determining on-peak and off-peak periods). Specifically, Case 2 considers the current scenario, where the TOU is set according to the electrical demand distribution of the commercial building sector (9:00 - 19:00 as the on-peak period and 19:00 - 9:00 as the off-peak period). While Case 3 considers the future scenario, where the TOU is set according to the large amounts of potential renewable energy generation and electrical demand distribution of the commercial building sector (8:00 - 10:00 and 18:00 - 21:00 as the on-peak period, 21:00 - 8:00 and 10:00 - 18:00 as the off-peak period). During the on-peak time preferring a lower net grid import, the renewable energy and storage supply are utilized for load coverage and surplus renewable energy is not used for storage charging. While during the off-peak time preferring a higher net grid import, only the renewable energy supply is utilized for load coverage and surplus renewable energy is used for storage charging before being fed into the grid.

System evaluation criteria: The technical, economic and environmental performance indicators are formulated for the system evaluation and comparison of three cases on the hybrid renewable energy systems integrated with pumped hydro storage and hydrogen vehicle storage.

(1) On-site self-consumption ratio (SCR) of the renewable energy system

$$SCR = \frac{\textit{on-site RE consumption}}{\textit{total RE generation}} = \frac{E_{RE\ to\ load}+E_{RE\ to\ HV}+E_{RE\ to\ PHS}}{E_{RE}} \qquad (1)$$

where $E_{RE\ to\ load}$ is the amount of renewable energy to meet electrical demand of commercial buildings, kWh. $E_{RE\ to\ HV}$ is the amount of renewable energy for driving electrolyzers to generate hydrogen in the hydrogen vehicle system, kWh. $E_{RE\ to\ PHS}$ is the utilized renewable energy for driving pumps to lift water from lower reservoirs to upper reservoirs, kWh. E_{RE} is the total renewable energy generation from PV panels and wind turbines, kWh.

(2) On-site load cover ratio (LCR) of the commercial building sector

$$LCR = \frac{\textit{on-site supply}}{\textit{total electrical load}} = \frac{E_{RE\ to\ load}+E_{PHS\ to\ load}+E_{HV\ to\ load}}{E_{load}} \qquad (2)$$

where $E_{PHS\ to\ load}$ is the supplied energy from the pumped hydro storage system to electrical load, kWh. $E_{HV\ to\ load}$ is the supplied energy from the hydrogen vehicle system by consuming hydrogen in fuel cells to generate electricity to cover electrical load, kWh. E_{load} is the total electrical load of the commercial building sector, kWh.

(3) Annual electricity bill (EBa) of the commercial building sector

$$NB_a = E_{grid\ import\_on} \cdot Pr_{on} + E_{grid\ import\_off} \cdot Pr_{off} - E_{grid\ export\_on} \cdot FiT_{on} - E_{grid\ export\_off} \cdot FiT_{off} \quad (3)$$

where $E_{grid\ import\_on}$ is the grid imported energy during on-peak time, kWh. Pr_{on} is the electricity price of the utility grid during on-peak time, US$/kWh. $E_{grid\ import\_off}$ is the grid imported energy during off-peak time, kWh. Pr_{off} is the electricity price of the utility grid during off-peak time, US$/kWh. $E_{grid\ export\_on}$ is the grid exported energy during on-peak time, kWh. FiT_{on} is the renewable energy grid feed-in tariff rate during on-peak time, US$/kWh. $E_{grid\ export\_off}$ is the grid exported energy during off-peak time, kWh. FiT_{off} is the renewable energy grid feed-in tariff rate during off-peak time, US$/kWh.

(4) Annual equivalent carbon emissions (CEa) of the commercial building sector

$$CE_a = \left(E_{grid\ import} - E_{grid\ export}\right) \cdot CEF_{eq} \quad (4)$$

where CEF_{eq} is the equivalent carbon emissions of the utility grid, 0.572 kg CO_2/kWh [12].

3. RESULTS AND DISCUSSION

This study develops simulation models and novel energy management strategies of hybrid renewable energy systems integrated with energy storage of pumped hydro and hydrogen taxis for achieving net-zero energy commercial building sector in Hong Kong considering the local solar PV and offshore wind turbine energy potentials. The technical, economic and environmental performances of three net-zero energy commercial building sector cases are evaluated and compared with different energy control strategies.

Fig. 2 compares the system technical performances of three net-zero energy commercial building cases including on-site renewable energy self-consumption ratio (SCR), on-site load cover ratio (LCR) and net grid import (NGI). It is indicated that the baseline case (Case 1) achieves the highest SCR and LCR compared with the cases considering TOU operations (Case 2 and Case 3), as the system energy exchange in Case 2 and Case 3 is limited by the TOU managements. The SCR and LCR are slightly improved in the future TOU case (Case 3) compared with the current TOU case (Case 2) by 5.04% and 2.81% respectively. Because more surplus renewable energy is utilized by the hybrid pumped hydro and hydrogen vehicle storage with improved TOU management considering renewable energy production. And the grid integration performance of TOU cases is obviously better than the baseline case (Case 1), where the NGI is reduced by 45.77% and 26.08% respectively in Case 2 and Case 3.

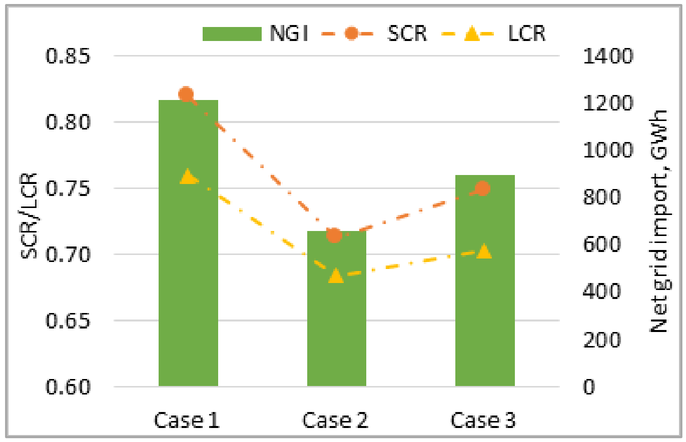

Fig. 2 Comparison of system technical performances of three net-zero energy commercial building cases

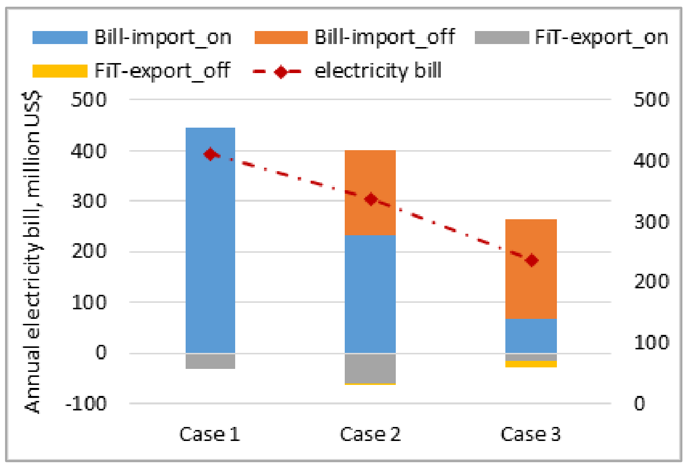

Fig. 3 Comparison of annual electricity bill of three net-zero energy commercial building sector cases

The annual electricity bill of three net-zero energy commercial building sector cases is analyzed and compared including the electricity bill and grid feed-in tariff (FiT) of on-peak and off-peak periods as per Fig. 3. It is assumed that the electricity price during on-peak and off-peak periods are 0.15 US$/kWh and 0.04 US$/kWh respectively, and the electricity price in the baseline case without TOU management is about 0.1 US$/kWh [13]. The grid FiT rate of renewable energy is calculated as the ratio (10%) of the corresponding electricity price with large amounts of renewable energy production. It is indicated that the baseline case without TOU management has the highest electricity bill with the maximum costs, while the electricity bill of cases considering TOU managements is lower by 18.10% and 42.54%, respectively. The future TOU case has a lower annual electricity bill than the current TOU case by 29.84% (US$ 100.69M) with much lower electricity bill during on-peak time.

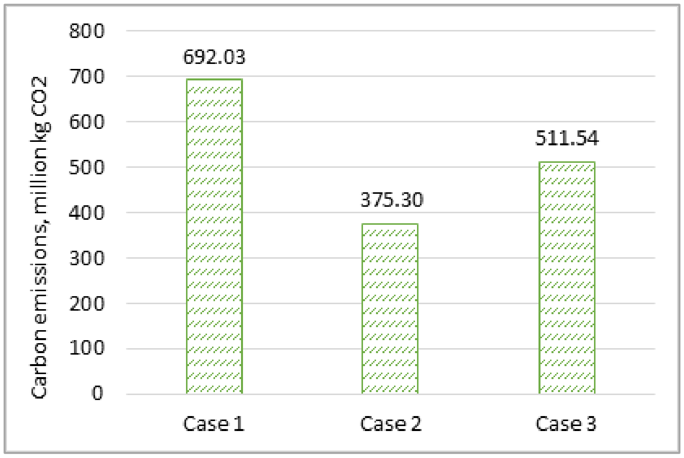

Fig. 4 Comparison of carbon emissions of three net-zero energy commercial building sector cases

The annual equivalent carbon emissions of three net-zero energy commercial building sector cases is calculated to evaluate the environmental performance of the hybrid renewable energy and storage systems with different energy management strategies as shown in Fig. 4. It shows that the TOU management significantly reduces the carbon emissions of the net-zero energy commercial building sector, by 45.77% in the current TOU case (Case 2) and by 26.08% in the future TOU case (Case 3) compared with the baseline case (Case 1). Because TOU management improves the grid integration with the hybrid renewable energy and storage systems. The carbon emissions of the future TOU case are 36.30% higher than the current TOU case as more renewable energy in the current TOU case is exported into the utility grid, and the current TOU operation has a high dynamic energy mismatch between the renewable energy generation and electrical demand without considering the renewable energy production in determining the on-peak and off-peak time periods.

This study develops simulation models and novel energy management strategies of hybrid renewable energy systems integrated with energy storage of pumped hydro and hydrogen taxis for a net-zero energy commercial building sector in Hong Kong. There are limitations in the present study, for example, the load profiles of the net-zero energy commercial building sector are obtained based on the on-site collected energy use data of a typical local high-rise commercial building and then considering a random variability of 10%. The hybrid renewable energy and storage systems are set up in the TRNSYS 18 platform with commonly used robust professional modules. The basic energy balance based energy management models of renewable energy and storage systems have been validated by experiments in a previous publication of the authors.

4. CONCLUSIONS

This study presents simulation models and novel energy management strategies of hybrid renewable energy systems integrated with energy storage of pumped hydro and hydrogen taxis for achieving the net-zero energy commercial building sector in Hong Kong. The future time-of-use system management strategy is proposed considering the local solar photovoltaic and offshore wind power potentials, and its techno-economic-environmental performances are compared with the current grid time-of-use case and the baseline case without time-of-use operation. The main conclusions of the present study are drawn as below:

(1) It is feasible to achieve net-zero energy commercial building sectors in high-density regions by developing local hybrid renewable energy systems integrated with pumped hydro and hydrogen vehicle storages.

(2) The time-of-use operations on the hybrid renewable energy and storage systems significantly reduce the annual electricity bill and annual equivalent carbon emissions of the net-zero energy commercial building sector, while decrease the renewable energy self-consumption and on-site load coverage.

(3) The future time-of-use management considering renewable energy generations in determining the on-peak and off-peak periods improves the renewable energy self-consumption, on-site load coverage and annual electricity bill of the net-zero energy commercial building sector, while also increases the system carbon emissions compared with the current time-of-use operation.

(4) This study analyzes and compares the technical, economic, and environmental feasibilities of developing hybrid renewable energy systems with pumped hydro and hydrogen taxis for a net-zero energy commercial building sector in Hong Kong under three different energy management strategies. It provides significant guidance for policy makers to develop future time-of-use operations of hybrid renewable energy and storage systems for achieving carbon neutrality in the commercial building sectors in urban regions.

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